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Seasonal variations of eddies in North Indian Ocean using wind data and satellite altimetry

Mina Mohammadi Pasand[1], Abbasali Aliakbari Bidokhti[1], and Hesameddin Mehrfar[2,*]

[1]Institute of Geophysics, University of Tehran Tehran, Iran

[2]Department of Physics, University of Ayatollah Ozma Borujerdi, Borujerd, Iran

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Abstract

Identifying surface current fluctuations on a monthly basis in an oceanic area, it is possible to recognize the manner of pollutant accumulations, sea fronts, and ocean eddies' propagations. Investigation of eddies as important factors in horizontal ocean mixing is also essential because of their influence on biological population in the sea, the transfer and distribution of heat and salinity, and the ocean heat exchange with the atmosphere. Observations show that the sea surface current is usually controlled by two factors including: Ekman component (wind driven) and geostrophic parameter (due to the changes in mean sea level). Because direct field measurements for ocean currents are difficult and time consuming, the monthly OSCAR satellite data for the Indian Ocean are used for a period of three years, to map current vectors that are illustrated in the ArcMap software. Indexed eddies for each season are identified and their characteristics are investigated. The results show that the eddies formed in summer and autumn have the higher speeds with maximum value of about 1.3 m/s of the Somali Coast and less energetic ones are formed over the other vast oceanic areas. While the ones created in winter have maximum velocity of about 1.5 m/s and also the currents with intermediate-scale have a velocity of 0.7 m/s.

Keywords: Eddy; North Indian Ocean; Surface currents; OSCAR data.

1. Introduction

Regular periodic study of surface ocean currents is particularly important. Studying the surface ocean currents can lead to understanding the transport of traces of biological harmful masses similar to algal blooms, coastal sediments, oil masses, and floating pollutants. Identifying

* Corresponding Author: hmehrfar@gmail.com

surface current patterns are also important in conducting ships in designated routes that can also be energy and time savings. Another important consideration is the recognition of how the heat is distributed over the ocean surface. Surface currents of the two Pacific and Atlantic Oceans, are typically modified by the topography of their basins. But the surface fluctuations of the North Indian Ocean are heavily influenced by the Indian monsoon. The Indian Ocean is surrounded by the countries such as Iran, Pakistan, India and Bangladesh in the north, the Malay Peninsula, the Swanda islands in Indonesia, and Australia in the east, the South Pole in the south, and Africa and the Arabian Peninsula in the west. The Gulf of Aden and the Oman Sea are in the northwest of the ocean. The Red Sea and the Persian Gulf are the two sources of salt water in the Indian Ocean. Underwater surface layers in the Indian Ocean, especially in the north, have the least amount of oxygen (Puthezhath, 2014).

The Indian monsoon has an annual cycle in which the winds' directions are reversed. The monsoon is like a coastal wind (breeze), on a much larger scale. A summer monsoon flows from south-west direction and brings a lot of moisture that is caused rainfall over the Indian subcontinent. In the winter, the winds come from the north-east direction (Sikhakolli *et al*., 2013).

Bansal *et al*. (2014) presented a report on the Indian Ocean surface currents. They showed that the currents can be calculated as a combination of wind-driven currents and other factors. Ekman current is obtained using OSCAT data and its ocean surface currents. Components of geostrophic currents are also estimated using sea surface elevation. Grid-maps refer to the local Coriolis Effect are used to estimate the geostrophic currents in the Indian Ocean. Coriolis Effect exacerbates its impact in the equatorial region at five degrees in the north and south sides of the equator (Liu and Weisberg, 2007).

Shinoda *et al*. (2013) made compact measurements during CINDY / DYNAMO field operations (autumn/winter-2011), from upper layer of the Indian Ocean. They described large-scale ocean current fluctuations based on the analysis of data extracted from the satellite. Surface currents, sea level elevation, salinity of surface water, surface winds, and sea surface temperatures during the CINDY/DYNAMO field operations, have been analyzed from satellite observations. Western surface winds near the equator, especially during late November and late December, exceed 10 m/s. These western winds produce strong eastward jets (larger than 1 m/s) on the equator.

Sanchez-Reales *et al*. (2012) studied the ocean surface geostrophic currents using satellite altimetry data. For this purpose, they used GOCE satellite data and satellite altimetry observations (T/P, Jason ½, ERS-½, and GEOSAT) and then compared the results with the general oceanic circulation model that showed a good agreement. Shenoi *et al*. (1999) examined the circulations and their kinetic energy in the North Indian Ocean using data from Lagrangian floats. In this research, 412 floating buoys were used in the North Indian Ocean to study the sea surface currents and their energy. These buoys were moving at a depth of 15 meters to estimate the velocity of near sea surface currents. Unlike previous studies, these surveys showed that the equatorial jet extends in the eastern Indian Ocean, and is appeared on the equator during the month of July to August and heads toward the west. Comparison of buoys data with seasonal mean dynamic topography showed that the patterns of surface circulations derived from the dynamical topographic were always described as surface currents in the Indian Ocean. Also, the results of bathymetry data and buoy data in the Bay of Bengal were different throughout the southwest monsoon, but the results were similar during the northeast monsoon.

Wyrtki (1976) examined the distribution of kinetic energy for all oceans around the world using data from the floating ship, and found similar estimates for the North Indian Ocean. In a study by the Heyderabad Research Oceanic Institute in India in 2014, the surface currents of the North Indian Ocean were estimated. The data were obtained from Oceansat-2 observations and SARAL Altika sea level elevation data. The research was conducted from March 2013 to November 2014, and the results were compared with the results of floating buoys and results of OSCAR currents and AVISO geostrophic currents that were in good agreement (INCOIS, 2015). Lagerloef *et al*. (1999) used the topographic data, the wind stress from satellite, the calibrated data from a physical statistical model, and the data from floats located in 15 meters of the water surface, to estimate the equatorial surface currents in Pacific Ocean.

Cutler and Swallow (1984) used data collected by the British Meteorological Office from the daily record notes to provide surface currents' information as a useful atlas. Their studies showed that during the year, the currents in the Indian Ocean are stronger than those in the Pacific Ocean and the Atlantic Ocean, and the data from the floating vessels are reliable with good approximation. The atlas is the best source for the data acquisition of surface currents near the equator (Alvarez *et al*., 2010).

The purpose of this study is to investigate the North Indian Ocean eddies, using satellite wind data and sea surface elevation data. After presenting the surface current vectors, the most significant eddies in each season and areas are investigated.

2. Methods and materials

Using satellite data, surface ocean currents can be estimated in regular intervals. The surface currents of the North Indian Ocean are due to the combination of two wind driven Ekman currents and the geostrophic currents. To calculate the Ekman current in the North Indian Ocean, wind data is obtained for a certain period of time from the ECMWF dataset and processed using GIS software.

Geostrophic currents are resulted from sea surface elevation data or the Absolute Dynamic Topography (ADT) as they are due to the balance of horizontal pressure gradient and the Coriolis force. For calculating the geostrophic current, satellite altimeter data can be obtained from AVISO and HYCOM datasets. The data of each datasets has some advantages and disadvantages. The sea elevation data at the HYCOM dataset in some cases, does not cover the entire North Indian Ocean, but has a higher spatial resolution in the mixed layer. A lot of studies have shown that the HYCOM data is just from a model and not from reality. These data were studied by many researchers for years and it was found that the results of these data are in contrary to local measurements and satellite estimates. The AVISO offers a variety of satellite altimetry data with spatial resolution of 0.25°and 1 day time step.

In this paper, the data is obtained from NOAA

Ocean Surface Current Analyses-Real Time (OSCAR) dataset, due to its reliability which is mainly based on Ekman and altimetry data. The OSCAR is a research project by NASA aimed at identifying the ocean surface currents around the world. In the project, the water velocities in the mixed layer are calculated using altimeter data (from TOPEX), ocean wind velocities (from QuickSCAT) and sea surface temperature (from AVHRR); and considering the dynamical rules of temporal winds, Ekman and geostrophic currents. The OSCAR is being continuously improved to have a better representation of momentum transitions within and between the boundaries of the ocean mixed layer. In this study, the OSCAR data are illustrated in the GIS environment (ArcMap) as directional current vectors, and the range of each vector is identified with a specific color. Using these data, the surface currents and eddies in the Northern Indian Ocean are investigated in seasonally averages during 2014, 2015, and 2016.

3. Results and Discussion

Figure 1 shows the currents and eddies in the North Indian Ocean during winter 2015. The overall patterns of the currents and eddies are similar in the next following two years, while in some places, the eddies have a slight spatial and directional changes.

In Figure 1, 18 specific areas with eddies are identified in the winter, 2015. Eddy in area 1 swirls in counterclockwise direction, and eddy in area 2 swirls in clockwise direction. The velocity of eddy 2 is much lower than the other eddy's speed. The average diameter of the eddy 1 is about 289 kilometers. Eddies in areas 3, 4, 5, and 6 are all formed along the Gulf of Aden. Among these eddies, only the eddy in 3 have a smaller speed. The velocity vectors of these currents in this eddy are in the green colour. The eddy in area 6 with a diameter of about 285 kilometers is in clockwise direction, the eddy in area 5 with smaller diameter and speed values is in counterclockwise direction. A weaker

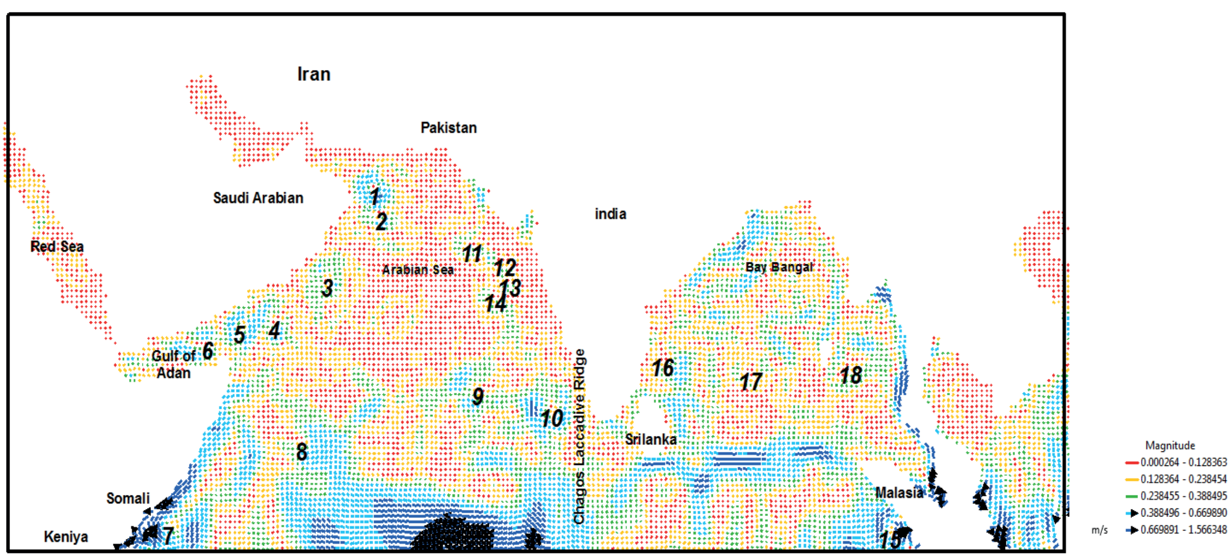

Figure 1. The currents and eddies in the Northern Indian Ocean in winter 2015

eddy in 4 moves in the clockwise direction, and the eddy in 3 moves in counterclockwise. The eddy in area 7 is a strong eddy located on the very large Somali Eddy track. The diameter of this fast eddy is 354 km and has a counterclockwise direction. The eddy in area 8 is along with the northern tropical current and has a counterclockwise direction. This eddy has high velocities in the area of dark-blue colors, in the east, and has low velocities in the green color area in its west.

In the regions of 9 and 10, the relatively strong eddies in the Laccadive Sea, are in the clockwise direction. There is also another weak eddy between these two areas eddies that moves in counterclockwise. In most cases, eddies that form beside each other have opposite directions (as a dipole). Eddy in area 10 near the Laccadive Sea has an average diameter of about 402 km. Eddies in the areas 11, 12, 13, and 14 regions are weak eddies with low velocities in the Arabian Sea. Their direction of each-one is different from the adjacent one. Eddy in area 15 is seen on the western border of Malaysia. This eddy is very fast and clockwise. Eddies in areas 16, 17 and 18 are in the Bay of Bengal and have moderate speeds.

Figure 2 shows the northern Indian Ocean eddies in the spring of 2016. The trend is similar for the next two following years, although in some places eddies have a slight spatial and temporal changes.

The eddy speed in the Oman Sea reduces in the spring. The eddy in area 3 in this season has shifted to the Arabian Sea with a lower speed than the prior value. Eddy in area 4 has been eliminated in the spring season. Eddy in areas 5 and 6 have lower speeds. The Eddy in area 8 has much lower speed than before, moving towards the Arabian Sea, and is disappearing in the spring season. Eddies areas 9 and 10 are not seen in this season. The Arabian Sea eddies, move towards the north, and remain steady. Eddies in the Bay of Bengal and Sri Lanka with high speed continue at their own spiral path. The dark-blue color indicates the high

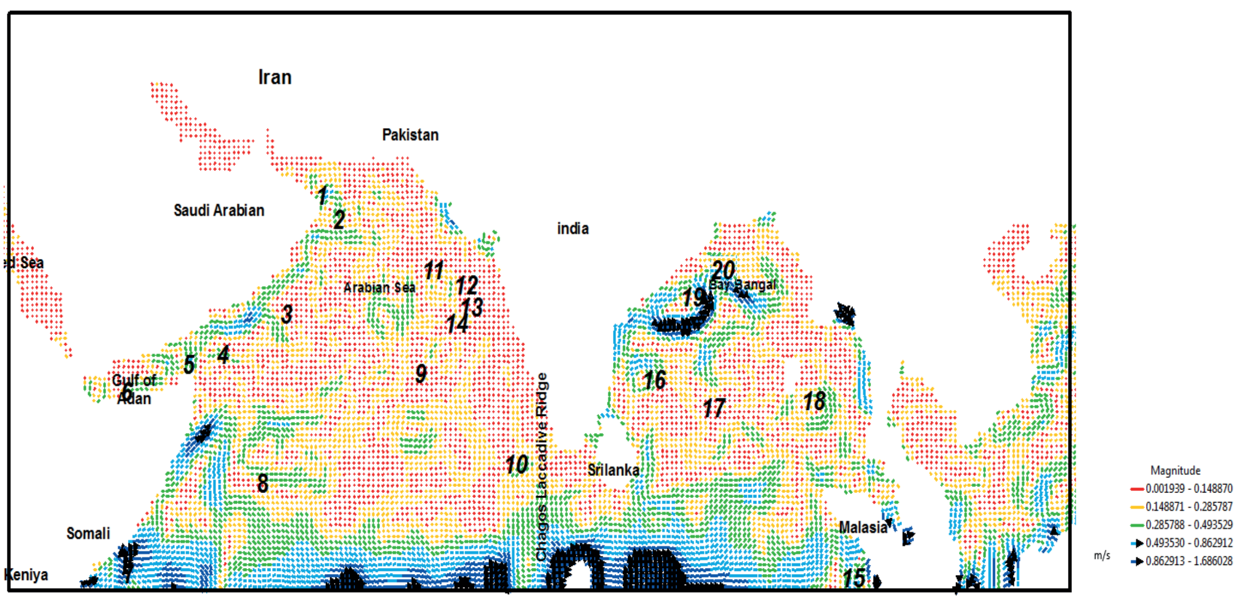

Figure 2. North Indian Ocean eddies in the spring of 2016

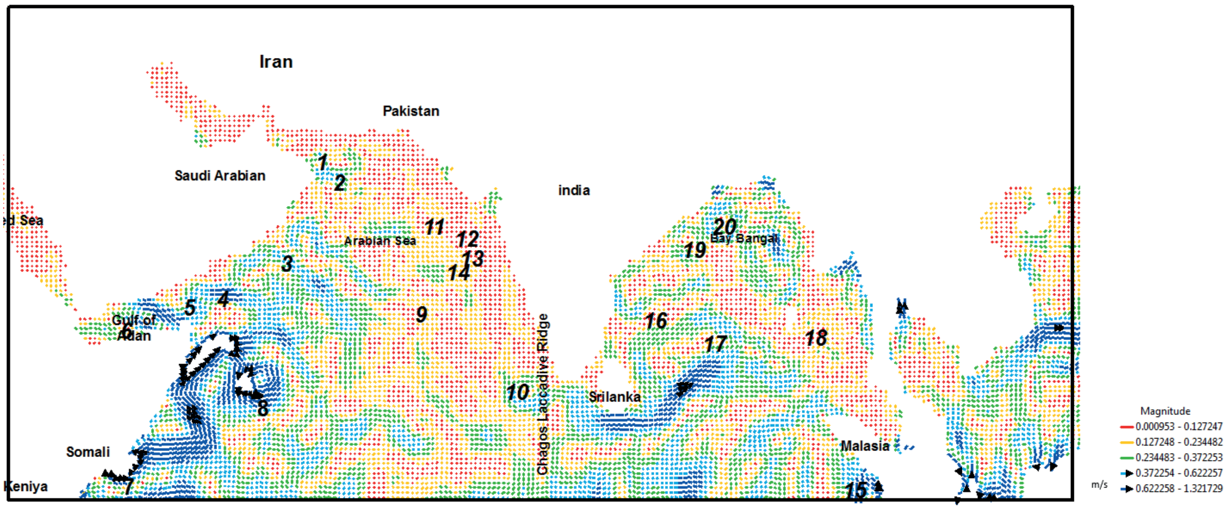

Figure 3. Northern Indian Ocean Eddies in the summer of 2014

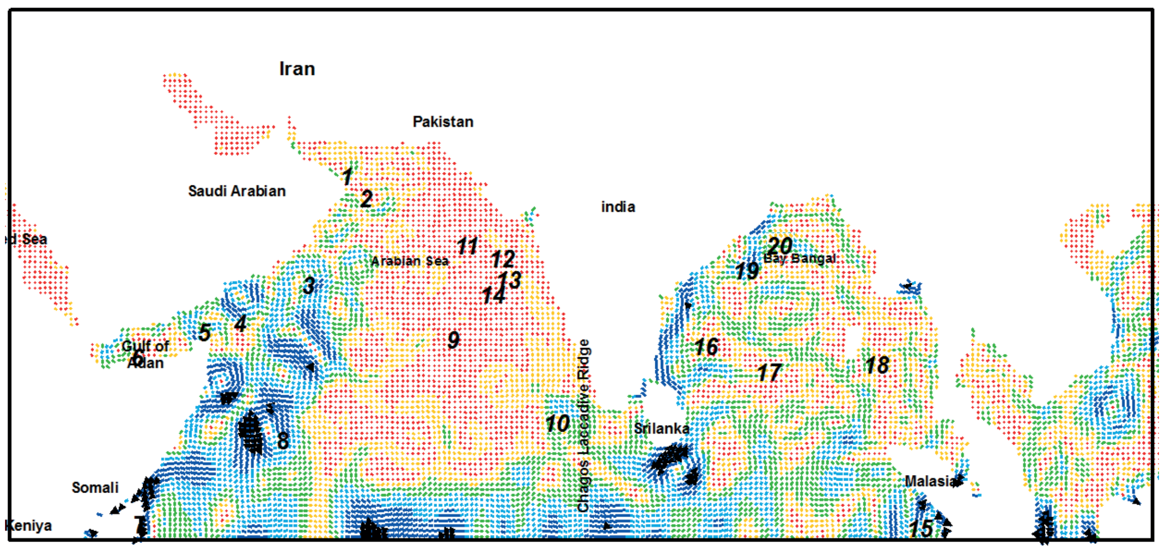

Figure 4.The North Indian Ocean eddies in the autumn of 2016

speed eddies in area 19. This Eddy did not have a permanent presence in the previous season, but in this season move strongly toward the Bay of Bengal. This eddy with an approximate diameter of 596 km has a counterclockwise direction. In the region 15 there is no eddy in this season.

Figure 3 shows the northern Indian Ocean eddies in the summer of 2014. The trend is again mostly similar for the next two following years, although in some places, there are slight spatial and temporal changes.

In the summer, most of eddies from the past season have been diminished. This trend is clearly seen in the Arabian Sea. In the Gulf of Eden, the Eddy in area 6 moves in clockwise direction. In this season, a large counterclockwise eddy is seen in the area 8. The diameter of the eddy is 672 km and its speed value is in blue range. All eddies in the

Table 1. General mean characteristics of seasonal large scale eddies in Northern Indian Ocean during 2014, 2015, and 2016

Season	Number of Eddies	Cyclonic	Anticyclonic	Eddy size (km)	Typical Speed (m/s)
Winter	13	10	3	387	1.5
Spring	20	9	11	418	1.3
Summer	17	13	4	584	1.3
Autumn	18	15	3	558	1.08

Bay of Bengal are visible in this time. A high-speed counterclockwise eddy is seen in the 20th area with an average diameter of about 376 km. The velocity of this eddy is in the light-blue range and in general, the speeds of these eddies have reduced in this time.

Figure 4 shows the North Indian Ocean eddies in the fall season of 2016. The trend is again largely similar for the next two years, although in some places, slight spatial and temporal variations are visible.

In the autumn, the number of eddies in the North Indian Ocean has increased. Both eddies 1 and 2 in the Oman Sea have a diminutive presence in this season. Eddy in area 6 in the Gulf of Aden is seen with medium speed in the counterclockwise. In area 4, a high-speed eddy moves in counterclockwise. Many eddies with high speeds appear along the Somali current in this season. In area 8, three eddies with large diameters are formed. The diameter of the eddy 8 was 570 km. In area 3, a curved eddy is formed with a mean diameter of 939 km in counterclockwise direction. In this season, there is a high-speed counterclockwise eddy in southern Sri Lanka. The average diameter of the eddy is 543 km. Eddy in area 10 can be seen in the light blue color. In the Bay of Bengal there is no strong and persistent eddy.

Table 1 shows the general characteristics of eddies in the Northern Indian Ocean during different seasons. Such mean characteristics are mainly determined by the changes in the wind fields over this ocean that have seasonal marked changes, including monsoon winds systems.

Conclusion

The strongest current in the north Indian Ocean is Somali Current. This current is observed in all seasons of a year in the northeastward direction, although it has a lower speed in the winter than in other seasons and it is particularly strong in summer due to strong summer monsoonal wind. An eddy is seen in the southern part of the Somali Current during all months of the year. This eddy has an average diameter of about 450 km. The current in the east of Sri Lanka is also a strong flow in the area. This current is slightly weaker only in spring than in other seasons. Several eddies are formed in this current path during most of the months of year in different directions and locations. The north tropical current has the highest speed in the winter. This current mainly moves parallel to the equator, and does not appear to have any stable eddy on its path. Eddies created in the summer and autumn have large areas and typical speed of 1.3 m/s, but eddies in the winter have small areas and a high speed of about 1.5 m/s. The currents with medium-scale eddies have also a velocity of 0.7 m/s.

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