Author response

The authors thank the Editor of "**Ocean Science**" and the two anonymous referees, for their time and efforts in reviewing the manuscript "**os-2018-47**". The manuscript is revised according to the reviewer suggestions and comments, which were very helpful to improve the manuscript. As part of the review process, additional analysis on eddy parameters and their interannual variability are included to the manuscript. I hope that the revised manuscript addressed all the review comments satisfactorily. Kindly consider the manuscript for possible publication in "Ocean Science".

The response to the referee comments and the marked-up version of the manuscript is given below.

1. Editor comments EC
2. Response to referee comments RC1
3. Response to referee comments RC2
4. Marked-up version of the manuscript

Response to Editor comments on "Estimation of geostrophic current in the Red Sea based on Sea level anomalies derived from extended satellite altimetry data" by Ahmed Mohammed Taqi et al.

Thank you very much for your interest in the manuscript, and for spending your effort and time in the review, comments, and suggestions, which helped in improving the manuscript. The manuscript was modified based on the comments. The responses to the comments are described below.

Comment [1] Lines 127-128. I think you should include here some of your response to referee 2 comment 1 about removing discontinuity between AVISO and FSMSLA. Maybe refer to Taqi et al (2017) for more detail?

Reply: modified in the manuscript.

Line number: [130-133].

Comment [2] Lines 131, 135. Two equations (2)!

Reply: modified in the manuscript.

Line number: [136].

Comment [3] Lines 137-138. The choice of level of no motion is still arbitrary. You have shown only pragmatism and not logic in choosing 500 m. There might be flow at all depths or indeed significant flow only in the top 200 m. Evidence should be used in the choice and Bower and Farrar (2015) refer to ship-borne ADCP measurements usually down to 600 m which would be good evidence. Does the choice between 500m and 700m make a significant difference to the near-surface geostrophic currents?

Reply: This part is also clarified in the reply to referee 1 comment 2. The following paragraph is added to the manuscript.

Previous study by Quadfasel and Baudner (1993) used 400 m as level of no motion to calculate geostrophic current in the Red Sea. Based on ADCP measurements, Bower and Farrar (2015) shown that, on average, 75–95 % of the vertical shear is occurred over the top 200 m of the water column. Moreover, the ADCP measurements of current speed below 500 m is very small; about

~0.06m/s at 600 m depth (Bower and Farrar, 2015). Therefore, expecting negligible variability below 500 m, a depth of 500 m was selected as a level of no motion. We have compared the geostrophic current corresponding to level of no motion at 500m and 700m. The observed difference between both are negligibly small.

Line number: [142-150].

Comment [4] Figure 2. You have not answered the Referee 2 question about how you show correlation with AVISO data near the coast where there are no AVISO data.

Reply: The answer to referee 2 question is improved for better understanding as follows.

Please note that the Gridded AVISO data is available in the coastal region as well as in the offshore area, but the accuracy of the AVISO data near the coast is questionable, especially in narrow basin like the Red Sea. FSM data was gridded to the same resolution as AVISO (0.25°x0.25°). We compared the data along the coast from both data products (AVISO and FSM) against the in-situ (tide gauge) measurements. The statistics of the comparison is shown in Table 2. The FSM data showed better correlation against the in-situ data in all the cases. For this reason, we have used FSM instead of AVISO data near the coast.

Comment [5] Figure 4. Referee 2 asked for justification for these specific areas and periods. Your revised text explains the times but not the areas; Referee 1 found that the cruise in Bower and Farrar (2015) covered a larger area. This is another case where the referee suggests more quantitative analysis.

Reply: The reply to referee 2 comment #1 is modified as follows based on your comment.

To validate the geostrophic current, we used the available in situ profiles during the available periods and regions. The in situ data include the following cruises; 1) March 16 to 29, 2010 onboard R/V Aegaeo between 22°N to 28°N along the eastern Red Sea, 2) April 3 to 7, 2011 onboard Poseidon between 17°N to 22°N in the central eastern Red Sea, and 3) October 16 to 19, 2011 onboard the same vessel between 19°N to 23°N in the central eastern Red Sea,. We understand that we are limited in space and time because of the spatial and temporal distribution of the available cruises. Regarding the cruise 1 by Bower and Farrar (2015), unfortunately, we do not have complete data set used by the Bower and Farrar (2015), and therefore we used only the available profiles for validation.

The text in the manuscript is modified accordingly.

Line number: [114-122].

Regarding the quantitative analysis please refer to reply to referee 1 comment #3, where the manuscript modified accordingly.

 Line number: [201-206, and Table 3].

Comment [6] Table 3 for March 2010. I am wondering if the values are all correct in that the RMSE and Stdv are both worse for FSM-SLA than for AVISO but the correlation coefficient is better. I can understand that the bias might affect RMSE but it should not affect the Stdv? There is a question as to whether Table 3 is informative in that agreement with CTD-derived geostrophic current is not necessarily agreement with the true current.

Reply: modified the table 3 in the manuscript.

We verified the values in table 3 and found that the values corresponding to the FSM-SLA during March-2010 is not correct. We revised all MATLAB codes used for calculation and we discovered an error in one of the codes. For this we have modified the code and recalculated the statistical parameters and replaced in the new table3. Please note that, the FSM-SLA is less biased with lower RMSE value and better correlation in all cases.

Comment [7] Line 196. Referee 1 questioned the 6-year averaging. You refer to 6 years but the SLA data only span part of 2009 and 2014. Then figure 8 for "2014" will contain some bias opposite to any October-December seasonal signal?

Reply: The manuscript is modified.

We agree that the previous data were from June 2009 to October 2014. We extend the data to the end of 2014 following (Taqi et al.2017). We processed data for all available tracks for the period from October (cycle 232) to December (cycle 239) following the same process as the previous data. After the extension of the data, figure 8 has been updated accordingly. Regarding referee 1 question, please refer to reply to comment # 4 of referee 1.

Line number: [101].

Comment [8] Page 13, figure 5. Where is the arrow showing the "reference current length =0.5m/s"?

Reply: modified in figure 5 and add reference current length.

Comment [9] Lines 274-275. "amplitude of eddies in the Red Sea is about 4 cm which is an agreement with global values". Is there any reason to hope for or expect "agreement". Lower latitudes and relatively narrow Red Sea might lead one to expect smaller eddy amplitudes.

Reply: The manuscript is modified, and the following paragraph is included.

The amplitude of an eddy has been defined as the differences between the estimated basic height of the eddy boundary and the extremum value of SLA inside the eddy interior parts. The mean amplitude for anticyclonic is between 1.3 cm at southern Red Sea to 5.3 cm at northern Red Sea and for cyclonic eddy is between 1.6 cm at southern Red Sea to 4.2 cm at northern Red Sea. The result indicates the average value of eddy amplitude in the Red Sea (including low latitude and high latitude) is about 4 cm, which is within the reasonable range defined by (Chelton et al., 2011).

Line number: [284-290].

Comment [10] Figure 8. Earlier Reviewer 1 commented "The comparison and error estimation is very qualitative (comparing figures) and in figure 4a&b (the largest area covered) it is impossible to visualize the results." I think the same now applies to the figures in response to Referee 1 comment [4] and to new figure 8. Perhaps the revision should include some statistics about the difference between 2010 and climatology. Or preferably, what is the standard deviation of SLA in the panels of figure 8 compared with the standard deviation of the "6-year mean"?

Reply:

Regarding referee comment #3, a statistical analysis to compare the FSM-SLA and AVISO derived geostrophic current with that derived from CTD, were added to the manuscript text and summarized in Table 3.

Line number: [201-206].

Regarding Figure 8 and referee comment # 4, We have computed the statistics, which is summarized in the manuscript (Table 4).

Line number: [308-316].

Comment [11] Figure 8 arrows. Do these show direction only (they seem to all have the same length)?

Reply: modified in the figure 8.

Comment [12] Referee 2 comment "it would be important in my opinion to add informations on where it provides new informations, particularly along the coasts." You have many statements about geostrophic flows, including along the coast, and about cyclonic and anticyclonic eddies. However, you also have many statements that what you find agrees with previous findings. I think the referee wants you to say what you have found that was NOT previously found. I want this too as an editor of Ocean Science which is for publishing new knowledge and understanding.

Reply: The manuscript is modified, and the following text is included in the "conclusion" section.

The finding of this paper considered the first of its type in the Red Sea for extending SLA and geostrophic currents to the coast beside giving more details of eddies spatial and temporal variabilities in the coastal region. In addition, in winter, the cyclonic eddies are along the west coast and anticyclonic eddies on the east side of the Red Sea, while in summer it is the opposite. Also, in some locations there is a noticeable change from anticyclonic during winter to cyclonic during summer and vice versa between 26.3°N –27.5°N.

The major new findings from the present study include the monthly geostrophic pattern in the Red Sea which has not been published before. Seasonally, the geostrophic currents in summer are flowing northward except the eastern coast which flows in the opposite. In winter, currents flow to the north for the entire sea except small part of the eastern coast (22°N-24°N) and the western coast (23°N-20°N).

Line number: [334-338, 342-344, 351-353].

<div align="center">**Response to referee comments RC1**</div>

Anonymous Referee on "Estimation of geostrophic current in the Red Sea based on Sea level anomalies derived from extended satellite altimetry data" by Ahmed Mohammed Taqi et al.

Anonymous Referee

Thank you very much for your interest in the manuscript, and for spending your effort and time in the review, comments, and suggestions, which helped in improving the manuscript. The manuscript was modified based on the Anonymous Referee comments. The responses to the comments are described below.

Comments to the *Anonymous Referee*

General comment

The paper "Estimation of geostrophic current in the Red Sea based on Sea level anomalies derived from extended satellite altimetry data" by Taqi et al. focuses on describing the geostrophic currents and eddy field in the Red Sea based on altimetry data, extended to the coast using a method proposed by same authors (Taqi et al., 2017). The first part consists of a continuation of the validation of the method (adding hydrographic data for estimating the geostrophic velocity) and the second part provides an analysis of the monthly climatology of the sea level anomaly (SLA) and the corresponding surface currents (averaging 6 years satellite data).

Comment [1]: The validation part provides very little additional analysis compared to the Taqi et al., 2017, while there is no information and/or reference related to the cruises that were used for estimating the geostrophic currents (lines 107-110). Actually, after checking the reference provided later in the text (e.g. Bower and Farrar, 2015) the cruise(s) covered a much larger area than the one used and shown in this paper. It is not understood why the authors selected the specific regions to perform the validation.

Reply: To validate the geostrophic current, we used the available in situ profiles during the available periods and regions. The in situ data include the following cruises; 1) March 16 to 29, 2010 onboard R/V Aegaeo between 22°N to 28°N along the eastern Red Sea, 2) April 3 to 7, 2011 onboard Poseidon between 17°N to 22°N in the central eastern Red Sea, and 3) October 16

to 19, 2011 onboard the same vessel between 19°N to 23°N in the central eastern Red Sea,. We understand that we are limited in space and time because of the spatial and temporal distribution of the available cruises. Regarding the cruise 1 by Bower and Farrar (2015), unfortunately, we do not have complete data set used by the Bower and Farrar (2015), and therefore we used only the available profiles for validation.

The text in the manuscript is modified accordingly.

Line number: [114-122].

Comment [2]: The cruises also used an LADCP and thus the adoption of 700 m reference level seems arbitrary (actually most of the stations are shallower than that).

Reply: The manuscript is modified, and the following paragraph is included .

Previous study by Quadfasel and Baudner (1993) used 400 m as level of no motion to calculate geostrophic current in the Red Sea. Based on ADCP measurements, Bower and Farrar (2015) shown that, on average, 75–95 % of the vertical shear is occurred over the top 200 m of the water column. Moreover, the ADCP measurements of current speed below 500 m is very small; about ~0.06m/s at 600 m depth (Bower and Farrar, 2015). Therefore, expecting negligible variability below 500 m, a depth of 500 m was selected as a level of no motion. We have compared the geostrophic current corresponding to level of no motion at 500m and 700m. The observed difference between both are negligibly small.

Line number: [142-150].

Comment [3]: The comparison and error estimation is very qualitative (comparing figures) and in figure 4a&b (the largest area covered) it is impossible to visualize the results.

Reply: As suggested a quantitative analysis is done for the data and added the same in the revised manuscript.

Line number: [201-206, and Table 3].

Comment [4]: The second part is very weak, merely describing the twelve monthly SLA/geostrophic velocity figures. The methodology of averaging 6 years of SLA data to describe the climatology of the complex Red Sea eddy field is not appropriate. While the basin-scale seasonal variability of the SLA can benefit very little from the new method of extending

the data to the coast (this comparison is not shown), the averaging could mask the eddy field and produce artificial features. More advanced methods, including the interannual variability of the SLA/geostrophic currents, could provide more reliable information (see Zhan et al., 2014 and many more).

Reply: A) We agree with the reviewer that the averaging of 6 years data will not give the variable eddies in the Red Sea, even it shows the permanent eddies clearly. Please see the attached figure, which compares the climatology with SLA of 2010. The patterns were similar, with small differences. The main differences are the short timing eddies are not visible in the climatology, but the general features of variability of circulation is present.

b) As suggested by the reviewer, more analysis on the SLA/geostrophic currents and the statistical analysis of eddies in the Red Sea are added in the manuscript in fig.7 .
Line number: [278-297].
We have also studied the interannual variability in the SLA and geostrophic current in Fig. 8 and Table 4
Line number: [308-316].

Comment [5]: Finally, the schematic circulation, presented in figure 7, based on the annual geostrophic currents is not convincing (at least compared to the black arrows shown in the figure). A seasonal schematic could be more appropriate.

Reply: The annual schematic has been changed to the winter and summer seasons see figure 10, in the revised manuscript.
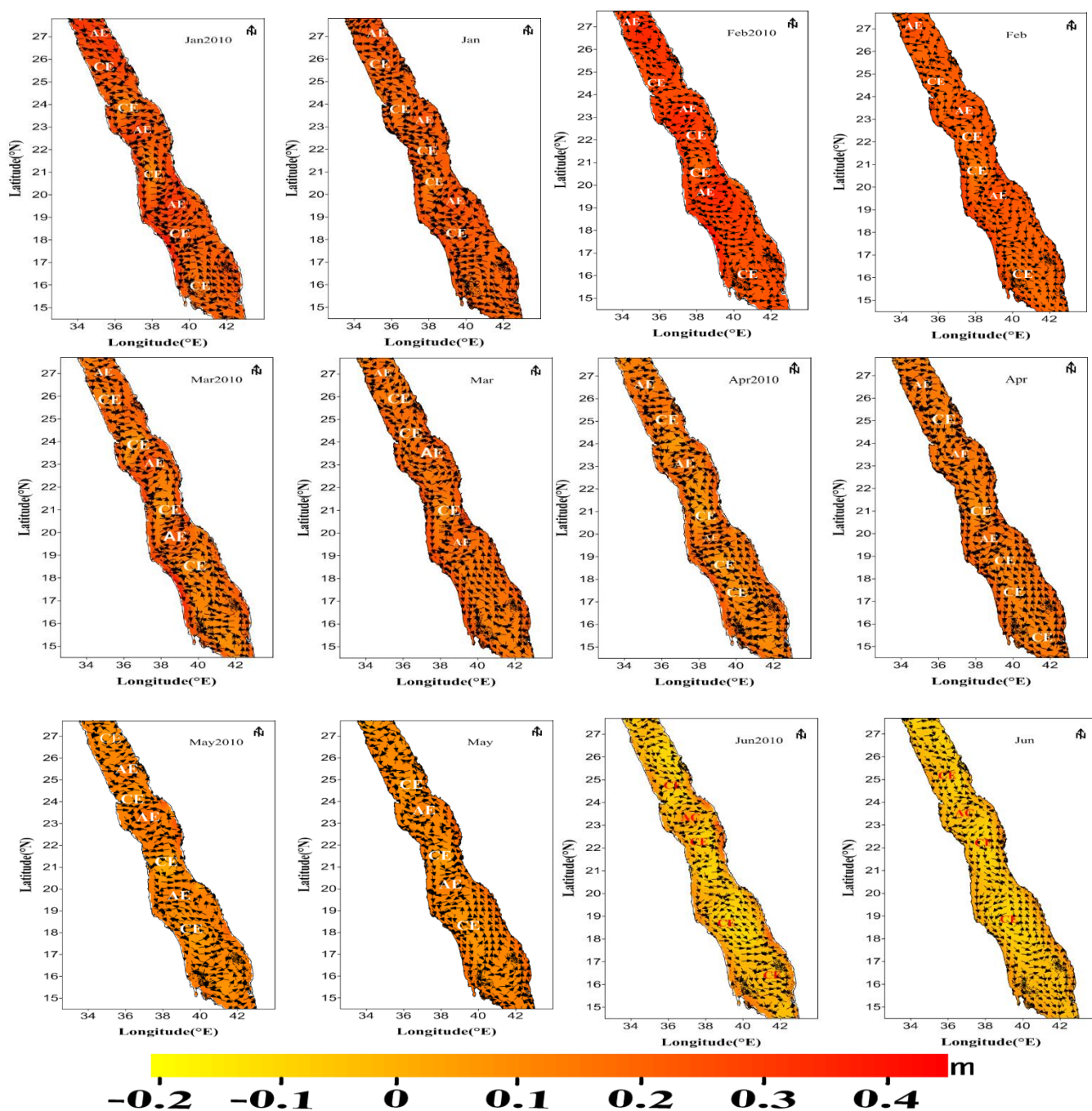
Figure compared between year 2010 and monthly climatology for geostrophic current and Sea level anomaly (Reference current length =0.5 m/sec)
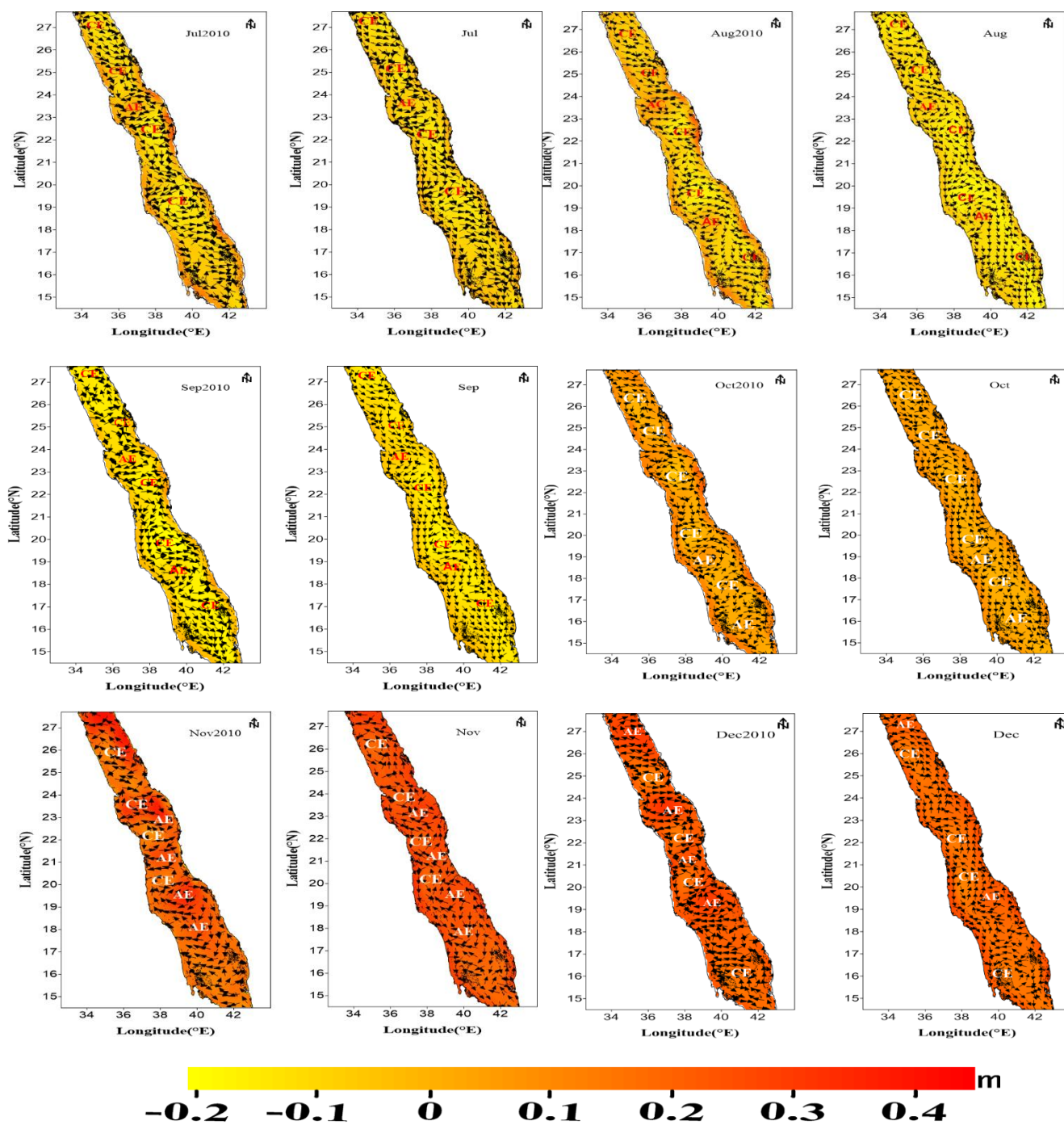
Figure 6 As figure 5 for July to December

Response to referee comments RC2

Anonymous Referee on "Estimation of geostrophic current in the Red Sea based on Sea level anomalies derived from extended satellite altimetry data" by Ahmed Mohammed Taqi et al.
Referee

Thank you very much for your interest in the manuscript, and for spending your effort and time in the review, comments, and suggestions, which helped in improving the manuscript. The manuscript was modified based on the Referee comments. The responses to the comments are described below.

Comments

General Comment:

In this article the authors use data from Jason-2 to extend SLA observations from AVISO towards the coasts of the Red Sea. Altimetric products from AVISO are commonly used to describe the open ocean dynamics but their resolutions are coarse near the coasts. The combined satellite dataset is validated with three tide gauges situated along the western coast of the Red Sea and with geostrophic surface velocities estimated from CTD. This new merged satellite product shows good agreement with the other available dataset and allows the authors to have better observations of the SLA C1 along the coasts. Once validation of the products, the authors describe the monthly climatological evolution of the the SLA and surface currents, exhibiting the evolution of mesoscale eddies, in size, position and rotation. A month to month analysis of the surface fields describe the observed eddies and link them to the structure previously studied in the scientific literature. I think this article is well written, the merged dataset allows us to understand the climatological circulation in the Red Sea, where previous satellite dataset allowed only a partial coverage linked to the geography of the basin.

Comment [1]: Still it lacks some informations of the dataset used to validate the data and the justifications of some diagnosed.

Reply: To validate the geostrophic current, we used the available in situ profiles during the available periods and regions. The in situ data include the following cruises; 1) March 16 to 29, 2010 onboard R/V Aegaeo between 22°N to 28°N along the eastern Red Sea, 2) April 3 to 7, 2011 onboard Poseidon between 17°N to 22°N in the central eastern Red Sea, and 3) October 16 to 19, 2011 onboard the same vessel between 19°N to 23°N in the central eastern Red Sea,. We understand that we are limited in space and time because of the spatial and temporal distribution of the available cruises. Regarding the cruise 1 by Bower and Farrar (2015), unfortunately, we do not have complete data set used by the Bower and Farrar (2015), and therefore we used only the available profiles for validation.

The text in the manuscript is modified accordingly.

Line number: [114-122].

Comment [2]: Nevertheless I felt that the last part of the article did not emphasize the main contribution of this study : the calculation of surface currents and SLA along the coast. As I wrote above, the authors did a good job comparing their results with previous studies, and where they agree, but it would be important in my opinion to add informations on where it provides new informations, particularly along the coasts.

Reply: The manuscript is modified, and the following text is included in the "conclusion" section.

The finding of this paper considered the first of its type in the Red Sea for extending SLA and geostrophic currents to the coast beside giving more details of eddies spatial and temporal variabilities in the coastal region. In addition, in winter, the cyclonic eddies are along the west coast and anticyclonic eddies on the east side of the Red Sea, while in summer it is the opposite. Also, in some locations there is a noticeable change from anticyclonic during winter to cyclonic during summer and vice versa between 26.3°N –27.5°N.

The major new findings from the present study include the monthly geostrophic pattern in the Red Sea which has not been published before. Seasonally, the geostrophic currents in summer are flowing northward except the eastern coast which flows in the opposite. In winter, currents flow to the north for the entire sea except small part of the eastern coast (22°N-24°N) and the western coast (23°N-20°N).

Line number: [334-338, 342-344, 351-353].

Comment[3]: The conclusion is a little short, and adding these informations will help wrapping the article nicely.

Reply: The conclusion in the manuscript is improved.

Comment [4]: The SLA from AVISO gives measurements offshore, while the FSMSLA method extends these measurements toward the coasts. I wonder how are the discontinuities between dataset removed or smoothed.

Reply: The AVISO data was removed near the coast using the polygon. The blank area was replaced by the FSMSLA data with space leaving between the two data set according to the width of the sea either one or two grid cells. This gap was filled using kriging interpolation method to smooth the dataset. See figure below which include two examples.
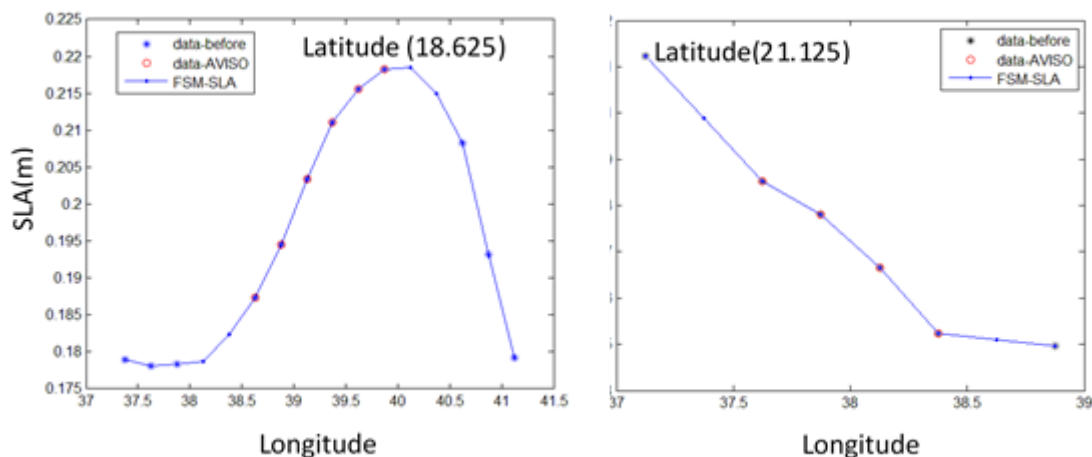
Comment [5]: On figure 2 the authors show the correlation between the AVSIO and FSM data, how are they calculated where the AVSIO dataset does not provide measurements (again along the coast)

Reply: Please note that the Gridded AVISO data is available in the coastal region as well as in the offshore area, but the accuracy of the AVISO data near the coast is questionable,

especially in narrow basin like the Red Sea. FSM data was gridded to the same resolution as AVISO (0.25°x0.25°). We compared the data along the coast from both data products (AVISO and FSM) against the in-situ (tide gauge) measurements. The statistics of the comparison is shown in Table 2. The FSM data showed better correlation against the in-situ data in all the cases. For this reason, we have used FSM instead of AVISO data near the coast.

Comment from Results:

Comment [6]: I suggest separating this section in two part, a first with the validation of the method (down to line 17), and a second with the analysis of the SLA.

Reply: The revised manuscript is modified accordingly.

Comment [7] About the CTD: on figure 4 the authors display different part of the Red Sea a different period comparing AVSIO and the FSM-SLA. What are the justifications for these specific area and periods. I think providing a quantitative analysis would help validating the approach.

Reply: To validate the geostrophic current, we used the available in situ profiles during the available periods and regions. The in situ data include the following cruises; 1) March 16 to 29, 2010 onboard R/V Aegaeo between 22°N to 28°N along the eastern Red Sea, 2) April 3 to 7, 2011 onboard Poseidon between 17°N to 22°N in the central eastern Red Sea, and 3) October 16 to 19, 2011 onboard the same vessel between 19°N to 23°N in the central eastern Red Sea,. We understand that we are limited in space and time because of the spatial and temporal distribution of the available cruises. Regarding the cruise 1 by Bower and Farrar (2015), unfortunately, we do not have complete data set used by the Bower and Farrar (2015), and therefore we used only the available profiles for validation.

The text in the manuscript is modified accordingly.

Line number: [114-122].

Comment [8] The visibility of the geostrophic currents and eddies name of figures 5 and 6 have a low visibility. As they exhibit the main results of the study I suggest remapping them by adding a light opaque filter on the SLA and then adding the arrows and names. The same goes for figure 4 where the arrows are difficult to see.

Reply: The visibility of the geostrophic currents and eddies names of figures 5 and 6 arrows and names has been changed.

Comment [9] Figure 7 wrap up the paper with a schematic representation of the currents, but, as the authors state, the monsoons have a strong impact on the Red Sea, particularly on its southern edge. I suggest adding a schematic representation for the winter and summer seasons in order to point out the differences in circulations.

Reply: The annual schematic has been changed to the winter and summer seasons see figure 10, in the revised manuscript.

Estimation of geostrophic current in the Red Sea based on Sea level anomalies derived from extended satellite altimetry data

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Abstract

The geostrophic currents data near the coast of the Red Sea has large gaps. Due to this, the sea level anomaly (SLA) data of Jason-2 has been reprocessed and extended towards the coast of the Red Sea and merged with AVISO data at the offshore region. This processing has been applied to build a gridded data to achieve best results for the SLA and geostrophic current. The results obtained from the new extended data at the coast are more consistent with the observed data (CTD) and hence geostrophic current calculation. The pattern of SLA distribution and geostrophic currents are divided into two seasons; winter (October – May) and summer (June – September). The geostrophic currents in summer are flowing northward except the eastern coast which flows in the opposite. In winter, currents flow to the north for the entire sea except a small part of the eastern coast (22°N-24°N). This flow is modified with the presence of the cyclonic and anticyclonic eddies, which are more concentrated in the central and northern Red Sea. The results show anticyclonic eddies (AE) on the eastern side of the Red Sea and cyclonic eddies (CE) on the western side during winter. In summer, cyclonic eddies are more dominant for the entire Red Sea while in winter both cyclonic and anticyclonic eddies are present. The result shows a change in some eddies from anticyclonic during winter to cyclonic during summer in the north between 26.3°N –27.5°N. Furthermore, the lifespan of cyclonic eddies is longer than that of anticyclonic eddies.

1. Introduction

The Red Sea is a narrow semi-enclosed water body that lies between continents of Asia and Africa. It is located between latitude 12.5°-30°N and longitude 32°E-44°E in an NW-SE orientation. Its average width is 220 km and the average depth is 524 m (Patzert, 1974). It is connected at its northern end with the Mediterranean Sea through the Suez Canal and at its southern end with the Indian Ocean through the strait of Bab El- Mandab. The exchange of water through Bab El- Mandab (shallow sill of 137 m) is the most significant factor that determines the oceanographic properties of the Red Sea (Smeed, 2004).

During winter, the southern part of the Red Sea is subject to SE monsoon wind, which is relatively strong from October to December, with a speed of 6.7-9.3 ms^{-1} (Patzert, 1974). During the summer season, the wind is shifting its direction to be from NW. On the other hand, in the northern part of the Red Sea, the dominant wind is NW all year around.

The circulation in the Red Sea is driven by strong thermohaline and wind forces (Neumann and McGill, 1961; Phillips, 1966; Quadfasel and Baudner, 1993; Siedler, 1969; Tragou and Garrett, 1997). Several studies in the Red Sea have focused on thermohaline circulation, where they found that the exchange flow between the Red Sea and Gulf of Aden consists of two layers in winter and three layers in summer through Bab El- Mandab (e.g.Phillips 1966; Tragou and Garrett 1997; Murray and Johns 1997; S. Sofianos and Johns 2015;Al Saafani and Shenoi, 2004; Smeed, 2004). Other studies describe the basin-scale circulation based on modelling approach, usually forced at a relatively low-resolution (1°x1°) by buoyancy flux and global wind (Clifford et al., 1997; Sofianos, 2003; Tragou and Garrett, 1997; Biton et al., 2008; Yao et al., 2014a,b). The horizontal circulation in the Red Sea consists of several eddies, some of them are semi-permanent eddies (Quadfasel and Baudner, 1993), that often present during the winter (Clifford et al., 1997; Sofianos and Johns, 2007) in the northern Red Sea. The circulation system in the central Red Sea is dominated by cyclonic (CE) and anticyclonic eddies (AE), mostly between 18°Nand 24°N. Eddies are also found in the southern Red Sea but not in a continuous pattern (Johns et al., 1999). Zhan et al., (2014) reported recurring or persistent eddies in the north and the central Red Sea, although there are differences in the number of eddies, their location, and type of vorticity (cyclonic or anticyclonic).

The long-term sea level variability in the Red Sea is largely affected by the wind stress and the combined impact of evaporation and water exchange across the strait of Bab El Mandeb (Edwards, 1987; Sultan et al., 1996). The Sea level in the Red Sea is higher during winter and lower during summer (Edwards, 1987; Sofianos and Johns, 2001; Manasrah et al., 2004). It is characterized by two cycles, annual and semi-annual, where the annual cycle is dominant (Abdallah and Eid, 1989; Sultan and Elghribi, 2003).

In recent years, there has been an increasing interest for using satellite altimetry Sea level anomaly (SLA) which offer large coverage and long data period for providing measurements of SSH, wave height and wind speed (Chelton et al., 2001). However, the altimeter data undergoes several processing stages for corrections due to the atmosphere and ocean effects (Chelton et al., 2001). The satellite altimetric data has been used for the open ocean for a long time with great success, while the data of the coastal region suffers from gaps of almost 50 km form the coastline. The coastal region requires further corrections due to additional difficulties based on the closeness of the land (Deng et al., 2001; Vignudelli et al., 2005; Desportes et al., 2007; Durand et al., 2009; Birol et al., 2010). In the past two decades, many researchers have sought to develop different methods to improve the quality, accuracy and availability of altimetric data near the coast (e.g. Vignudelli et al., 2000; Deng and Featherstone, 2006; Hwang et al., 2006; Guo et al. 2009, 2010; Vignudelli et al., 2005; Desportes et al., 2007; Durand et al., 2009; Birol et al., 2010; Khaki et al., 2014; Ghosh et al., 2015; Taqi et al., 2017). The satellite altimetry faces three types of problems near the coast; (1) the echo interference with the surrounding ground as well as the inland water surface reflection (Andersen and Knudsen, 2000; Mantripp, 1966), (2) environmental and geophysical corrections such as dry tropospheric correction, wave height, high frequency and tidal corrections from global models, etc. and (3) spatial and temporal corrections during sampling (Birol et al., 2010).

The ocean currents circulate water worldwide. They have significant influence on the transfer of energy and moisture between the ocean and the atmosphere. Ocean currents play a significant role in climate change in general. In addition, they contribute to the distribution of hydrological characteristics, nutrients, contaminants and other dissolved materials between the coastal and the open areas, and among the adjacent coastal regions. Ocean currents carry sediment from and to the coasts, so play a significant role in shaping of the coasts. That is

important in the coastal region where in the densely inhabited coastal region, producing large amounts of pollutants. Understanding of the currents helps us in dealing with the pollutants and coastal management.

The objective of the present research is to study the geostrophic current in the Red Sea including the coastal region using the modified along track Jason-2 SLA along the coast produced by Taqi et al., (2017).

2. Material and Methods

2.1. Description of data

2.1.1 Fourier series model (FSM) SLA

The SLA data used in this study is weekly Jason-2 along the track from June 2009 (cycle 33) to October 2014 (cycle 232) which has been extended to the coastal region by Taqi et al., (2017). To cover all the period, additional tracks were added up to December 2014 (cycle 239). The extended data shows a good agreement with the coastal tide gauge station data. In brief, the FSM method of extending SLA consists of four steps; the first step is the removal from SLA the outliers which are outside three times standard deviation from mean. Second step; the SLA is recomputed using Fourier series equation along the track. Third step; the data is then filtered to remove the outliers in the SLA with time similar to the first step. Finally, the SLA data is linearly interpolated over the time to form the new extended data which is called FSM. For more details on the FSM method, refer to Taqi et al., (2017).

2.1.2 AVISO, Tide Gauge, and hydrographic datasets

This study uses two types of SLA data; The first set is the (SLA), which has been downloaded from the Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) (ftp://ftp.aviso.altimetry.fr/global/delayed-time/grids/msla/all-sat-merged). The second dataset is the SLA from the extended FSM data. The temperature and salinity profiles used for geostrophic estimation are received from three cruises, the first cruise was during March 16 to 29, 2010 onboard R/V Aegaeo between 22°N to 28°N along the eastern Red Sea with a total of 111 Conductivity, Temperature and Depth (CTD) profiles. For more details; see Bower and Farrar (2015). The second cruise was on April 3 to 7, 2011 onboard Poseidon between 17°N to 22°N in the central eastern Red Sea and the third one was during October 16 to 19, 2011 onboard the same vessel between 19°N to 23°N in the central eastern Red Sea as a part of Jeddah transect,

KAU-KEIL Project. For more details; consult R/V POSEIDON cruise P408/1 report (Schmidt et al., 2011). The availability of in-situ observations is limited in space and time because of the spatial and temporal distribution of the available cruises. Finally, three tide gauges data at the eastern coastline of the Red Sea are obtained from the General Commission of Survey (SGS) at the Kingdom of Saudi Arabia (Fig.1) and their location details are shown in Table 1.

2.2 Method

The SLA data used in this study are coming from two sources: (1) the FSM data near the coast and (2) the AVISO data along the axis of the Red Sea. The steps to merge the two datasets and calculating the geostrophic currents are given below.

First, the along-track FSM data are used to produce gridded data to a spatial resolution of $0.25° \times 0.25°$ for the comparison with Aviso data. In the second step, AVISO data near the coast is removed, and replaced with the coastal FSM gridded data leaving space between the two data set according to the width of the sea either one or two grid cells. This gap was filled using kriging interpolation method to smooth the dataset. The merged data hereafter called as FSM-SLA. Finally, surface geostrophic currents are estimated from FSM-SLA data using the following equation;

$$u_g = -\frac{g}{f}\frac{\partial \zeta}{\partial y} \qquad\qquad v_g = \frac{g}{f}\frac{\partial \zeta}{\partial x} \qquad (1)$$

Where (u_g, v_g) is the surface geostrophic current, g is gravity, f is the Coriolis parameter and ζ is the sea surface height. The estimation of geostrophic currents from CTD data is using the following equation;

$$u_g = -\frac{1}{f\rho}\frac{\partial p}{\partial y} \qquad\qquad v_g = \frac{1}{f\rho}\frac{\partial p}{\partial x} \qquad (2)$$

where ρ is the density of seawater, p is hydrostatic pressure derived from the density. The stations have depths that very from 50 up to 2344 m. However, most of the stations (~90 %) exceed the 500 m depth. Previous study by Quadfasel and Baudner (1993) used 400 m as level of no motion to calculate geostrophic current in the Red Sea. Based on ADCP measurements, Bower and Farrar (2015) shown that, on average, 75–95 % of the vertical shear is occurred over the top 200 m of the water column. Moreover, the ADCP measurements of current speed below 500 m is very small; about ~0.06m/s at 600 m depth (Bower and Farrar, 2015). Therefore, expecting negligible variability below 500 m, a depth of 500 m was selected as a level of no

motion. We have compared the geostrophic current corresponding to level of no motion at 500m and 700m. The observed difference between both are negligibly small.

Table 1. The location of tide gauge stations and period of measurement.

Station	Latitude	Longitude	Period
Jazan	16.87	42.55	1/1/2013 to 31/12/2013
Jeddah	21.42	39.15	1/1/2013 to 31/12/2013
Yanbu	23.95	38.25	1/1/2013 to 31/12/2013
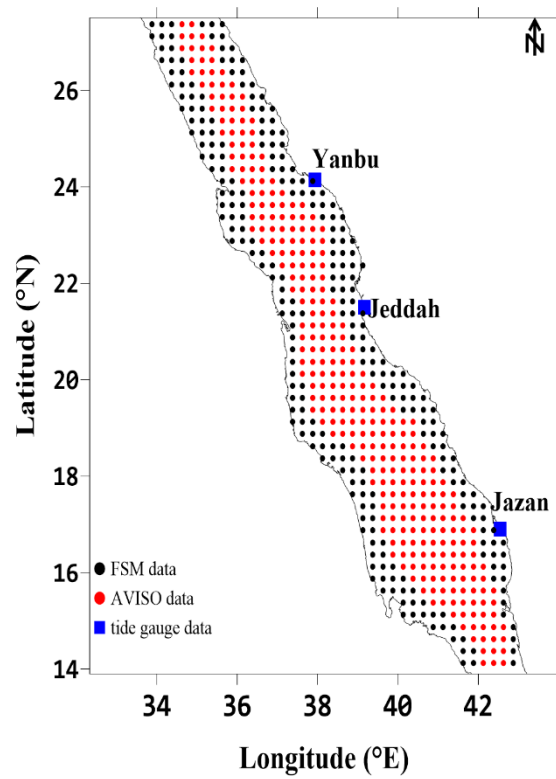
Figure 1. show the study area and the grid-points locations with a spatial resolution of 0.25° × 0.25° and locations of the tide gauges.

3. Result and Discussion

3.1 Validation of FSM-SLA and geostrophic current

The statistical analysis has been conducted to show the quality of FSM-SLA as compared with AVISO. The Correlation Coefficient (CC) reveals a good agreement between the two

datasets in the open sea (about 0.7 to 0.9) and is shown in Fig. 2. Near the coasts, on the other hands, shows weak correlation coefficient between the two data sets; 0.45 to 0.7.

Furthermore, the observed SLA from the coastal tide gauge is compared with the FSM-SLA data and AVISO datasets. Table 2. illustrates some of the statistical analysis, where the root mean square error (RMSE) is lower for FSM-SLA as compared to that of AVISO.

Table 2. statistical analysis for AVISO and FSM-SLA data with observed data (in 2013).

	Jasan		Jeddah		Yanbu	
	FSM-SLA	AVISO	FSM-SLA	AVISO	FSM-SLA	AVISO
CC	0.936	0.914	0.915	0.906	0.907	0.895
RMSE(m)	0.073	0.085	0.069	0.094	0.067	0.104
Note: The p-value corresponding to all comparison is very low (P<0.0001), indicating that the results from correlation are significant.						
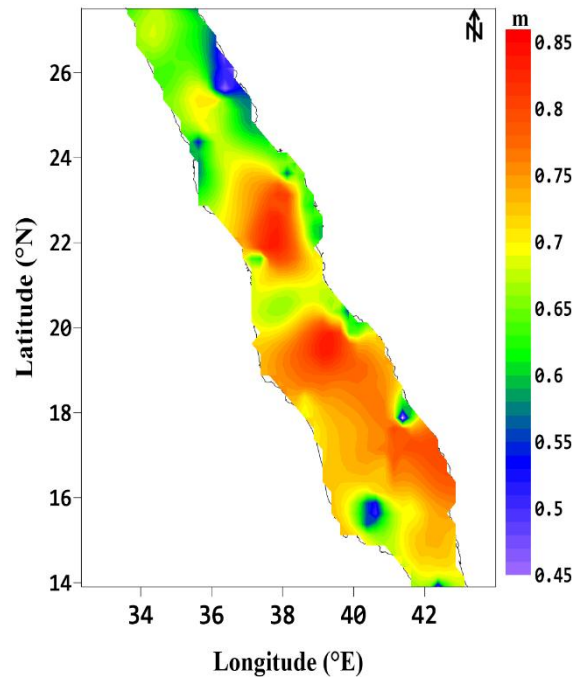
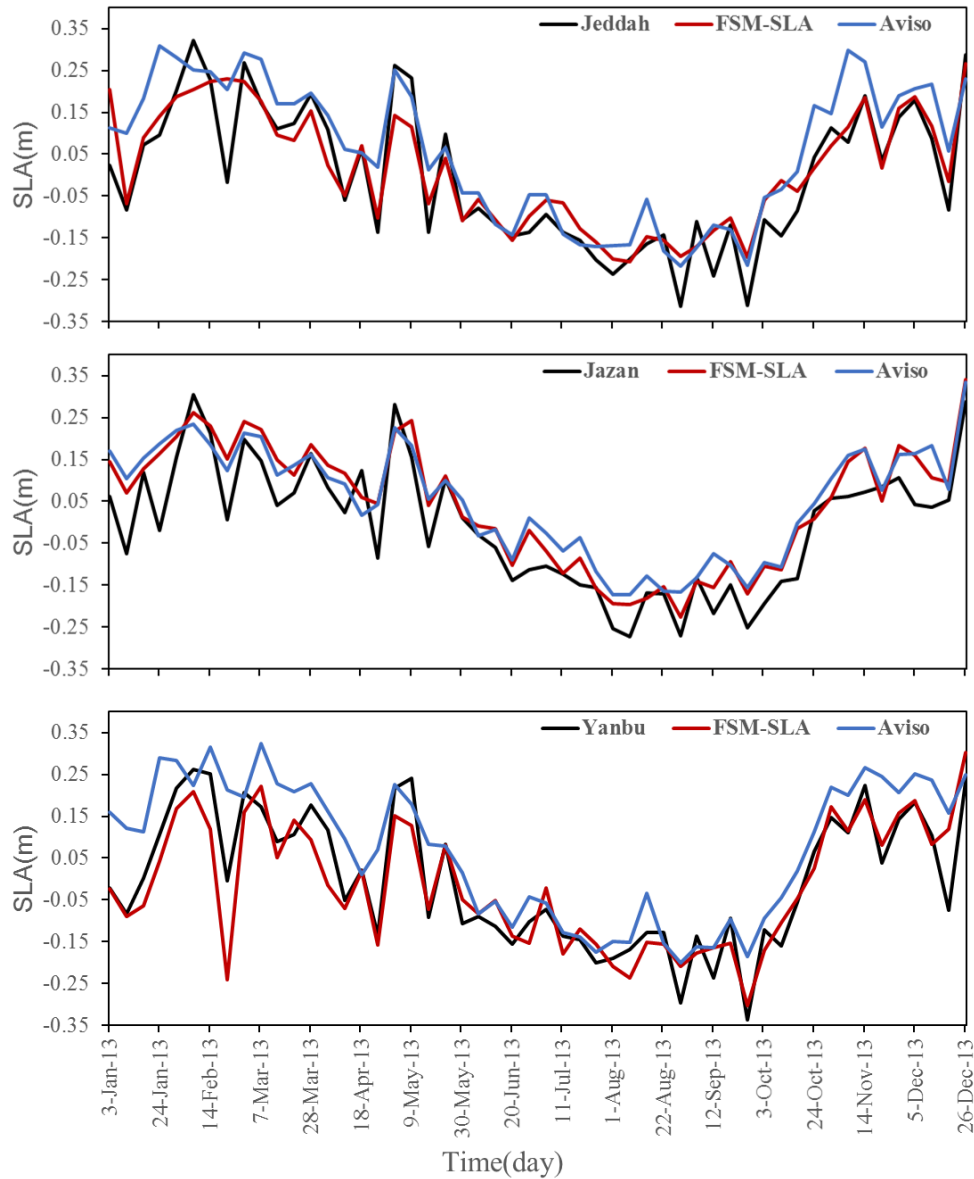Figure 2. show the correlation coefficient between AVISO and FSM data

Figure 3. Comparison of SLA from three tide gauge (black), with grid FSM-SLA data (red) and Aviso (blue)

Figure 3 shows the SLA time series for 2013 from the three coastal stations as compared with the FSM-SLA and AVISO. The three stations datasets have similar seasonal pattern and FSM-SLA coincides with observed SLA in shorter-duration fluctuations. This agreement is clearly shown in Table 2. The comparison of FSM-SLA data and the observed SLA data (at Jazan, Jeddah, and Yanbu stations) show a better correlation than between the AVISO and observed SLA data as shown in Fig.3 and Table .2. These correlation coefficient differences

indicate that the FSM-SLA shows better accuracy near the coast. These results were consistent with those obtained for along-track Jason-2 SLA with coastal stations by Taqi et al., (2017).
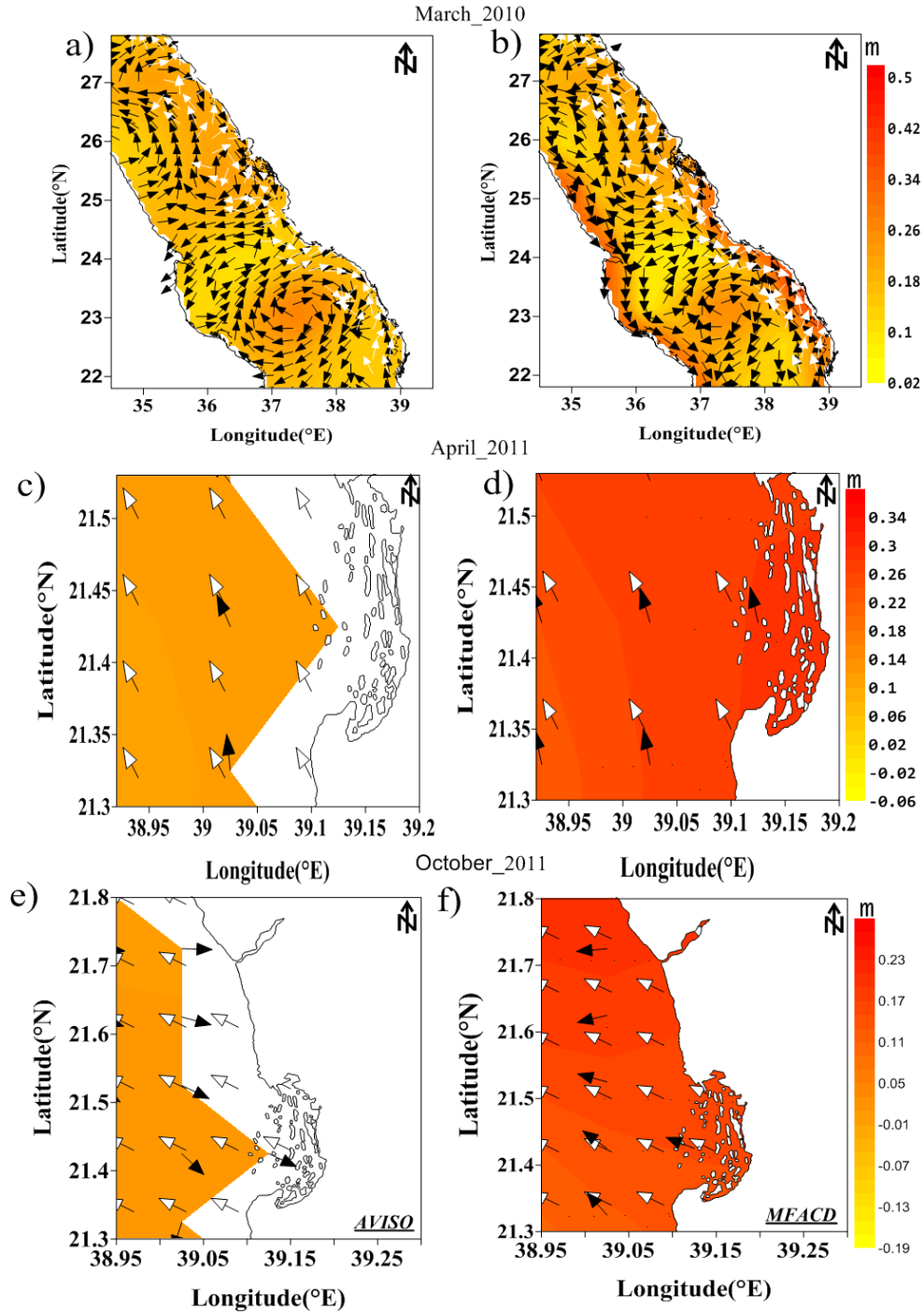
Figure 4. Comparison for three months' SLA (color) and geostrophic currents (black vectors) between (left) AVISO and (right) FSM-SLA white vectors show geostrophic currents from CTD data.

Figure 4 shows a comparison between the geostrophic currents for the central Red Sea derived from AVISO and FSM-SLA for three different times (March 2010, April 2011, and October 2011), those different periods corresponding to the timing of three cruises described in section 2.1.

It can be seen from the Fig. 4(b, d & f) that there is a significant matching in the directions of geostrophic currents from FSM-SLA with CTD data near the coast and offshore. This result is in agreement with Bower and Farrar (2015) findings, especially in October 2011 (Fig. 4f). In March 2010, the geostrophic current near the coast estimated from FSM-SLA is in match with directions of CTD-derived geostrophic current in most regions. However, the directions of geostrophic currents from AVISO are not always in match with CTD-derived one especially in October 2011.

In March 2010 the geostrophic currents along the eastern coast of the Red Sea are towards the north for both FSM-SLA and AVISO, except between 22.2° – 23°N, where the FSM-SLA and CTD data geostrophic currents are in the same direction while AVISO geostrophic current is in the opposite direction (see Fig. 4a,4b).

Table 3. statistical analysis for the speed of geostrophic current from FSM-SLA and AVISO compared with CTD-derived geostrophic current from the thress cruises.

		Month-Year	Bias (m/s)	RMSE (m/s)	Stdv (m/s)	CC
current speed	FSM-SLA	Mar-2010	-0.0085	0.065	0.066	0.54
	AVISO		-0.01	0.08	0.08	0.48
	FSM-SLA	Apr-2011	-0.28	0.31	0.15	0.61
	AVISO		-0.87	0.89	0.21	0.44
	FSM-SLA	Oct-2011	-0.19	0.49	0.45	0.53
	AVISO		-0.51	0.70	0.48	0.49

The speed of geostrophic current data derived from FSM-SLA and CTD during the months (March 2010, April 2011, October 2011) shows a stronger correlation compared with the speed of geostrophic current derived from AVISO and CTD as shown in Fig. 4 and Table 3.

3.2 Description of FSM-SLA and geostrophic current

Figure 5 shows monthly climatology variation for the 6-year period for SLA and geostrophic current. The SLA is higher during the period from October to May and lower during rest of the year, this pattern is consistent with previous studies (Patzert, 1974; Edwards, 1987; Ahmad and Sultan, 1989; Sofianos and Johns, 2001; Sultan and Elghribi, 2003;Manasrah et al., 2004, 2009). Based on calculations made here, the geostrophic current of Red Sea along the eastern coast is northward while along the western coast is southward. This northward flowing current is consistent with a previous study by Bower and Farrar (2015). Similar results are also obtained from three-dimensional modeling by (Clifford et al., 1997; Eshel and Naik, 1997; Sofianos, 2003, 2002). The Fig.5 presents the surface circulation during January in the northern part, where two eddies formed between $25^o – 27.5^oN$. The first eddy is an anticyclone between $26.3^o – 27.5^oN$ on the eastern side of the Red Sea. The other eddy is cyclonic located between $25^o – 26.3^oN$ near the western coast. To the south of that, there are two other eddies between $22.5^o – 24.7^oN$, cyclonic on the western side and anticyclonic on the eastern side. These results match those observed in previous studies by (Eladawy et al., 2017; Sofianos and Johns, 2003a). Two cyclonic eddies and an anticyclonic eddy found at $19.5^o – 22.5^oN$ are consistent with those modeled by Sofianos and Johns, (2003). Near Bab al-Mandab, there is a cyclonic eddy on the western side between $15^o – 16.5^oN$.

In February, the surface circulation of the Red Sea is similar to that during January, with some differences in the eddies structure. The anticyclonic eddy near 27^oN on the eastern sides of the Red Sea starts shifting toward the western coast, while a cyclonic eddy at $25^o – 26.3^o N$ start appearing. The cyclonic eddies between $22.5^o – 24.7^oN$ on the western side are less clear in this month.

In March and April, all the eddies are located along the central axis of the Red Sea. In the north, the anticyclonic eddy near 27^oN is shown in both months, while the cyclonic eddy is not clear during March and April. The anticyclonic eddy shown near $23-24^oN$ during March is weakening during April. Also, the anticyclonic eddy between $19-20^oN$ is shrinking during April.

In May, there is no clear eddy between 27.5ºN and 25ºN. However, four eddies are clearly existing between 19.5º –25ºN; two cyclonic eddies at 24º – 25ºN, and 20º – 22ºN, two anticyclonic eddies at 23º – 24ºN, and 19.5º – 20ºN. From the previous results, it can be seen several cyclonic and anticyclonic eddies distributed all over the Red Sea and these results match those in modelling studies (Clifford et al., 1997; Eladawy et al., 2017; Sofianos, 2003, 2002, Yao et al., 2014a)

During June, the flow of the geostrophic currents in the northern part reversed its direction. This accompanies a formation of large cyclonic eddy extending from 25.5º– 27.5ºN occupying the entire width of the Red Sea. To the south of it, another cyclonic eddy observed between 24º – 25ºN and an anticyclonic eddy between 23º – 24ºN are also noticed during June with a similar strength during May. The cyclonic eddy seen between 17º – 20ºN during May, is also seen during this month with more strength. To the south of it, the flow is towards the Bab el-Mandab following normal summer pattern. The flow pattern along the coast is similar to results of (Chen et al., 2014) for winter (January to April). The short-term climatology of geostrophic current in the Red Sea is dominated by cyclonic and anticyclonic eddies all over the Red Sea, and especially in the central and northern parts of the sea.

During July-September, the flow of the geostrophic currents structure is similar to that of June with two cyclonic eddies north of 24.5ºN and an anticyclonic eddy between 23º – 24ºN. South of these eddies, another cyclonic eddy extends to 19ºN. Furthermore, south of 19ºN, there is an outflow towards the south all over the width of the Red Sea with narrow inflow along the eastern coast of the Red Sea. The Fig. 6 also shows an anticyclonic between 18°-19ºN and a cyclonic between 16°-17ºN during August and September. These results are consistent with the results from previous studies (Clifford et al., 1997; Eladawy et al., 2017; Sofianos, 2003, 2002, Yao et al., 2014b).

During summer (June-September), the changes in wind speed and direction cause reversed of changes in the direction of flow consequently, the locations of eddies are also changed (Chen et al., 2014). The surface current flows from the Red Sea to the Gulf of Aden through the Bab-el-Mandeb. The anticyclonic eddy shown in the north at 27.5ºN in winter is replaced with cyclonic eddy, during this season. Summer is dominated by cyclonic eddies as shown in Fig. 6.
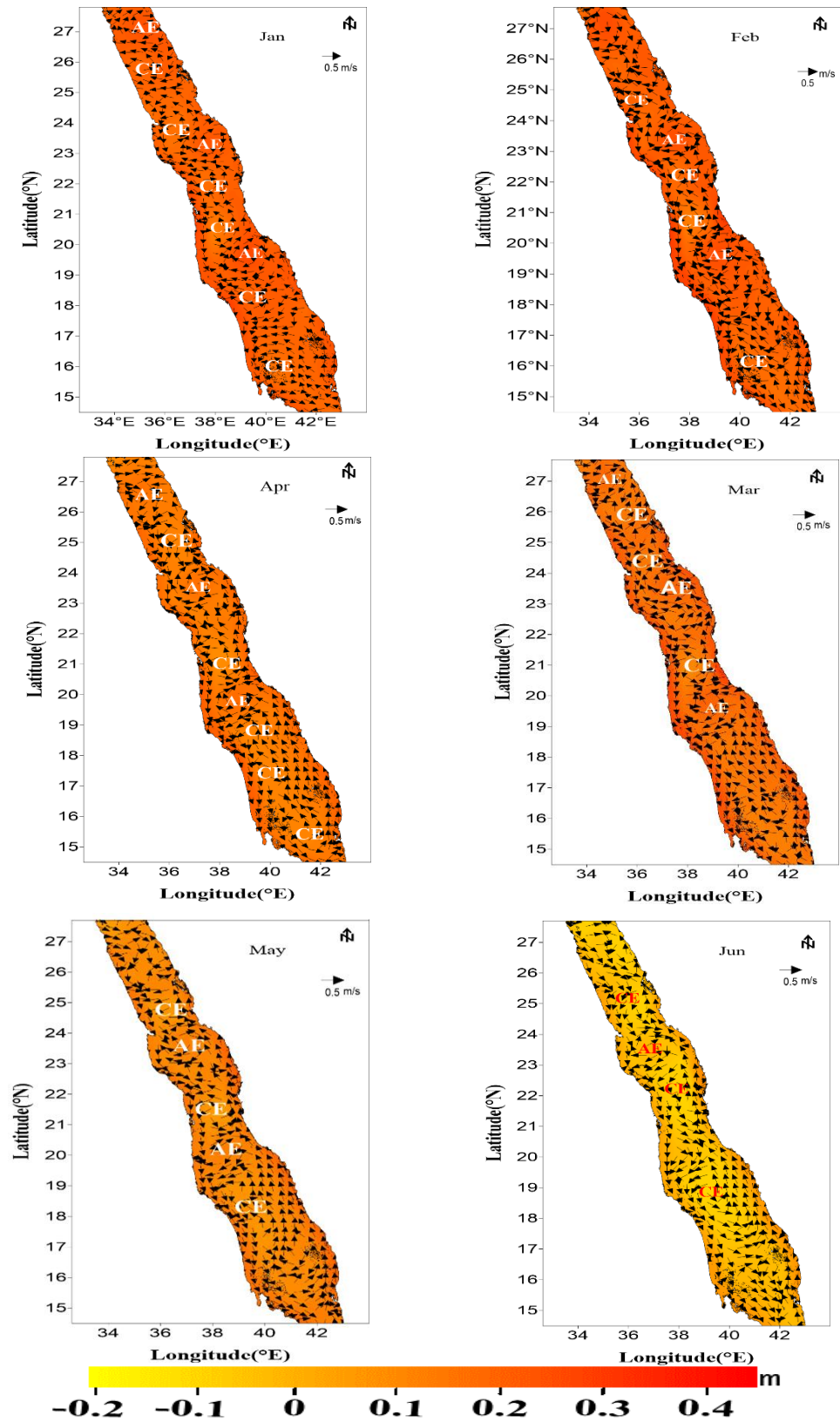
Figure 5. shown monthly climatology for geostrophic current and Sea level anomaly (Reference current length =0.5m/s)
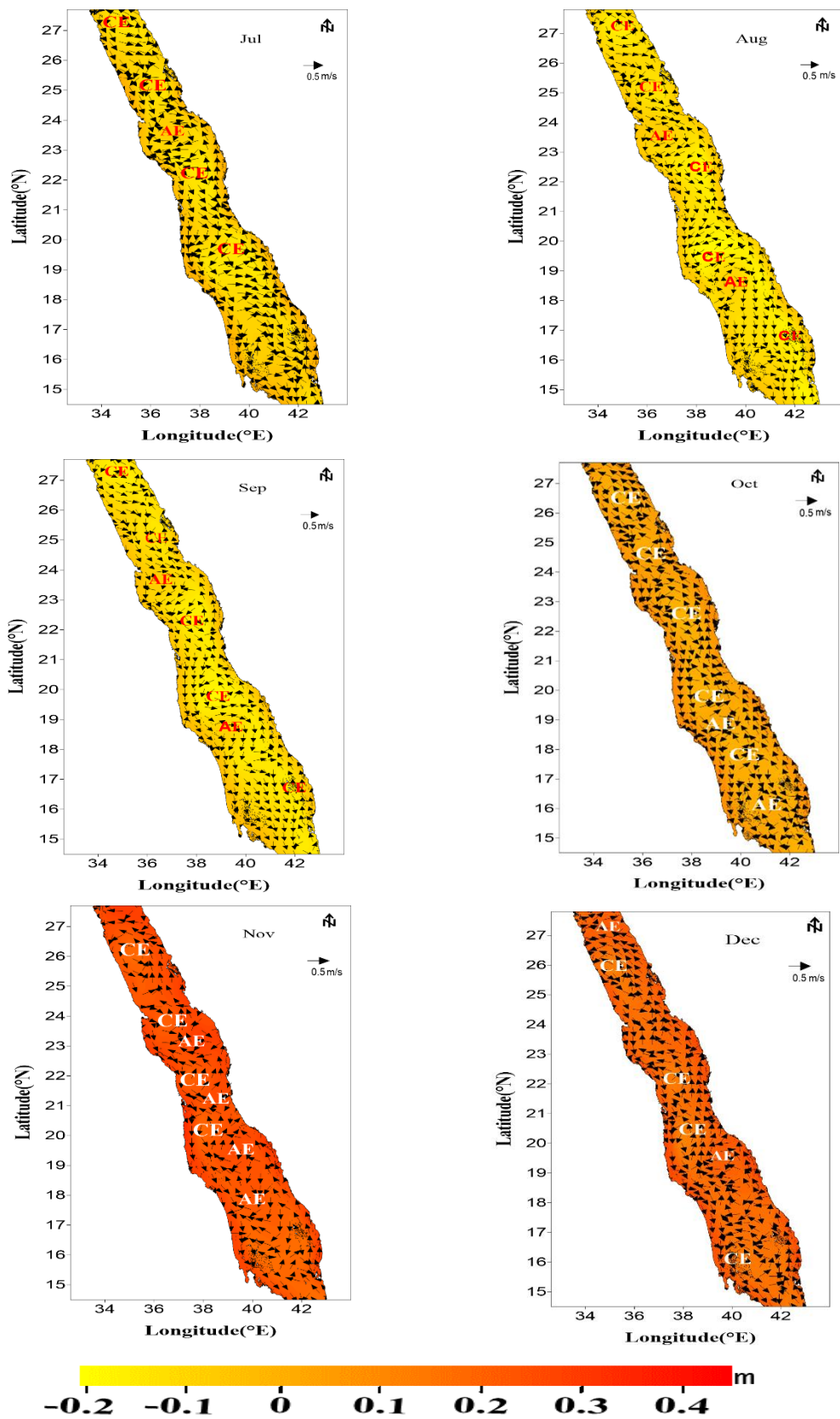
Figure 6. As Fig. 5 for July to December

During October, the geostrophic current is weak as compared with that during September, still cyclonic but with less strength. The anticyclone seen during September between 23º – 24ºN is not clear during October and formation anticyclone eddy between 15º-16ºN. In the central and southern parts, the flow of the geostrophic currents is towards south along the western coast and towards the north along the eastern side with the presence of cyclonic and anticyclonic eddies in the central axis of the Red Sea with a weak flow. In November and December, the structure of geostrophic currents are similar to that of October but with stronger currents and well established cyclonic and anticyclonic eddies.

During summer, the cyclonic eddies are often concentrated on the west side and the anticyclonic eddies on the eastern side of the Red Sea, while in winter it is the opposite. Their formation might be related to wind forces and thermohaline (Neumann and McGill, 1961; Phillips, 1966; Quadfasel and Baudner, 1993; Siedler, 1969; Tragou and Garrett, 1997).

Since the general circulation in the Red Sea is largely modified with the presence of cyclonic and anticyclonic eddies, the identification of eddies in the study area were conducted based on defining the eddies in terms of SLA (Chelton et al., 2011). Figure 7 shows statistical variability of lifespan, number of eddies, amplitude, and the mean speed of geostrophic current in the center of the eddies with latitude for 6 years. Statistical analysis indicates that eddies are generated over the entire Red Sea, mostly concentrated between 18°-24ºN, obviously stronger than any other latitude. The amplitude of an eddy has been defined as the differences between the estimated basic height of the eddy boundary and the extremum value of SLA inside the eddy interior parts. The mean amplitude for anticyclonic is between 1.3 cm at southern Red Sea to 5.3 cm at northern Red Sea and for cyclonic eddy is between 1.6 cm at southern Red Sea to 4.2 cm at northern Red Sea. The result indicates the average value of eddy amplitude in the Red Sea (including low latitude and high latitude) is about 4 cm, which is within the reasonable range defined by (Chelton et al., 2011). The average lifespan of the cyclonic eddies is longer than that of the anticyclonic eddies. Moreover, the mean speed of geostrophic current for the entire Red Sea is about 5-10 cm/s, which has reached three-times higher in the 25°-26ºN latitude band for both cyclonic and anticyclonic. These results match those observed in previous study Zhan et al., (2014).
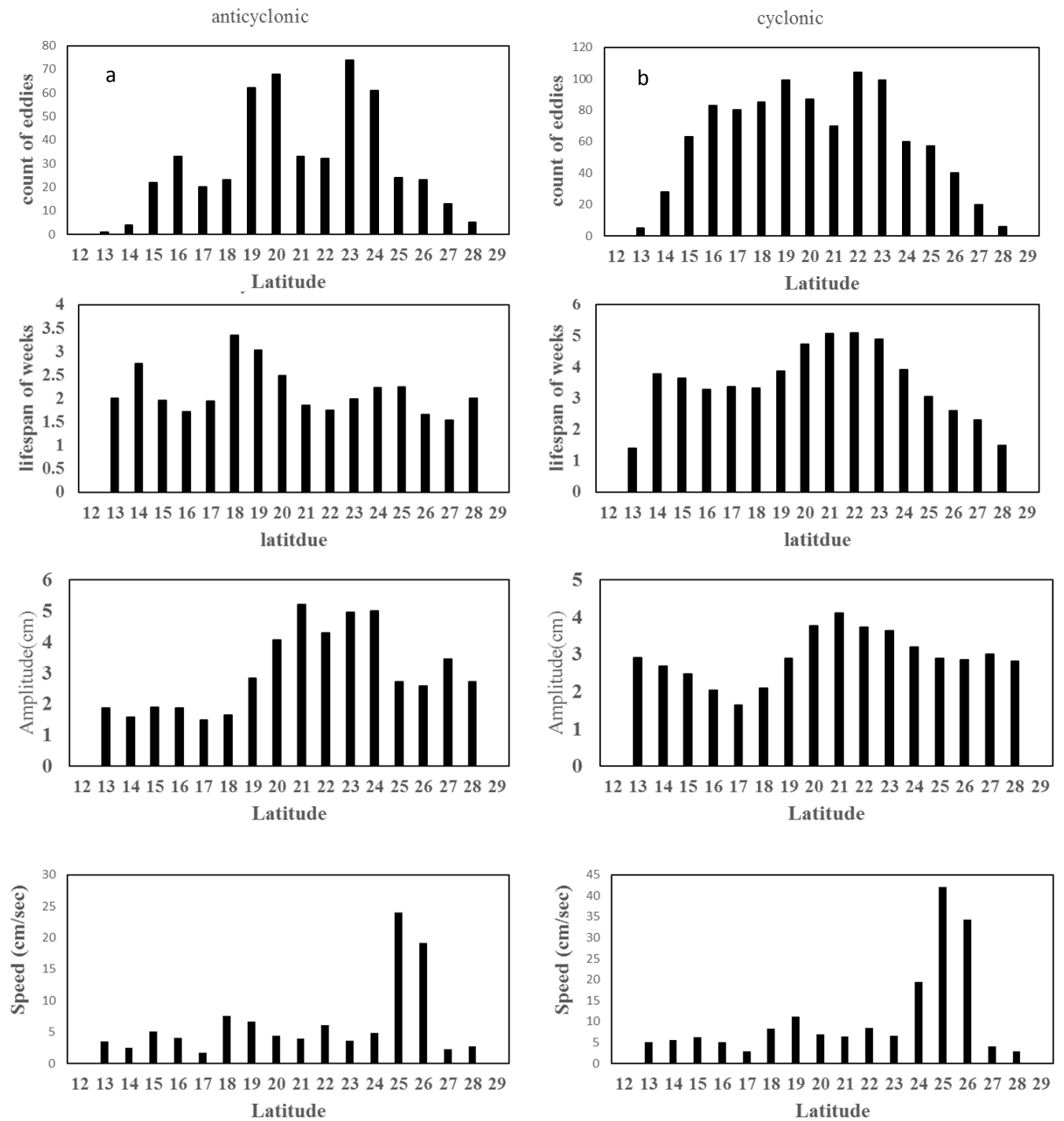
Figure 7. the variability of eddies with latitude for cyclonic (right panel) and anticyclonic (left panel).
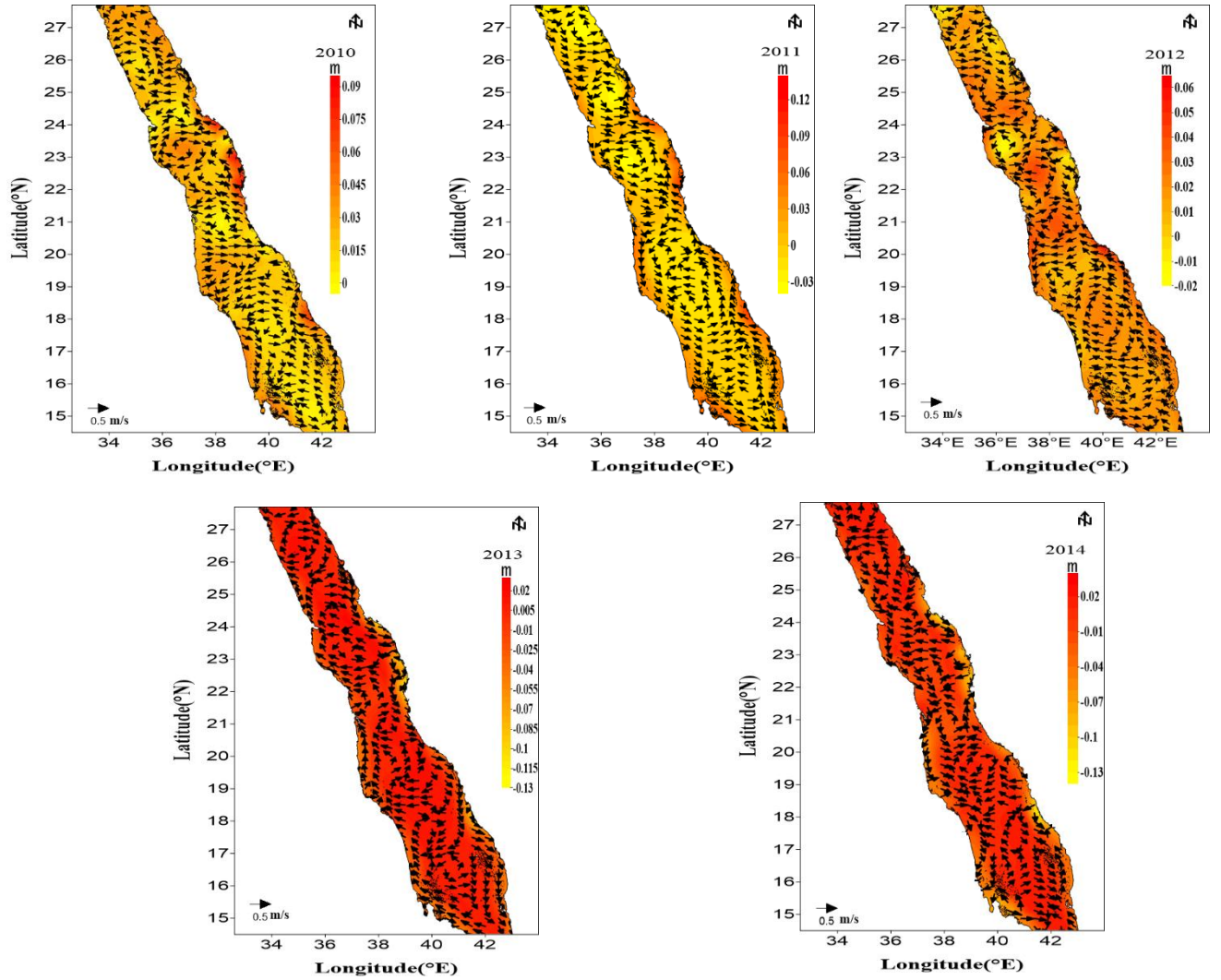
Figure 8. Maps of the annual mean SLA as a deviation from 6-yr mean.

Figure 8 shows the annual mean of SLA as deviation from the 6-year mean. The interannual variability of SLA and geostrophic currents is clearly seen in the southern part of the Red Sea while in the northern part, the pattern is similar for all years except for 2013 where the cyclonic replaced by anticyclonic eddy. The SLA and geostrophic distribution observed during 2011 are similar to that shown in Papadopoulos et al., (2015), with the cyclonic eddy along the eastern side seen more clearly. Moreover, due to extension of our data we could compute the cyclonic pattern up to the coast. The geostrophic currents direction is irregular along the coast, which is northward most of the time. The eddies were mostly concentrated in the north and central parts of the Red Sea.

The statistical analysis between annual FSM-SLA with 6-year mean (Table 4) is less biased with lower RMSE value and strong correlation. The standard deviation shows low value for each year.

Table 4. Statistical analysis for the annual mean of FSM-SLA compared deviation from 6-yr mean.

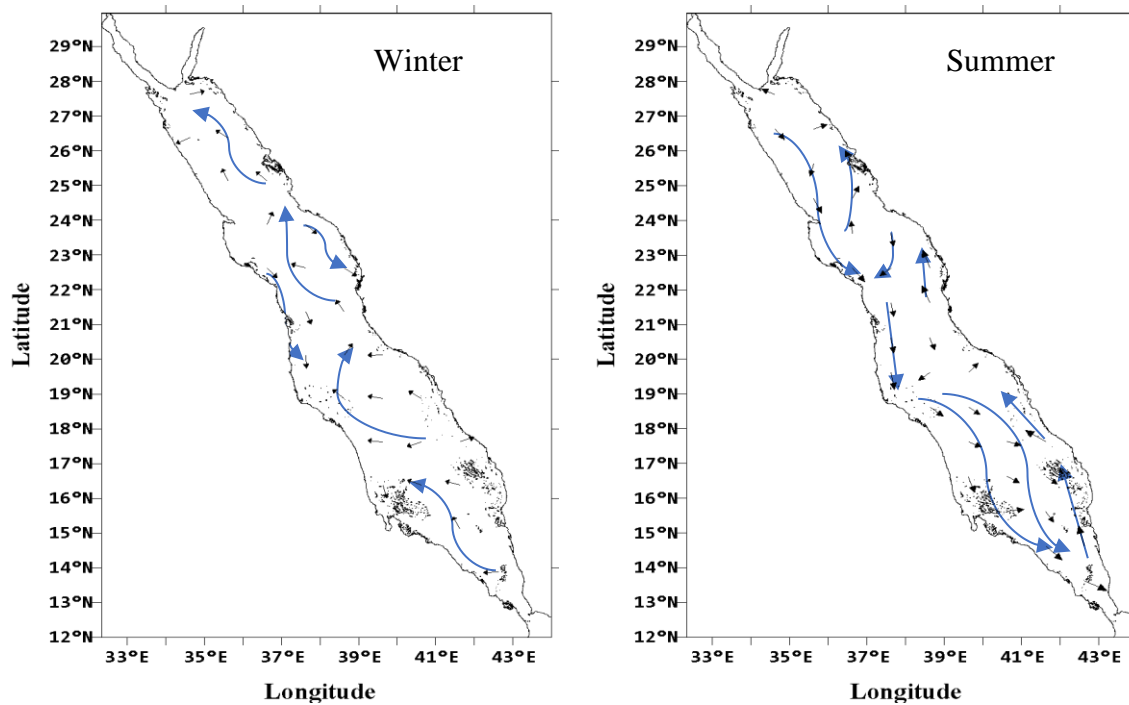| Year	Bias	RMSE	STD	CC
2010	-0.009	0.023	0.019	0.544
2011	-0.012	0.029	0.024	0.774
2012	-0.009	0.025	0.022	0.548
2013	-0.013	0.037	0.032	0.791
2014	-0.013	0.036	0.032	0.726

Figure 9. Winter and summer seasonal average surface geostrophic currents, black arrows are actual surface geostrophic currents and blue arrows are schematic streamline.

Figure 9 shows the general schematic of the seasonal variability of geostrophic currents derived from 6 years. During winter, the mean flow is toward the north mostly along the western coast up to 16°N, this result agrees with Sofianos and Johns, (2003) then it shifts to the eastern

coast up to 20°N. The flow is along the middle from 20°N to the north. The mean flow is toward the north mostly along the western coast and center up to 23°N then it shifts to the eastern coast. Apart from this, southward coastal geostrophic currents are observed along the eastern coast (22°N-24°N) and the western coast (23°N-20°N). During summer, the flow is towards the south along the western side of the sea while in the southern part the flow spreads for most of the area of the Red Sea with a narrow northward direction near the eastern coast.

4. Conclusion

In general, the geostrophic current has been estimated from FSM-SLA for Red Sea region, and the distribution of the geostrophic current shows that the winter period extends from October to May and summer period extends from June to September. This pattern is similar to that shown by (Sofianos and Johns, 2001). There was a lack in measurements of coastal currents in the Red Sea. This study was able to produce data near the coast. The major new findings from the present study include the monthly geostrophic pattern in the Red Sea which has not been published before. The finding of this paper considered the first of its type in the Red Sea for extending SLA and geostrophic currents to the coast beside giving more details of eddies spatial and temporal variabilities in the coastal region.

The southern Red Sea show significant interannual variability in the geostrophic current pattern, while the central and northern parts are negligible difference over the years. The geostrophic along the eastern coast is towards the north while along the western coast of the sea it is southward. Seasonally, the geostrophic currents in summer are flowing northward except the eastern coast which flows in the opposite. In winter, currents flow to the north for the entire sea except small part of the eastern coast (22°N-24°N) and the western coast (23°N-20°N). In this study, northward flowing eastern coastal current during summer is documented for the first time in the Red Sea.

The cyclonic eddies were relatively larger than the anticyclonic eddies in the Red Sea. The eddies are concentrated in the central and north of the Red Sea more than the southern side. That the mean amplitude for anticyclonic and cyclonic at lower latitudes has low amplitude and at higher latitudes has high amplitude. In winter, the cyclonic eddies are beside the west coast and anticyclonic eddies on the east side in the Red Sea, while in summer it is the opposite. Also, in some locations there is a noticeable change from anticyclonic during winter to cyclonic during

summer and vice versa between 26.3°N –27.5°N. The analysis of the eddies found that during the summer the cyclonic eddies are dominant than winter in the entire Red Sea, while eddies of both polarities observed during winter. The finding of this paper considered the first of its type in the Red Sea for extending SLA and geostrophic currents to the coast beside giving more details of eddies spatial and temporal variabilities in the coastal region.

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