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Study of Internal Waves in the Persian Gulf Using Field Data and Satellite Images

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ABSTRACT

In this research, density, temperature and salinity fields were investigated in different seasons using observational data of ROPME Marine Cruise in the Persian Gulf (PG). Based on in-situ measurements, areas with density stratification were identified. Having analyzed Landsat and SAR satellite images, internal waves (IW) were detected in different regions of the Persian Gulf and more frequently in the eastern part of the PG related to seawater stratification. Based on analysis of satellite images, it is shown that the length of internal waves crest detected in the north-eastern part of Al-Zhahirah (Qatar) was more than 120 km; while it's in range of 5 to 20 km in the south and east of Larak Island, 15 to 40 km in the north-east of Abu Musa Island, and 3 to 65 km in the south-east and south of Hondurabi Island. Moreover, IWs with shorter crest's wide were recognized near Lavan, Siri, Farur, Halul, Khark Islands and Bandar Lengeh, as well. In addition, studying satellite images in the above mentioned areas for a longer time period from 2000 to 2017 showed that IWs mostly occur in the eastern part of the PG in summer and disappear in other seasons.

1. Introduction

Nowadays, the seas and the oceans have important effects on human life and consideration of those effects is a main subject of research in marine environments. Humans exploit the ocean and marine resources and use coasts, extensively. Coastal and offshore constructions are increasingly developed to exploit marine resources including oil and gas resources. On the other hand, seas are considered as one of the best transportation routes in the world. In addition, the oceans play a significant role in the formation of atmospheric systems, climatic changes, rainfall formation, storms, and so on. Although, coastal zones comprise a limited area of the earth's surface, the importance of those areas is far greater than their size. The beaches are places for habitation, recreation, boating, fishing, diving, etc. Therefore, recognizing the processes associated with oceans, seas, and especially coastal waters, such as waves, wind, flow, etc., are of great importance [1].

The processes are affected by physical factors; therefore, to understand the processes and their impacts on human life is necessary to understand the effective and dominant physical processes in such regions [2]. Understanding the physical processes in marine environment helps in better awareness of the resources available to develop and conserve the sustainability of marine environment. For example, temperature and salinity, along with pressure, are important physical properties affecting the seawater density, which play an important role in controlling the dynamics and thermodynamic behavior of seawater and oceanic waters [3]. Heat flux, evaporation, rain, river flow, freezing and melting of sea ice are main factors affecting the temperature and salinity distribution in the oceans. Temperature and salinity changes also directly affect the water density. The distribution of density in the water column in oceans also directly affects the horizontal gradient of pressure as well as oceanic currents. Therefore, the distributions of temperature, salinity and density in the oceans are of great importance [1]. As these physical characteristics are changed temporally and spatially, it is important to study these changes.

Since water covers nearly 70% of the earth's surface, global climatic changes are dependent on the exchange of matter and energy between the atmosphere and hydrosphere. Increasing concerns about the global threat of climate change has increased interests in research and development of renewable energy technologies. The ocean provides a vast source of potential energy resources, and investment in ocean energy is growing as a renewable energy technology. Research on the conversion of thermal energy of the ocean, and waves, tidal and wind energy in the seas and oceans has led to the development of new technologies and, in some cases, commercial development. As it is noted, one of those energy sources is the energy obtained from the oceans and seas. It is hoped that these new energy sources will help reduce the global threats of climate change caused by the use of fossil fuels [4].

The Persian Gulf is a waterbody that runs along the Oman Sea and located between Iran and the Arabian Peninsula. The length of the Persian Gulf from the Strait of Hormuz to its last point in the west is about 990 km and its maximum width is 370 km, which form a semi-enclosed basin that is located between the geographic latitudes 24˚N and 30˚N and geographic longitudes 48˚E and 56˚E [5].

There are no marine ridges in the Strait of Hormuz, and water depth reaches up to 2000 meters only about 200 km far from the Strait of Hormuz toward the Oman Sea. The maximum width of the Persian Gulf is 290 km. The deepest point of the Persian Gulf is 93 m that is located at 15 km distance from Greater Tunb and the Shallowest point with a depth of 10 to 30 m is located in in the western part [6]. The Persian Gulf in the Middle East is considered as a major way to connect Europe, Africa, South Asia and Southeast Asia. It has the most privileged strategic and political status in this region, and establishment of several military bases in neighboring countries of the Persian Gulf shows its military and strategic importance [7].

The internal waves are produced at the interface between two fluids of different densities, which the difference in density is due to the difference in water temperature and salinity at various depths [8]. In other words, similar to different waves are formed in the sea surface, some waves may be formed inside the sea and between different layers with different densities called internal waves [9]. Previous studies conducted on the internal waves have shown that tidal flows are the most important factor in producing these waves [10].

Internal waves created by ship movement were identified by Ekman for the first time in 1904. These waves with wavelengths ranging from a few meters to tens of kilometers, the frequency of a few minutes to several hours and a range of few meters to tens of meters can cause environmental changes such as nutrient mixing, fluctuation in the distribution of biomass and suspended materials in water column [11]. Internal waves can strongly affect the processes in the ocean. The movements caused by internal waves play an important role in the oceanic surface processes. They can move more than a few hundred kilometers, causing mass transmission and impulses. Generally, the formation of internal waves is associated with a significant shear vertically, followed by the processes such as turbulence and mixing. For this reason, the mechanism for the formation, development, and propagation of internal waves is always focused by marine science researchers [12].

These waves may also influence the sound velocity distribution in horizontal and vertical directions, so it is required to investigate such waves specially for submarine navigation. It seems to be essential to conduct research on the internal waves regarding the marine transportation, coastal engineering, aquatic organism movements (as it is important for the fishery), oil projects and offshore platforms [13, 14].

Research on the internal sea waves and turbulence began about a century ago. Jackson (2007) studied the internal waves detection using the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor. In this study, internal waves were studied in 15 regions around the world, including the southern China Sea, the Gulf of California, the Sulu Sea, etc. [15]. Harris and Decker (2017) evaluated the internal waves on the basis of field measurements at Port Susan and Puget Sound. In this study, the data were collected from 2003 and 2005 using CTD, ADCP and visual observation recordes [16]. In another study, Eqtesadi and Bidokhti (2004) studied the role of internal waves in marine water stratification.

In addition to experimental simulation and field study in the Persian Gulf, this study examines the theory of

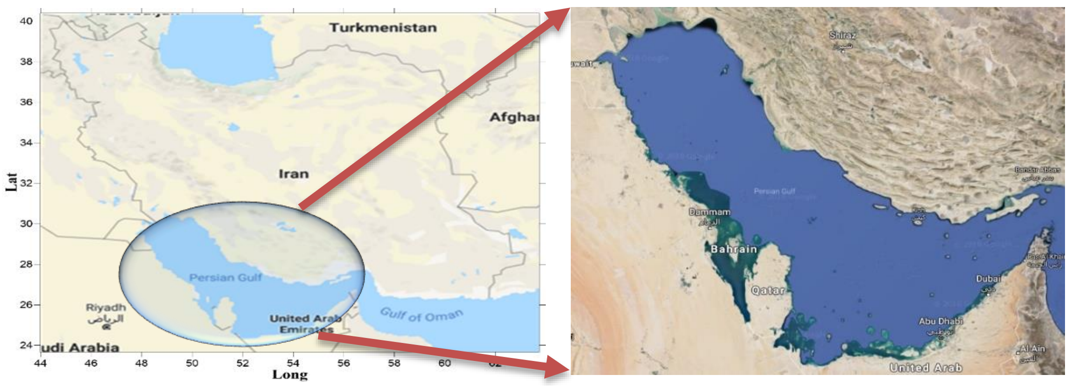

Figure 1. Geographical Location of Persian Gulf

the normal modes of internal waves, which both methods are compared and interpreted [17]. Deldar and Heidari (2017) conducted a study in Iran regarding the identification of internal waves in the Persian Gulf [18].

Generally, measuring the water temperature, or applying salinity sensors, flowmeter and acoustic devices were used to identify the internal waves in the previous studies (e.g., Zhou et al., 1991). Today, satellites are used to detect internal waves, given that internal waves are propagated in a large-scale environment (e.g., Small and Martin, 2001).

2. Materials and Methods

In previous works, the mechanism of formation of the internal waves that is associated with topographic effects, and the formation of these waves due to the movement of tidal currents over the sea bottom friction, oceanic ridges and continental shelf fractures were studied by field measurements, numerical models and satellite images in different oceanic regions. Accordingly, the main objective of this study was to detect internal waves using Landsat 7, Landsat 8, ASTER satellite images and SAR images in the Persian Gulf.

Based on field measurements by marine patrol projects conducted by Regional Organization for the Protection of the Marine Environment (ROPME) and PG-GOOS in the Persian Gulf, the formation of density stratification is evident in most parts of the Persian Gulf, especially in the warm seasons [19].

In this study, the data from marine patrols and associated marine organizations including the Iranian National Institute for Oceanography and Atmospheric Science in 2000, 2001, 2012 and 2013 was used to identify the internal waves formed by stratification of the water column. The location of the measurement stations in those marine patrols, including ROPME, is shown in Figure 3.

To investigate the water stratification, vertical cross-sectional distribution profiles of physical parameters such as salinity, temperature and Sigma-t have been plotted in different seasons using the Grapher software. In the next step, existing field data were analyzed and the areas with density stratification were identified. Then, the satellite images were obtained, which were captured at the same time (in 2000, 2001, 2012, and 2013). Afterward, Internal waves were detected by performing required corrections.

The SNAP and ArcMap software were used to make the corrections to detect internal waves. To find out the permanent or seasonal nature of the internal waves in the Persian Gulf, the satellite images from the five years in all seasons were analyzed and processed after primary processing using appropriate filters by the SNAP and ArcMap software.

In this study, Landsat 7, 8 and Sentinel-1 SAR images captured from 2000 to 2017 were used to detect internal waves in the Persian Gulf. Landsat 8 is the eighth satellite in the Landsat Satellites Program, and is the seventh satellite successfully launched on February 11, 2013 (Landsat 6 was not successfully launched). The satellite has two sensors, one is the operational land imaging sensor and the other is thermal infrared sensor. It also has 11 bands [20]. In this study, bands 4 to 6 were used to detect internal waves in the desired range. The SAR is a radar imaging system extracting a two-dimensional image of a target in both Range and Azimuth directions. As SAR images extract the radial cross section profile of surface or volumetric elements within the microwave wavelengths, they can be a good source for the detection of scattering centers [21]. The C frequency band in SAR radar images was also used to detect internal waves.

Due to the lack of annual field data for the Persian Gulf, Landsat 7, 8, ASTER and SAR images were used for the years without field data, then the internal waves were detected using SNAP and ArcMap software.

3. Results and Discussion

In the present study, by examining a series of physical parameters measured by ROPME and PG-GOOS marine patrols, such as salinity, temperature and sigma t, it was found that internal waves occur in the Persian Gulf during warm seasons. Sea water temperature and salinity changes with depth during the warm seasons, which causes water stratification and form thermocline. It is expected that this stratification will produces internal waves. Also, the satellite images were verified by measured field data. Based on the analysis of satellite images using SNAP and ArcMap software, the crest of internal waves was identified in these areas. These waves are observed mostly in the eastern and central parts of the Persian Gulf.

The incident zones of the internal waves, along with the RAPME patrol stations in 2000 and 2001, and the PG-GOOS patrol in 2012 and 2013, were presented below (Figure 2). It can be shown by investigating the internal waves using the satellite images in the warm season.

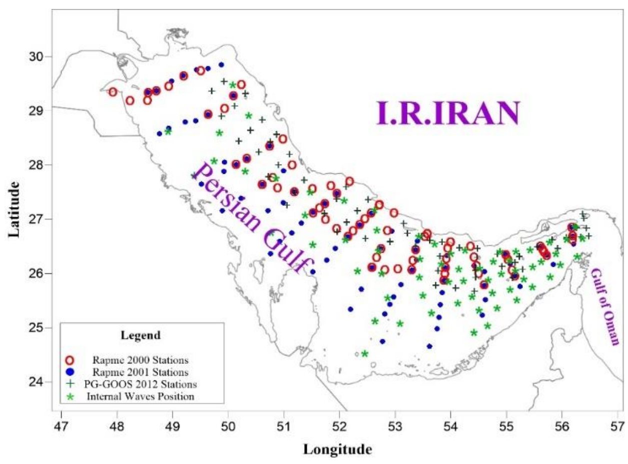

Figure 2. The position of the field measuring stations and the position of the internal waves in the Persian Gulf

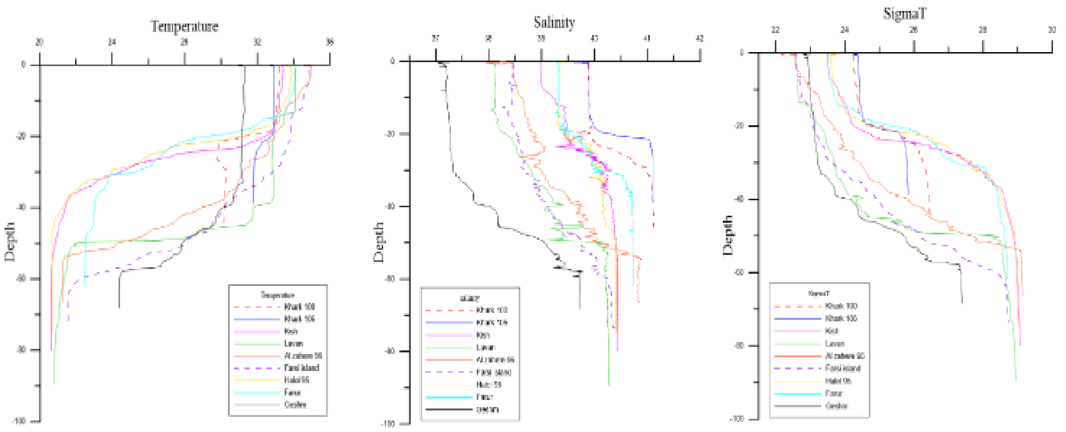

Figure 3. The changes in temperature, salinity and sigma t with depths in different regions of the Persian Gulf during one year in 2000

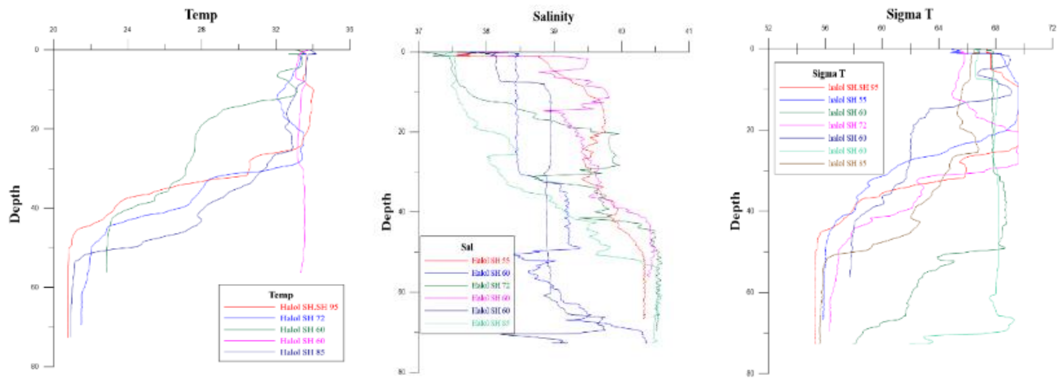

Figure 4. Diagrams of the variations in temperature, salinity and sigma t around Al-Zahereh in 2000

The changes in temperature, salinity and sigma t diagrams in the Persian Gulf were analyzed using the data from ROPME during one year in 2000 (Figure 3). According to these diagrams, it is found that the changes in temperature and salinity were not significant in the cold seasons. On the contrary, the changes in temperature and salinity in warm seasons were high in most areas, indicating the stratification of the water column in such areas.

The vertical diagrams of the physical parameters show that there are high changes in temperature, salinity, and sigma t in the warm seasons, resulting in high stratification variations, which form thermocline in the warm seasons when the internal waves are formed based on the stratification in water column.

All possible areas were investigated using satellite images and compared with field data, some of which are presented here. Figure 4 shows the temperature, salinity and sigma t changes in 2000 around the Al-Zahereh. According to the temperature diagram, the temperature strongly changes around the Al-Zahereh at a depth of 20 to 40 meters (decreased from 31°C to 21°C), but no significant changes can be seen in in salinity. The changes in sigma t were also observed at a depth of 20 to 45 meters. These variations indicate that the stratification and thermocline occur in the basin due to the strong changes in temperature and sigma t.

As a result, stratification is more evident in water bodies of this region based on temperature and sigma t changes. Therefore, according to the field data, internal waves are expected to occur around the Al-Zahereh, as it easily can be seen on the satellite images.The image recorded by Landsat 7 on 15/04/2003, shows the internal waves around the Al-Zahereh (Figure 5). The waves begin to spread at a distance of 55 km from the north-east of Al-Zahereh, and progressed to the northern parts of the city. The direction of these waves are towards the north and west. This image was captured at the same time when the field data were measured. Therefore, it can be concluded that the main cause of the internal waves in this region is the effect of water column stratification.

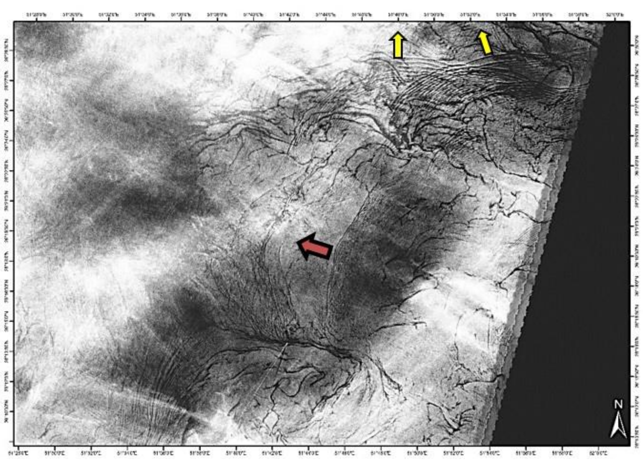

Figure 5. Landsat 7 image, internal waves around the Al-Zahereh on 15 April 2003

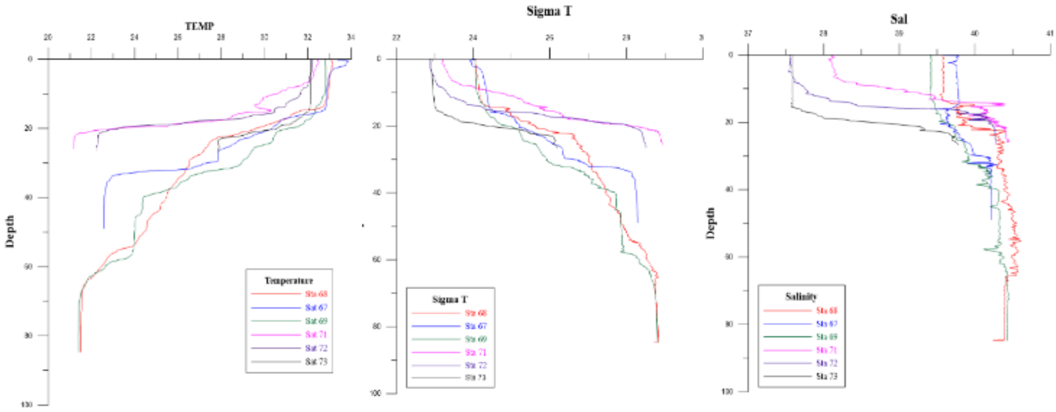

Figure 6. Diagrams of temperature, salinity and sigma t variations with depth around Abu Musa Island in 2001

The temperature, salinity and sigma t variations with respect to the water depth around the Abu Musa Island in 2001 are illustrated in Figure 6. There are strong changes in temperature at depths between 15 and 40 m, as well as strong changes in sigma t at depths between 18 and 35 m indicating that water stratification and thermocline occurred in this basin due to the strong changes in temperature and sigma t. Salinity changes are negligible as the depth is changed, therefore it has lower effect on stratification than temperature and salinity (sigma-T). Accordingly, internal waves are expected to occur around the Abu Musa Island, as it can be seen in satellite images.

Figure 7 shows the internal waves around the Abu Musa Island captured by ASTER in the summer of 2001. These waves propagate to the west and south-west. There are two internal wave packages that are located at 15 km distance from northeast and 20 km distance from the northwest of the island. According to the temperature and salinity diagrams, their variations are high in this area and stratification occurs. As expected, the internal waves are due to the water column stratification in this region.

The diagrams of temperature, salinity and sigma t variations with respect to the water depth around the Hondurabi Island in 2013 are presented in Figure 8. There are strong changes in temperature at depths between 35 and 60 m, as well as strong changes in sigma t at depths between 35 and 50 m indicating that water stratification and thermocline occurred in this basin due to the strong changes in temperature and sigma t. Salinity has lower effect on stratification than temperature and salinity (sigma-T), because it changes slightly by changes in the water depth. Accordingly, internal waves are expected to occur around the

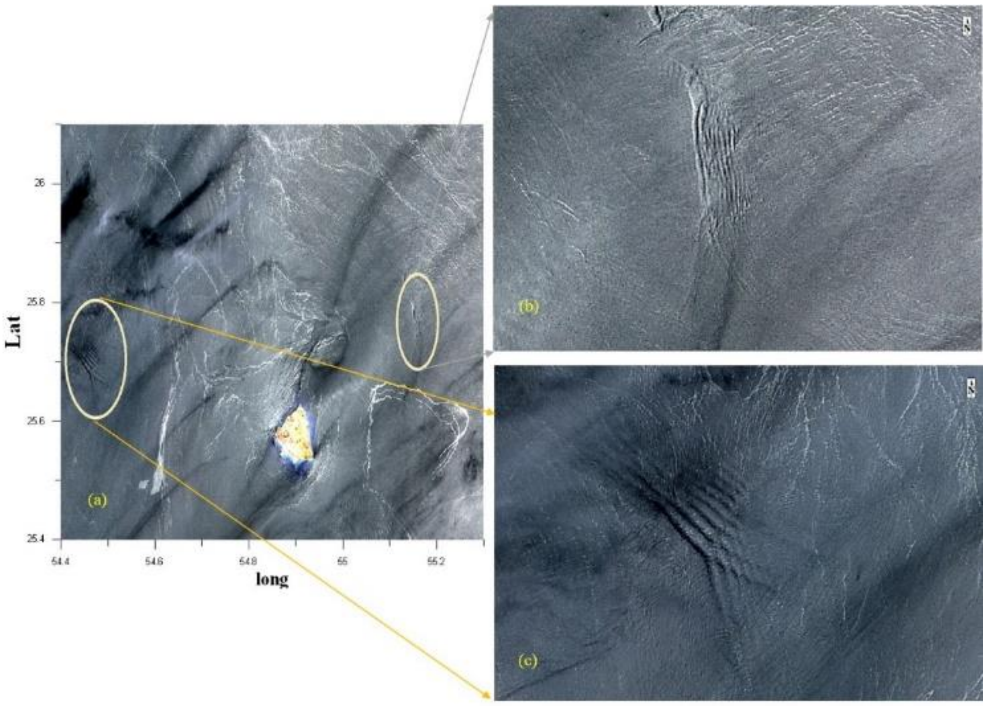

Figure 7. ASTER image recorded on 13 May 2001, (a) An overall view of Abu Musa Island and areas around it; (b) Internal waves at 15 km distance from the northeast of Abu Musa Island; (c) Internal waves at 20 km distance from the west of Abu- Musa Island

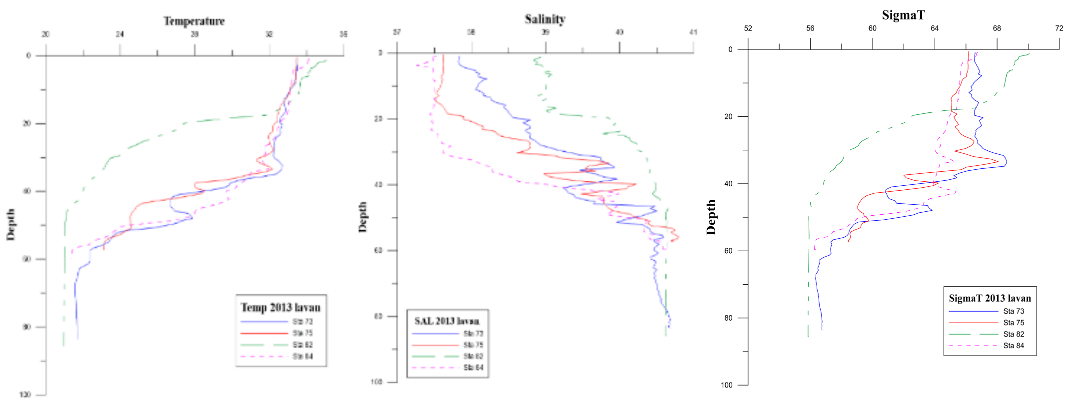

Figure 8. Diagrams of temperature, salinity and sigma-T variations with depth around Hondurabi Island in 2013

Hondurabi Island, as it can also be seen in satellite images recorded in the warm season of 2013.

The image recorded by Landsat 8 on 23 June 2013, shows the internal waves at a distance of 46 to 60 km from south of Hondurabi Island (Figure 9). This waves package propagates toward the southeast and western. According to the temperature and salinity diagrams, their variations are high in this area which result in water column stratification. As expected, the internal waves occurred due to the water stratification in this region.

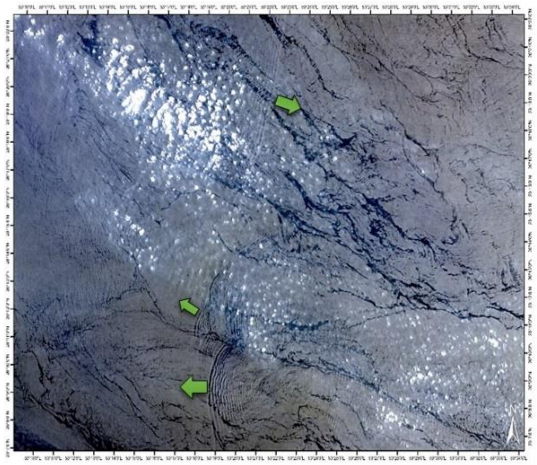

Figure 9. Landsat 8 image showing internal waves around the Hondurabi Island on 23 June 2013

Also, water column stratification is not expected to occurs in the cold season due to the lower temperature and low changes in water salinity and sigma t. To evaluate this hypothesis, field data recorded in the Das Island was analyzed. Figure 10 shows temperature, salinity and sigma t changes in the cold season of 2012. The results showed that water column stratification do not occurs in these area in the cold season. Therefore, water internal waves are not expected to occur in the region during the cold season, which can be clearly seen by analyzing the satellite images in the cold season of 2012.

The location of Das Island is shown in the image recorded by ASTER on 2 October 2012 (Figure 11). Analysis of the satellite images showed that internal waves do not occur around Das Island in the cold season. According to the temperature, salinity and sigma-T diagrams, the variations of these parameters are low in this area and there is no stratification in the water column. As expected, the internal waves also do not occur due to lack of stratification in this region in the cold season.

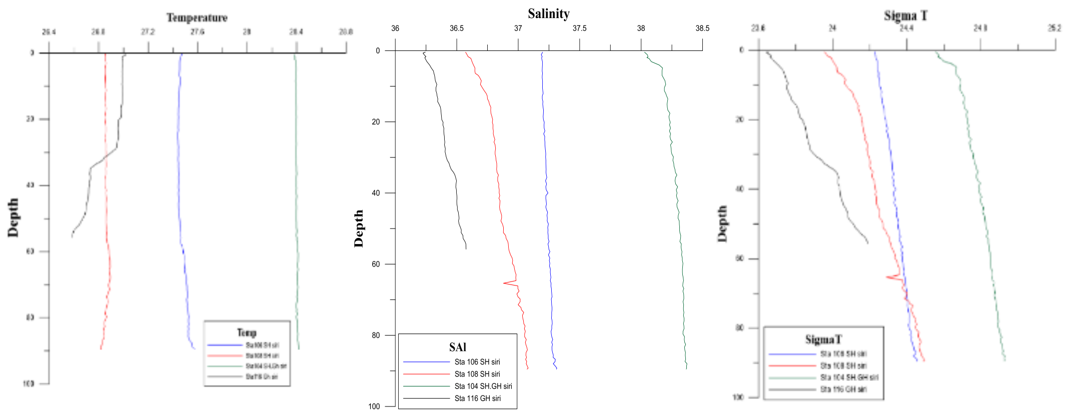

Figure 10. Temperature, salinity and sigma-T variations around Das Island in the cold season of 2012

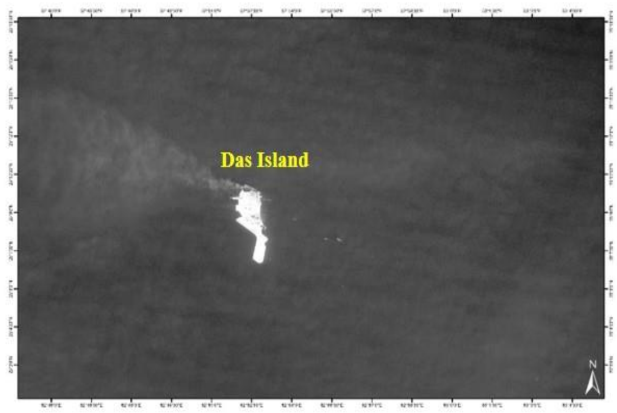

Figure 11. ASTER image showing internal waves around Das Island on 10 October 2012

In this study, due to the lack of field data from 2000 to 2017, Landsat, ASTER and SAR images were used for the years that field data were not available to determine the existence of internal waves in different areas of the Persian Gulf, as well as the continuity of these waves in the warm season. Then, the internal waves were detected using SNAP and ArcMap software. Figure 12 shows Landsat satellite images for the years 2002 and 2014. It shows how the waves may be generated. Figure (12a) shows the internal waves at a distance of 12 km from north of the Farur Islands in 2014 and Figure (12b) shows the internal waves at a distance of 6.5 km from west of Larak Island in 2002 that their direction is toward the northwest.

The internal waves were detected based on the satellite images from Landsat and SAR in 2000 and 2017. Figure (13c) is the sentinel-1 image recorded on 20 August 2015 showing the internal waves in the northwest of Farsi Island, and Figure (13d) is the SAR satellite image of Sentinel-1 recorded on 29 March 2015 showing the formation of internal waves at a distance of 35 km from the east of Khark Island (Figure 13).

The internal waves were not considerable based on the Landsat, ASTER and SAR images in the studied area

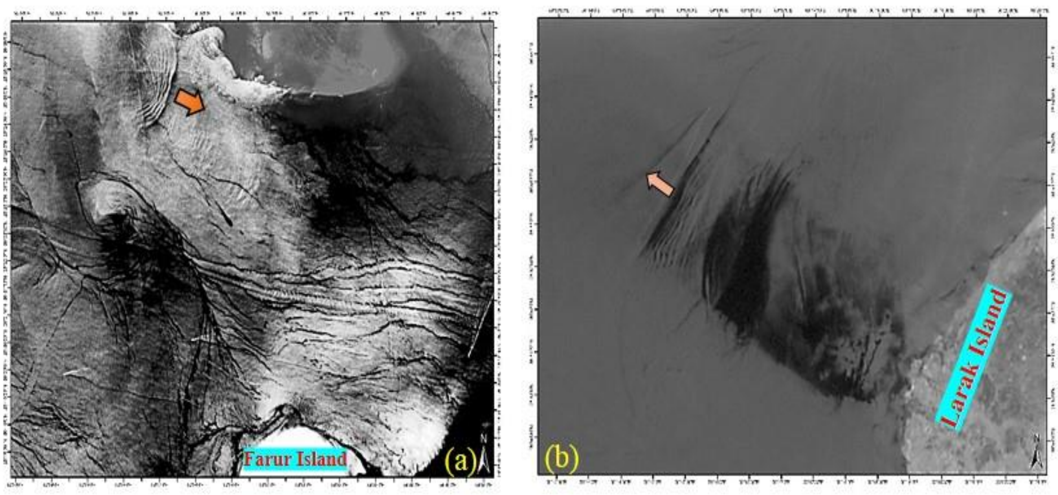

Figure 12. Landsat image showing the internal waves, (a) the internal waves around Farur Islands recorded on 07 April 2014; (b) the internal waves around the Larak Island on 25 May 2002.

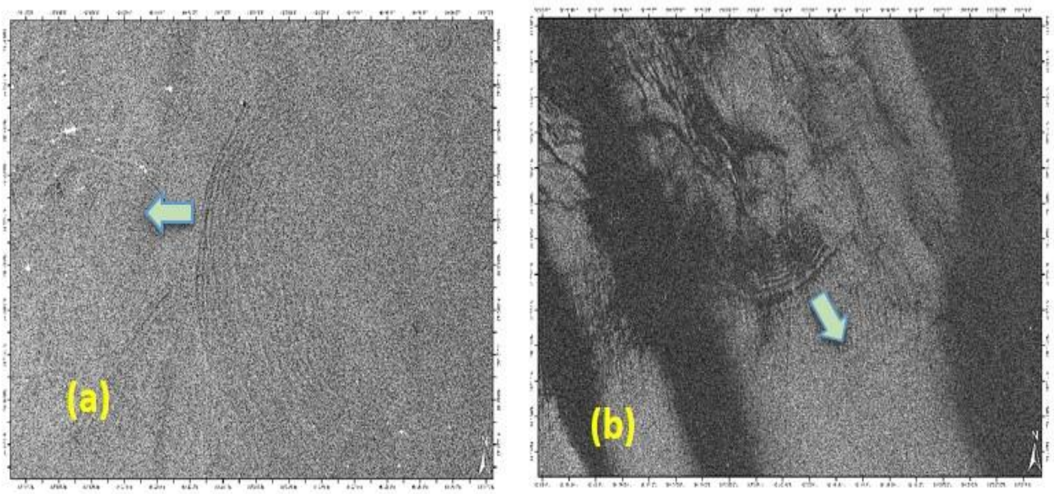

Figure 13. SAR Satellite images of Sentinel-1 showing the internal waves, (a) the internal waves around Farsi Island recorded on 20 August 2015; (b) the internal waves around the Khark Island on 29 March 2015.

during the cold seasons. Thus, it can be concluded that the internal waves occurring in different parts of the Persian Gulf are not permanent and occur only in the warm season during summer, when strong changes in temperature, salinity, and density in the vertical direction lead to the stratification of water column. Therefore, the occurrence of internal waves in different regions of the Persian Gulf can be considered as seasonal phenomenon that is corresponded to the water column stratification.

4. Conclusions

In this study, water temperature, salinity and density were studied in different seasons of the year based on the field data from marine patrols in the Persian Gulf. In addition, Landsat, ASTER and Sentinel-1 (SAR) images were analyzed by SNAP and ArcMap software to detect the occurrence of internal waves in the Persian Gulf. Internal waves were detected during

warm season according to the satellite images. Based on the analysis of satellite images, the length of the crest of the internal waves detected in the north-eastern part of the city of Al-Zahereh (Qatar) were more than 120 km; the south and southwest of Khark Island were about 100 km, the north-west of Abu Musa Island 3 to 35 km; and south and southwest of Hondurabi Island was estimated as 20 to 65 km.

In conclusion, internal waves in the Persian Gulf appear to be observed at relatively high density (frequency) in the warm seasons, corresponding to the stratification of the sea water column. Finally, other factors, such as the movement of tidal currents over the sea bottom with variable slope, do not play a significant role in the formation of internal waves.

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