Sea Surface Height Variability and Eddy Statistical Properties in the Red Sea

Thesis by
Peng Zhan

In Partial Fulfillment of the Requirements
For the Degree of
Master of Science

King Abdullah University of Science and Technology
Thuwal, Kingdom of Saudi Arabia

May 14, 2013
The thesis of Peng Zhan is approved by the examination committee.

Dionysios Raitsos
Committee Member
Signature
Date

Burton Jones
Committee Member
Signature
Date

Ibrahim Hoteit
Committee Chair
Signature
Date

King Abdullah University of Science and Technology
2013
ABSTRACT

Sea Surface Height Variability and Eddy Statistical Properties in the Red Sea

Peng Zhan

Satellite sea surface height (SSH) data over 1992-2012 are analyzed to study the spatial and temporal variability of sea level in the Red Sea. Empirical orthogonal functions (EOF) analysis suggests the remarkable seasonality of SSH in the Red Sea, and a significant correlation is found between SSH variation and seasonal wind cycle.

A winding-angle based eddy identification algorithm is employed to derive the mesoscale eddy information from SSH data. Totally more than 5500 eddies are detected, belonging to 2583 eddy tracks. Statistics suggest that eddies generate over the entire Red Sea, with two regions in the central basin of high eddy frequency. 76% of the detected eddies have a radius ranging from 40km to 100km, of which both intensity and absolute vorticity decrease with eddy radius. The average eddy lifespan is about 5 weeks, and eddies with longer lifespan tend to have larger radius but less intensity. Different deformation rate exists between anticyclonic eddies (AEs) and cyclonic eddies (CEs), those eddies with higher intensity appear to be less
deformed and more circular. Inspection of the 84 long-lived eddies suggests the AEs tend to move a little more northward than CEs. AE generation during summer is obviously lower than that during other seasons, while CE generation is higher during spring and summer. Other features of AEs and CEs are similar with both vorticity and intensity reaching the summer peaks in August and winter peaks in January. Inter-annual variability reveals that the eddies in the Red Sea are isolated from the global event. The eddy property tendencies are different from the south and north basin, both of which exhibit a two-year cycle. Showing a correlation coefficient of -0.91, Brunt–Väisälä frequency is negatively correlated with eddy kinetic energy (EKE), which results from AE activities in the high eddy frequency region. Climatological vertical velocity shear variation is identical with EKE except in the autumn, suggesting the vertical shear could convert the energy from baroclinic instability into eddy activity.

Finally, numerical simulation results from the MIT general circulation model (MITgcm) are validated with previous studies and observations. The vertical structure of the simulated flux through Bab el Mandeb is successfully reproduced. Further validation with the 2010 cruise suggests that the thermocline occurs at ~200m, but the model vertical salinity gradient is lower than the observations. The model surface eddy variability is also examined, suggesting good agreement with satellite observations.
ACKNOWLEDGEMENTS

Sincere thanks to my supervisor, Prof. Ibrahim Hoteit, for his profound knowledge, patience and enthusiasm.

Thanks to the members of my thesis examination committee, Prof. Burton Jones and Dr. Dionysios Raitos, for their valuable comments and precious time.

Thanks to Dr. Fengchao Yao, for the interesting discussion and suggestions.

Thanks to Dr. Yaswant Pradhan, for his kindly help and invaluable comments.

Thanks to Mr. Sabique Langodan, for his great encouragement.

Thanks to my parents, for raising me up.

Last but not least, special thanks to Mr. Song Gao, for his selfless support.

My appreciation also goes to my friends and colleagues and the department faculty and staff for making my time at King Abdullah University of Science and Technology a great experience. I also want to extend my gratitude to the King Abdullah University of Science and Technology.
Table of Contents

ABSTRACT ................................................................................................................................................. 4
ACKNOWLEDGEMENTS............................................................................................................................... 6
LIST OF ABBREVIATIONS.......................................................................................................................... 9
LIST OF SYMBOLS................................................................................................................................ 10
LIST OF ILLUSTRATIONS........................................................................................................................ 12
LIST OF TABLES.................................................................................................................................. 14
1. Introduction ...................................................................................................................................... 15
2. Data and Methods........................................................................................................................... 20
   2.1 SSH................................................................................................................................................. 20
   2.2 WOA .............................................................................................................................................. 21
   2.3 Model............................................................................................................................................ 21
   2.4 Eddy Identification Scheme and Tracking Procedure ......................................................... 23
3. Analysis and Discussion ............................................................................................................... 26
   3.1 Analysis of SSH ......................................................................................................................... 26
   3.2 Eddy activity .............................................................................................................................. 31
   3.3 Definition of eddy Kinematic Properties ........................................................................ 32
   3.4 Eddy statistical properties ................................................................................................... 33
       3.4.1 Mean Eddy Genesis ............................................................................................................ 33
       3.4.2 Eddy Frequency .................................................................................................................... 35
       3.4.3 Eddy Radius ............................................................................................................................ 37
       3.4.4 Eddy Kinematics .................................................................................................................. 39
       3.4.5 Eddy Lifespan ........................................................................................................................ 41
3.4.6 Eddy Evolution ...................................................................................................................... 43
3.4.7 Seasonal Variability ............................................................................................................. 45
3.4.8 Inter-annual Variability ..................................................................................................... 47
3.4.9 Eddy Vertical stability ........................................................................................................ 48
4 Model Validation .............................................................................................................................. 52
  4.1 Transport Through Bab el Mandeb ................................................................................ 52
  4.2 Model comparison With Cruise Cross-section ............................................................. 53
  4.3. Validation With SSH ............................................................................................................... 55
5. Conclusions and future work ..................................................................................................... 57
References .............................................................................................................................................. 60
  A.1 Concepts of satellite products ............................................................................................ 63
  A.2 Figures ......................................................................................................................................... 64
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE</td>
<td>Anticyclonic eddy</td>
</tr>
<tr>
<td>CE</td>
<td>Cyclonic eddy</td>
</tr>
<tr>
<td>EI</td>
<td>Eddy intensity</td>
</tr>
<tr>
<td>EKE</td>
<td>Eddy kinetic energy</td>
</tr>
<tr>
<td>EOF</td>
<td>Empirical orthogonal function</td>
</tr>
<tr>
<td>GAIW</td>
<td>Gulf of Aden Intrusion Water</td>
</tr>
<tr>
<td>MITgcm</td>
<td>MIT general circulation model</td>
</tr>
<tr>
<td>PC</td>
<td>Principal Component</td>
</tr>
<tr>
<td>RSOW</td>
<td>Red Sea Overflow Water</td>
</tr>
<tr>
<td>SLA</td>
<td>Sea Level Anomaly</td>
</tr>
<tr>
<td>SSH</td>
<td>Sea Surface Height</td>
</tr>
<tr>
<td>SW</td>
<td>Surface Water</td>
</tr>
<tr>
<td>TD</td>
<td>Total deformation rate</td>
</tr>
</tbody>
</table>
# LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>the angle between consecutive streamline segments</td>
</tr>
<tr>
<td>$\Delta D$</td>
<td>spatial distance of eddy center</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>difference of eddy radius</td>
</tr>
<tr>
<td>$\Delta \zeta$</td>
<td>difference of eddy vorticity</td>
</tr>
<tr>
<td>$\Delta EKE$</td>
<td>difference of EKE</td>
</tr>
<tr>
<td>$D_0$</td>
<td>characteristic distance of eddy center</td>
</tr>
<tr>
<td>$R_0$</td>
<td>characteristic difference of eddy radius</td>
</tr>
<tr>
<td>$\zeta_0$</td>
<td>characteristic difference of eddy vorticity</td>
</tr>
<tr>
<td>$EKE_0$</td>
<td>characteristic difference of EKE</td>
</tr>
<tr>
<td>$D_{e_1,e_2}$</td>
<td>$D_{e_1,e_2} = \sqrt{(\frac{\Delta D}{D_0})^2 + (\frac{\Delta R}{R_0})^2 + (\frac{\Delta \zeta}{\zeta_0})^2 + (\frac{\Delta EKE}{EKE_0})^2}$</td>
</tr>
<tr>
<td>$U'_e$</td>
<td>zonal component of geostrophic velocity anomaly</td>
</tr>
<tr>
<td>$V'_m$</td>
<td>meridional component of geostrophic velocity anomaly</td>
</tr>
<tr>
<td>$g$</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>$f$</td>
<td>Coriolis parameter</td>
</tr>
<tr>
<td>$\eta$</td>
<td>sea level anomaly</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>eddy vorticity</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>eddy shearing deformation rate</td>
</tr>
</tbody>
</table>
\( \gamma_2 \) eddy stretching deformation rate
\( \gamma \) total deformation rate
\( \Psi \) eddy divergence
\( N \) Brunt–Väisälä frequency
\( \rho_0 \) background density of seawater
\( \rho \) seawater density
LIST OF ILLUSTRATIONS

Figure 1.1: Topography of the Red Sea with the white arrows indicating the locations of mountain gaps ............................................................................................................ 16

Figure 1.2: Stratified layer flow schematic at Bab el Mandeb. SW = Surface Water, RSOW = Red Sea Overflow Water, GAIW = Gulf of Aden Intrusion Water ............... 17

Figure 2.1: Winding-angle schematic representation for a segmented streamline ... 24

Figure 3.1: Standard deviation of SSH over 1993-2012. .................................................. 27

Figure 3.2: Standard deviation of SSH for the four seasons, (a) spring, (b) summer, (c) autumn, (d) winter ....................................................................................................................... 27

Figure 3.3: The first EOF mode of the SSH. The percentage denotes the fraction of the explained variance. ................................................................................................................. 28

Figure 3.4: The PC corresponding to the first EOF mode of the SSH. ................................. 29

Figure 3.5: Eddy genesis in the Red Sea over October 1992 to December 2012. Units are the number of events. ......................................................................................... 34

Figure 3.6: (a) Eddy frequency, (b) Eddy polarity, and (c) Mean EKE. ............................... 36

Figure 3.7: Radius distributions: (a) probability density function of the radius, mean distribution of (b) EKE, (c) EI, (d) vorticity, as a function of radius. ......................... 38

Figure 3.8: Mean vorticity and TD as functions of EI. .......................................................... 41

Figure 3.9: (a) Vortex lifespan distributions. Mean distribution of the (b) radius and (c) EI as functions of vortex lifespan. (d) Meridional variation of the eddy lifespan. .......................................................................................... 42

Figure 3.10: Mean properties of long-lived eddy: (a) radius, (b) EI, (c) vorticity and (d) meridional displacement of AEs and CEs ......................................................... 44

Figure 3.11: Seasonal variability of eddy properties: number of eddy genesis per season for (a) AE and (b) CE, (c) radius, (d) vorticity, (e) EKE and (F) EI ............................. 45

Figure 3.12: Inter-annual variations of eddies properties in the south Red Sea: (a) number of eddies generated per month, (b) EI, (c) radius and (d) vorticity ............. 47
Figure 3.13: Inter-annual variations of eddies properties in the north Red Sea: (a) number of eddies generated per month, (b) EI, (c) radius and (d) vorticity .......... 47

Figure 3.14: Climatological monthly mean Brunt–Väisälä frequency, EKE and vertical shear over 18ºN to 24ºN of the Red Sea basin ........................................ 50

Figure 4.1: Meridinal flux through Bab el Mandeb (a) averaged between November of 2009 and May of 2010, and (b) between June and October 2010. Hovmöller diagram of (c) temperature and (d) salinity at 43.27ºE 12.89ºN in the strait........ 52

Figure 4.2: Map of cruise stations (in black dots), the selected cross-sections from cruise observations (~23ºN cross-section in red dots, along basin-axis cross-section in purple dots) and from the model (in blue dots) ................................................................. 54

Figure 4.3: Vertical distribution for the along basin-axis cross-section: (a) salinity from cruise observation, (b) salinity from model, (c) temperature from cruise observation and (d) temperature from model .................................................. 54

Figure 4.4: (a) Monthly mean of sea surface geostrophic velocity derived from SSH for June, 2010. (b) Monthly mean of sea surface velocity from model. .................................. 55

Figure A.1: Drifter track on top of eddy vorticity derived from SSH ...................... 64

Figure A.2: Eddy representation with the first mode of SSH EOF subtracted for 2010 ............................................................................................................. 65

Figure A.3: Vertical distribution for the ~23ºN cross-section: (a) salinity from cruise observation, (b) temperature from cruise observation, (c) salinity from model, and (d) temperature from model ........................................................................... 66
LIST OF TABLES

Table 3.1 Mean statistics of the eddy kinematics .......................................................... 40
1. Introduction

The Red Sea has recently attracted attention from the geophysical and the engineering communities, for its potential exploration of petroleum resources and its unique structures in the ocean hydrology and circulation system.

The Red Sea, a long and narrow basin located between Asia and Africa surrounded by hot deserts isolated from world oceans, characterized by high temperature and salinity water due to high evaporation, negligible precipitation and lack of runoff supply. Since the Suez Canal in the north is negligible, the only connection is with the Gulf of Aden through the strait of Bab el Mandeb, a narrow and shallow channel with a sill depth of 160m and a minimum width of about 25km. The average depth is about 490m [Zhai, 2011]. However, along the bottom of the sea is a central trench, which reaches depths of 2134m. Figure 1.1 shows the major surface and bottom features of the Red Sea.

The Red Sea is bordered by high mountain ranges that constrain the winds to be closely aligned along the axis of the basin except at few locations where gaps in the mountains exist. The wind field over the Red Sea exhibits considerable seasonality. The climatological wind over the northern Red Sea is northwesterly all around the year, in contrast with the southern Red Sea, where winds are southeasterly during winter and northwesterly during summer. Thus, strong wind convergence zone
exists at about 19°N in the winter, south of which is monsoon-dominated atmosphere, and north of which is the continental-dominated atmosphere. Near the mountain gaps, the winter wind jets blowing from the Saudi land can cause huge evaporation and ocean heat lost, which would densify the seawater and potentially drive deep convection along the northeastern Red Sea coast [Jiang et al., 2009; Sofianos and Johns, 2003]. Besides, a huge mountain gap exists near 18°N on the west coast of the Red Sea, where wind jet blows through the Tokar Gap during the summer monsoon season. This strong cross-axis wind (up to 20-25 m/s) disturbs the prevailing along-axis winds and can last days or over weeks.

Figure 1.1: Topography of the Red Sea with the white arrows indicating the locations of mountain gaps
Bab el Mandeb is the only connection between the Red Sea and the Gulf of Aden. Observations during winter indicate that a two-layer water exchange structure persists, while summer-time observations illustrate the existence of exchange seasonal variability [Siddall et al., 2004]. The overall picture across the strait is a two-layer winter exchange (November-May), that is, a relatively fresh surface inflow on the top of the Red Sea outflow; while during summer (June-October), a three-layer exchange occurs consisting of a shallow surface outflow water, and intermediate intrusion water with relatively low salinity and low temperature from Gulf of Aden, and a deep hypersaline outflow weaker than that during winter [Sofianos and Johns, 2002]. Seasonal change of winds is the key factor that drives
the seasonal cycle of the water exchange through Bab el Mandeb. The southeastern winds in winter and northwestern winds in summer acts conversely as the forcing for both wind-driven circulation and thermohaline circulation [Sofianos and Johns, 2007]. Another possible reason is due to the upwelling current in the western Gulf of Aden during summer, which changes the stratification and sea level by steric effect and further affects the along-strait pressure gradient.

The horizontal circulation in the Red Sea consists of multiple eddies, some of which are semi-permanent. In the northern Red Sea, a cyclonic eddy (CE) exists at least in winter. In the central Red Sea, the circulation is dominated by both CEs and anticyclonic eddies (AEs) that occur most around 23-24⁰N and 18-20⁰N, which are tied to coastline and topography variations. Many of them have the size comparable to the width of Red Sea, and are much more energetic than the large-scale thermohaline circulation [Tragou and Garrett, 1997; William E. Johns, 1999]. Coastal boundary currents seem to exist along the east coast in the southern Red Sea, as well as both east and west coast of the northern Red Sea.

There is very limited information on the spatial variability of sea level and eddy structures in the Red Sea, as most studies tend to treat the Red Sea as a two-dimensional basin confining to its central axis. In this study, firstly, Sea Surface Height (SSH) data is analyzed to study the spatial and temporal patterns in the Red Sea. Secondly, a winding-angle based eddy identification algorithm is employed to derive the mesoscale eddy information from SSH data and provide the eddy statistic
features over the entire Red Sea, including the eddy genesis, frequency, radius and kinematics, lifespan and temporal variability. Finally, numerical simulation results by MITgcm (MIT general circulation model) are validated with previous studies and observations.
2. Data and Methods

In this chapter, the SSH remote sensing data and WOA climatological data are briefly introduced, and the model configuration and eddy identification scheme are described in details.

2.1 SSH

SSH data consist of a merged product of TOPEX/POSEIDON, Jason-1, Envisat and European Research Satellite (ERS). The data cover the period October 1992 to June 2012 (without ERS from January 1994 to March 1995), weekly available with $1/4^\circ \times 1/4^\circ$ resolution. The merged SSH data have lower mapping errors and better spatial coverage than the data merely from one satellite alone [Ducet et al., 2000]. Relative corrections have been incorporated, including solid Earth and ocean tides, ionosphere delay, sea level pressure, and so forth. Here they are used to identify and track eddies in the Red Sea.

Comparisons between geostrophic velocity patterns and drifter tracks in the Red Sea show that, the geostrophic velocity anomalies extracted from SSH work reasonably well to reproduce the eddy. (See in Appendix for the Figure A.1 of drifter tracks on top of surface vorticity, provided by Dr. Amy Bower)
2.2 WOA

WOA05 (World Ocean Atlas 2005) is an objectively analyzed global dataset [Antonov et al., 2006; Locarnini et al., 2006]. In this study, monthly gridded climatological temperature and salinity data are used to study the baroclinic stabilities and eddy-relative dynamical features.

2.3 Model

We use the MITgcm, which solves the Navier-Stokes equation with vertical z-coordinate, an advantage of which is that the vertical resolution is horizontally uniform, thus decreases the computational error where the bottom topography is steep.

The model domain includes the entire Red Sea basin, Gulf of Aqaba and the Gulf of Suez in the north end, as well as a part of the Gulf of Aden. Bathymetry data is based on 2-minute Worldwide Bathymetry/Topography dataset (ETOPO2) [National Geophysical Data Center., 2001]. The curvilinear grid system is used to save the number of total grids (zonally 288 and meridinally 1232), with an approximate horizontal resolution of 1.8km. Vertical resolution is non-uniform; with 25 layers spaced thinner near the surface to resolve the thermal stratification. The simulation is conducted for 7 years from 2004 to 2010 using a time step of 75s.
The model is initialized using previous model result [Fengchao et al., 2012b], which end on 2004/04/11. There are four variables serving as open boundary conditions, including zonal velocity, meridional velocity, temperature and salinity. The above four variables are interpolated from a coarser model covering the seas surrounding the Arabia peninsula, including the north Indian Ocean, the Persian Gulf and the Gulf of Aden, and the Red Sea with horizontal resolution of 1/10°, available once every six days. Since the coordinate systems between these two models (curvilinear grid for the Red Sea model vs. spherical polar grid for the coarser model) are different, one needs to convert the momentum variables because of the angle between these two base coordinate systems. Besides, no-flux boundary conditions are applied for the zonal velocity normal to the east open boundary, in order to ensure water mass conservation. The number of sponge layers is set with 60 to reduce the effect of perturbations on boundary, and the time prescribed for relaxing the open boundary conditions with the interior matters is 1 day for innermost sponge layer point and 1/5 day for outer ones.

Totally seven atmospheric forcing fields from National Centers for Environmental Prediction Reanalysis data (provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, available at http://www.esrl.noaa.gov/psd/) are employed to drive the Red Sea model, including surface zonal wind velocity, surface meridional wind velocity, surface air temperature, surface specific humidity, precipitation, downward shortwave radiation and downward longwave radiation. The
NCEP/NCAR Reanalysis data is performed with data assimilation using past data from 1948 to the present [Kalnay et al., 1996]. The 4x daily data is available at 0Z, 6Z, 12Z, and 18Z, and here the data from 2004/01/01 to 2010/12/31 are selected. Bulk formulae are implemented to convert atmospheric fields to surface fluxes, and an interpolation routine provides on-the-fly interpolation of forcing fields an arbitrary grid onto the model grid.

2.4 Eddy Identification Scheme and Tracking Procedure

One of the most straightforward methods to identify eddies is based on geometric criteria by finding instantaneous streamlines mapped onto a plane normal to the vortex core [Robinson, 1991]. Winding-angle (WA) method, a method that was proved efficient and accurate for detecting mesoscale eddies with small detection errors, could be utilized to find the streamline [A. Chaigneau et al., 2008]. The WA method calculates the cumulated sum of the angles between the consecutive segments. Clockwise curves correspond to negative $\alpha$ (the angle between consecutive streamline segments) and counterclockwise curves correspond to positive $\alpha$. This eddy identification algorithm is to find a streamline with its winding-angle greater than $2\pi$. 
The WA method first finds a point defined as the eddy center and then a closed streamline surrounded corresponding to the eddy edge, the eddy-tracking algorithm is adapted from Penven [Penven et al., 2005]. Specific steps for eddy identification are as follows:

1. For AE, eddy centers are identified by finding the local maximum SSH within a non-overlap moving window of $80 \times 80$ km; vice versa, for CE, by finding the local minimum SSH.

2. Streamlines are computed surrounding each eddy center referring to the geostrophic current field.

3. Closed streamlines are selected by finding the ones with winding angle greater than $2\pi$ [Sadarjoen and Post, 2000].

4. Streamlines belonging to a given eddy center are grouped, which ends up with each cluster consisting of closed streamlines rotating around the same eddy center, with the outer streamline characterizes the eddy edge.
It is pointed that the eddy center might not be at the exact maximum or minimum location and streamlines might be unclosed when the eddy is embedded in a background flow [Isern-Fontanet et al., 2003]. However, eddies detected from SSH data using the WA method are similar with the ones computed from the total streamfunction field adding the barotropic currents [A. Chaigneau et al., 2008]. WA is a hybrid method since a physical quantity of SSH is used to identify eddies, and the streamlines are used to define the eddy boundaries based on geometry.

A nondimensional distance

\[ D_{e_1,e_2} = \sqrt{\frac{\Delta D}{D_0}^2 + \left(\frac{\Delta R}{R_0}\right)^2 + \left(\frac{\Delta \zeta}{\zeta_0}\right)^2 + \left(\frac{\Delta EKE}{EKE_0}\right)^2} \]

is defined, where \( \Delta D, \Delta R, \Delta \zeta, \Delta EKE \) are the spatial distance, difference of radius, vorticity and the EKE, from the eddy at adjacent time step; \( D_0, R_0, \zeta_0, EKE_0 \) are the characteristic value of 100km, 50km, \( 10^{-6} / s \), and 100cm\(^2\) / s\(^2\), respectively. \( D_{e_1,e_2} \) represents the extent of similarity of two eddies, the smaller the value, the higher similarity between \( e_1 \) and \( e_2 \). A minimum of \( D_{e_1,e_2} \) among eddy pairs between two adjacent times is found to identify two eddies as the same one tracked from the first time to the second time. Restriction for the eddy propagation distance per week is set of 150km to prevent jumping from one track to another [A. Chaigneau et al., 2008].
3. Analysis and Discussion

This chapter includes the analysis and discussion of SSH. The first part is based on EOF analysis that exhibits the spatial and temporal variations of SSH in the Red Sea. The second part provides the eddy statistical properties derived from the SSH.

3.1 Analysis of SSH

As can be seen from Figure 3.1, the standard deviation of SSH field over the 20 years. Three main regions of high SSH variability with a magnitude over 15cm located at 27°N, 23°N, and most widely spread at 18°N-20°N of east coast. Further investigation of the standard deviation SSH field in the Red Sea shows significant seasonality. The weekly SSH data over the 20 years are binned into individual seasons as spring (Mar-Apr-May), summer (Jun-Jul-Aug) and autumn (Sep-Oct-Nov) and winter (Dec-Jan-Feb). Relative high standard deviation in each season corresponds to the aforementioned areas. Generally speaking, the SSH variability is higher in the northeast of the Red Sea basin. Peaks appear near the mountain gaps along the Saudi coast of the Red Sea where the zonal wind jet might happen, and also on the Sudanese Red Sea coast where the Tokar Gap blows[Jiang et al., 2009].
Figure 3.1: Standard deviation of SSH over 1993-2012.

Figure 3.2: Standard deviation of SSH for the four seasons, (a) spring, (b) summer, (c) autumn, (d) winter
In order to extract more information on both temporal and spatial patterns of the SSH in the Red Sea, the 20 years of SSH data are analyzed to examine the sea level variation using Empirical Orthogonal Functions (EOFs). EOF analysis extracts the dominant modes from a spatiotemporal dataset and decomposes it into spatial patterns (EOFs) and time series (PCs). EOFs are shown as contour maps, from which one can access the relationship among regions. The PCs, plotted as time series, quantify the amplitude of the associated EOF pattern over time. The modes are ranked by their contribution to the overall variance of the dataset. The first few PCs/EOFs modes exhibit the strongest signals.

Figure 3.3: The first EOF mode of the SSH. The percentage denotes the fraction of the explained variance.
Figure 3.4: The PC corresponding to the first EOF mode of the SSH.

As can be seen from Figure 3.3 plotting the first EOF mode and from Figure 3.4 plotting the first mode of PC, in which the dot black curve represents the PCs in each year from 10/1992 to 12/2010, and the solid red curve represents the mean curve of each month during that period, a prevailing SSH annual cycle (variance contribution of 90.5%) is found from the first mode. The clearest feature in the curves lies in the sign change from positive to negative in May before it becomes again positive in October, that is, an obvious seasonal variation with positive values during the cold season and negative values during the warm season. Given that the first EOF mode is always positive, this implies that the overall tendency of SSH in the entire Red Sea is higher than its mean during winter times and is lower than its mean during summer times, with the strongest variability (over 20cm) generally lie east of the basin and peaks at around $19^\circ$N, where the convergence of wind occurs and Tokar Jet alternates direction.
The wind over the entire Red Sea basin could be clearly separated into two regions: over the basin south of $19^\circ N - 20^\circ N$, the monsoon system controls the surface wind distinctly, with southeastern wind during winter but northwestern wind during summer; and over the north basin, the winds blow southeastward throughout the year. Over the southern Red Sea, the variation of SSH could be explained by the Ekman transport due to the wind, that is, during summer, the northwestern wind leads to a water transport to the west; and during winter, the southeastern wind causes the water transport to the east. The alternation of wind direction tendency agrees remarkably well with the first PC curve. The largest SSH area around $19^\circ N$ is a result of the wind convergence zone that contributes to the water convergence during winter. The northern Red Sea shares the similar mechanism to that in the southern Red Sea during summer; nevertheless, one cannot similarly explain the variation during winter. During the winter, wind blows from the northwest to the southeast along the Red Sea axis, according to the Ekman transport theory, water should be transported to west and cause a high SSH in the west basin, however the high SSH appears in the east basin. Therefore, a northward boundary current along the east coast that serves as the supplemental water to the high SSH is speculated, which is also illustrated in the recent study [Fengchao et al., 2012a].

The seasonal variation of SSH is presented with the governing of two effects: the inverse barometer effect (caused by atmospheric pressure variations) and the steric effect (a result from the changes in the density of the water column). [Patzert, 1974] According to the simplified model of the sea level response to winds, wind-setup
creates a large sea level bulge in the central Red Sea with amplitude of over 15cm
[Sofianos and Johns, 2001].

### 3.2 Eddy activity

Usually, eddies are more vigorous than the background currents. They are very important to hydrodynamics in the ocean and are also responsible for transporting kinetic energy, heat, and biogeochemical particles and even changing of circulation structure. Oceanic mesoscale eddies have characteristic spatial scales of ~10km to ~100km, and could have a lifespan between tens and hundreds of days.

In order to illustrate the eddy patterns on the annual time scale in a clear way, the first EOF mode is removed from the raw SSH data of the year 2010, to eliminate the seasonal current, after which the monthly mean SSH and corresponding velocity fields are shown in Figure A.2 in the appendix. The SSH is generally characterized by multiple eddy system, mainly observed from 16°N to 24°N. The overall current pattern in the Red Sea basin is occupied with eddies covering the width of the basin, which can provide rapid transport of organisms and nutrients from one coast side to another. In the north Red Sea, ‘eddy’ is stretched by the coast and could span over 400km for meridional axis, south of which around 23°N, the basin is dominated by AE from September to May. Near 20°N, CE and relative weaker AE alternately exist throughout the year, and seem to propagate to the north. During summer, the dipole system due to the Tokar Jet is not obvious in 2010. For the southern Red Sea, eddies
are observed near 15°N-16°N, either off east coast in January, May, July and October, or off west coast in December, February, April and November.

### 3.3 Definition of eddy Kinematic Properties

Eddy energy and shape evolution are investigated by computing the EKE, eddy deformation rates and vorticity, from the altimeter data. Considering the balance between the pressure gradient force and the Coriolis force, the geostrophic velocity anomalies are based on the geostrophic approximation in terms of the SSH gradients as

\[
U'_g = -gf^{-1} \frac{\partial \eta'}{\partial y}, \quad V'_g = gf^{-1} \frac{\partial \eta'}{\partial x},
\]

where \( U'_g \) and \( V'_g \) are the zonal and meridional components of the geostrophic velocity, \( g \) is the acceleration due to gravity, \( f \) is the Coriolis parameter, and \( \eta' \) is the sea surface height.

The EKE is computed from velocity components using the relation of

\[
EKE = \frac{(U'_g)^2 + (V'_g)^2}{2}.
\]

The eddy intensity (EI) is the mean EKE over the eddy normalized by its area, which is defined as

\[
EI = \overline{EKE}_R \pi^{-1} R^{-1},
\]

where \( R \) represents the eddy radius.
By definition, the vorticity (describes the rotation extent) of an eddy is determined by

$$\Omega = \frac{\partial U_{x}'}{\partial x} - \frac{\partial V_{y}'}{\partial y},$$

the divergence (describes the magnitude of fluid lost) by

$$\Psi = \frac{\partial U_{x}'}{\partial x} + \frac{\partial V_{y}'}{\partial y},$$

the shearing deformation rate (describes the extension/compression in the west-east and south-north direction) by

$$\gamma_1 = \frac{\partial V_{y}'}{\partial x} + \frac{\partial U_{x}'}{\partial y},$$

the stretching deformation rate (describes the extension/compression in the northeast-southwest and northwest-southwest direction) by

$$\gamma_2 = \frac{\partial U_{x}'}{\partial x} - \frac{\partial V_{y}'}{\partial y},$$

and the total deformation rate (describes the extent of total deformation) by

$$\gamma = (\gamma_1^2 + \gamma_2^2)^{1/2}.$$

### 3.4 Eddy statistical properties

This subchapter discusses the eddy statistical properties including eddy genesis, eddy frequency, eddy radius, eddy kinematics, eddy lifespan, eddy evolution and seasonal variability as well as the inter-annual variability. In addition, eddy vertical stability is discussed based on climatological data.

#### 3.4.1 Mean Eddy Genesis
As Figure 3.5 shows, the distribution map of the eddy genesis, counted as the number of new eddies formed within that grid over the 20 years. Totally, 1321 cyclonic and 1262 anticyclonic generated eddies are identified. Little difference is detected in the number of the two types of eddies.

Figure 3.5: Eddy genesis in the Red Sea over October 1992 to December 2012. Units are the number of events.

In the Red Sea, eddy generation fills the entire basin, and region of high generation corresponds well with the SSH standard deviation (Figure 3.1). The largest value
appearing at around 27°N probably results from the enclosing constrain of the coastline and coming across of the boundary current, and perhaps, the relatively stronger wind. There is also a peak of the formation of eddy around 15°N, which is likely due to the Gulf of Aden intrusion water and its extension, as the interaction between barotropic shelf currents and local topography generally leads to the generation of eddies\cite{Cai et al., 2002}. The high eddy genesis between 18°N and 20°N is associated with the Tokar Wind Jet, often spinning up an intense ocean dipolar eddy in less than one week in response to the wind jet\cite{Zhai, 2011}. Around 23°N, high eddy generation reveals the close relationship between seasonal SSH variability and eddy genesis, but the mechanism behind it is not yet clear.

### 3.4.2 Eddy Frequency

In total 2583 CEs and 2742 AEs are identified. Figure 3.6(a) represents the distribution of the eddy frequency, which at each location is defined by the percentage of time that the point is located within an eddy. Following this definition, regions with higher eddy frequency appear to be more likely covered by eddies. The eddy frequency ranges between 0% and 81%. The highest eddy frequency is observed at 22°N-24°N and 18°N-20°N, which coincides with local maxima in EKE $\sim$120 cm²/s², as can be seen from Figure 3.6(c). We split the domain of high eddy frequency into two regions; Region- I from 18°N to 20°N, Region- II from 22°N to 24°N.
As Figure 3.6(c) indicates, there are three peaks of 20-year mean EKE in the Red Sea, located around 23\textdegree N, 19\textdegree N and 14\textdegree N, respectively, of which the 14\textdegree N region is missing from the eddy frequency map because of the narrow physical constrain that blocks the eddy identification algorithm. In addition, even though the eddy genesis is rather high at the very north end of the Red Sea, the eddy lifetime is significantly short. The low eddy frequency suggests that the eddies generated in this area are short-lived. Moreover, in this region the ‘eddy’ is stretched into a flat one spanning even over 400km. Thus, although the small eddies could be detected when it just generated, WA algorithm is not able to find closed streamlines with one moving window to follow the extensions of the eddy, which could explain the estimated weak eddy frequency in this region.

Eddy polarity \cite{Alexis Chaigneau et al., 2009} represents the probability of a point within an AE or CE. The mean polarity distribution in the Red Sea is shown in Figure
3.6(b), computed as $(F_{AE}-F_{CE})/(F_{ZE}+F_{CE})$, where the $F$ represents the eddy frequency. The most obvious polarity is found at $\sim 19^0N$ and $22^0N-27^0N$. Region-I and Region-II are dominated by weak polarity (less than 5%), suggesting both AE and CE exist in this region, but AE is more dominant. The zero-line around $19^0N$ matches the strong dipolar eddy resulting from the Tokar Jet. While the main negative polarity region locates at $\sim 19^0N$, and over the south basin from $24^0N$ to $28^0N$ except for the weak positive region $\sim 15^0N$, although the eddy probability is not high in those regions.

### 3.4.3 Eddy Radius

The eddy radius statistics is based on the 2583 CEs and 2742 AEs. As Figure 3.7(a) indicates, the probability density of eddy radius has a strong asymmetric distribution. The majority of the eddies have a radius of 40-50km, and averaged at 70km. Eddies with radius of 40-100km account for 76% of all detected eddies. As the Red Sea is a relatively narrow basin with zonal range of $\sim 200$km, most eddies could occupy nearly half of the basin width. There is no significant difference of distribution between the AEs and CEs.
Figure 3.7: Radius distributions: (a) probability density function of the radius, mean distribution of (b) EKE, (c) EI, (d) vorticity as functions of radius.

Figure 3.7(b) suggests that most eddies appear with EKE of 80-110cm²s⁻², and it increases with eddy radius until reaching the sill of ~100cm²s⁻² with radius around 90km. One can conjecture that the eddies with small radius (<~60km) is associated with relatively low kinetic energy; bigger eddies tend to be more energetic with strong velocity that contributes to a high EKE; for eddy with even bigger size (>~110km), the velocity decreases slowly with the radius’ increasing. The mean EI distribution with regards to eddy radius is shown in Figure 3.7(c). The mean EI decreases as quasi-Gaussian (as indicated by the grey line fitted from Gaussian Function) from 0.025cm²s⁻²km⁻² for eddy radius of 30km to almost 0cm²s⁻²km⁻² for radius of 160km. The sharply decreasing distribution of the intensity is a result of
the relatively low EKE range in the Red Sea and the high range of eddy radius. For instance, EKE varies of a factor ~2 (from ~65 to ~110 cm²/s²) while the size varies by a factor of ~25, thus, eddies with more intensity correspond to small structures.

### 3.4.4 Eddy Kinematics

The statistics of eddy kinematic parameters are listed in Table 3.1. All the detected CEs and AEs share similar mean absolute vorticities of order of \( \sim 3 \times 10^{-6} \text{s}^{-1} \). The shearing deformation rate \( (\gamma_1) \) and stretching deformation rate \( (\gamma_2) \) rate as well as the divergence \( \Psi \) have smaller order of magnitude than that of the vorticity \( \Omega \). A total deformation rate (TD) of \( \sim 1.5 \times 10^{-6} \text{s}^{-1} \) indicates that eddies tend to be deformed and are not perfectly circular [A. Chaigneau et al., 2008]. Similar to the TD for AEs and CEs, however, their deformation is different. For CEs, \( \gamma_1 \) is positive and \( \gamma_2 \) is negative, indicating that CEs tend to be compressed in the northwest-southeast and west-east direction, and extended in the northeast-southwest and south-north direction [Chen et al., 2011]. This is due to the width limitation of the Red Sea basin. For AEs however, \( \gamma_1 \) is negative and \( \gamma_2 \) is positive, thus AEs tend to be with extension in the northwest-southeast and west-east direction, and compression in the northeast-southwest and south-north direction. The almost zero divergences of both AEs and CEs indicate that the eddies are rather steady throughout their entire lifetime with very little loss of fluid [Hwang et al., 2004].
Table 3.1 Mean statistics of the eddy kinematics.

$\Omega$ is the vorticity, $\gamma_1$ is the shearing deformation rate, and $\gamma_2$ is the stretching deformation rate, $\gamma$ is the total deformation rate, and $\Psi$ is the divergence.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cyclonic eddies (Unit: $10^{-6}$s$^{-1}$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td>2.950</td>
<td>1.660</td>
<td>0.003</td>
<td>10.706</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>0.244</td>
<td>1.126</td>
<td>-3.891</td>
<td>5.073</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>-0.171</td>
<td>1.206</td>
<td>-5.090</td>
<td>5.678</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1.419</td>
<td>0.892</td>
<td>0.029</td>
<td>6.931</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>-0.009</td>
<td>0.182</td>
<td>-1.884</td>
<td>1.660</td>
</tr>
<tr>
<td><strong>Anticyclonic eddies (Unit: $10^{-6}$s$^{-1}$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td>-3.058</td>
<td>1.670</td>
<td>-10.706</td>
<td>-0.003</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>-0.253</td>
<td>1.218</td>
<td>-5.170</td>
<td>5.180</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>0.178</td>
<td>1.248</td>
<td>-6.097</td>
<td>5.586</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1.499</td>
<td>0.944</td>
<td>0.036</td>
<td>7.100</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>0.011</td>
<td>0.206</td>
<td>-1.956</td>
<td>2.579</td>
</tr>
</tbody>
</table>

The distributions of the absolute vorticity and the TD rate as functions of EI are shown in Figure 3.8. The TD increases slowly from $1.1 \times 10^{-6}$s$^{-1}$ to $1.6 \times 10^{-6}$s$^{-1}$ without much variation, whereas the vorticity increases by a factor of 3 from $1.4 \times 10^{-6}$s$^{-1}$ to $4.6 \times 10^{-6}$s$^{-1}$. The ratio between the TD and the vorticity represents the extent of deformation, and its drop from 0.81 to 0.36 reveals that, for most eddies in
the Red Sea, more intense eddies (with stronger EI) appears to be less deformed and more circular.

![Figure 3.8: Mean vorticity and TD as functions of EI.](image)

### 3.4.5 Eddy Lifespan

The lifespan distributions of averaged eddy characteristics based on 379 AEs and 378 CEs are shown in Figure 3.9. As the SSH data are weekly available, eddy lifespan less than one week cannot be detected. As figure 3.9(a) suggests, the eddy number sharply decreases for eddies with lifespan. Eddies with lifespan shorter than 15 weeks account for 93% of total 757 eddies. The difference of lifespan between AEs and CEs is not significant. Boundary constrain, steep topography and interaction with background current limit the eddy lifespan.
Figure 3.9: (a) Vortex lifespan distributions. Mean distribution of the (b) radius and (c) EI as functions of vortex lifespan. (d) Meridional variation of the eddy lifespan.

The statistics (Figure 3.9(b), (c)) also show that the mean eddy radius increases from 58km to 85km, and EI decreases from 0.01cm²s⁻²km⁻² to 0.004cm²s⁻²km⁻², with an increasing of eddy lifespan from 2 to 15 weeks. It appears that eddies with shorter lifespan are of higher intensity and smaller structure. Smaller eddies are more likely being affected by the background current, and they are usually not as stable and as deep as the large ones that take the energy from deep water baroclinic instability. Therefore, even though being more intense, the small eddies could not live for a very long time.
Besides, the location of eddies could also be a factor that affects the eddy lifespan. Figure 3.9(d) shows the scatter of latitude with eddy lifespan. In the Red Sea basin, long-lived eddies appear in the middle from $18^\circ\text{N}$ to $24^\circ\text{N}$ that have a mean lifespan of 5-9 weeks, which strikes with where high eddy frequency occurs.

### 3.4.6 Eddy Evolution

To better investigate the mean evolution of long-lived eddies, 35 CEs and 49 AEs living more than 12 weeks are examined, as Figure 3.10 shows. In the first three weeks, the long-lived eddy radius increase at a rate of $\sim8\text{km per week}$. After reaching $\sim90\text{km}$, the eddy radius drop to $\sim80\text{km}$, suggesting that the characteristic radius. Similarly, the temporal evolution of EKE exhibits the same tendency, which increases sharply in the first five weeks and remain at $\sim140\text{cm}^2\text{s}^{-2}$. The EKE of long-lived eddies is rather stable during their lifetime, after adjusting about five weeks since the genesis. The temporal evolution of vorticity (Figure 3.10 (c)) is also stable with little variability of $\sim1\times10^{-6}\text{s}^{-1}$.
Figure 3.10: Mean properties of long-lived eddy: (a) radius, (b) EKE (c) vorticity and (d) meridional displacement of AEs and CEs

The mean meridional propagation of long-lived eddies is shown in Figure 3.10 (d). A clear separation is observed between AEs and CEs. AEs tend to move northward with positive latitude displacement, while CEs appears move to the south in the first few weeks and then turn to move northward, but not as far as AEs. The divergence in eddy pathways is probably related to the $\beta$ effect [Barenghi et al., 2009]. Other factors such as wind curl and change of depth and lateral boundary friction also link with the budget of relative vorticity. The latitude displacement of AEs is not as far as those in the South China Sea [Chen et al., 2011] and the sea off Peru [A. Chaigneau et al., 2008]. Because eddies usually propagate both zonally and meridionally,
however, the Red Sea basin is constrained by the relatively narrow coastline. Thus, the eddies could not propagate freely in the zonal direction, besides, interactions of high-temporal coastal current variability and possible presence of vertical front might also affect the zonal propagation.

3.4.7 Seasonal Variability

![Figure 3.11: Seasonal variability of eddy properties: number of eddy genesis per season for (a) AE and (b) CE, (c) radius, (d) vorticity, (e) EKE and (f) EI.](image-url)
The mean seasonal cycle of eddy properties are shown in Figure 3.11(a) and (b). The number of eddies that generates among seasons is remarkably different for AEs and CEs. For the entire Red Sea, AEs turn to be more likely generated during cold seasons and the number of generated AEs in the summer over the 20 years accounts for 19%, which is obviously lower than that in other seasons. However, the CEs’ curve shows that more eddies generated during the spring and summer seasons. Autumn is the season that the eddy genesis varies most for AE.

The rest of Figure 3.11 show that the eddy radiuses, vorticity, EKE and EI for AEs and CEs are comparable throughout the year except for EI in January when AEs are significantly more intense than that of CEs. All of the above features reach the peaks in December-January and August-September, which might be a result of high wind speed and extreme heat flux. August is the most vigorous period for eddies during hot season, however with the smallest size for both AEs and CEs. High values of EKE and EI in January reach up to 110cm$^2$/s$^2$ and 0.017cm$^2$/s$^2$km$^{-2}$, respectively.
3.4.8 Inter-annual Variability

Figure 3.12: Inter-annual variations of eddies properties in the south Red Sea: (a) number of eddies generated per month, (b) EI, (c) radius and (d) vorticity

Figure 3.13: Inter-annual variations of eddies properties in the north Red Sea: (a) number of eddies generated per month, (b) EI, (c) radius and (d) vorticity
A one-year running-mean helps to remove the seasonal and intraseasonal fluctuations of eddy properties. The mean eddy properties in the south Red Sea (south of 19°N) and the north Red Sea (north of 19°N) are shown in Figure 3.12 and Figure 3.13. The eddy genesis is rather steady in the south Red Sea, but more variable with a slight decreasing trend in the north basin. Fluctuations exist in each of EI, radius and vorticity variations over both south and north basin, from which a two-year cycle is found. However, the eddy inter-annual variability in the Red Sea seems not to be as sensitive to the El Niño/La Niña events as the eddies in the open wide ocean such as the South China Sea [Chen et al., 2011] and the off Peru [A. Chaigneau et al., 2008], even though ENSO events have profound impact on the India monsoon. Additionally, little evidence is found from the mean eddy properties with the corresponding wind stress or wind curl (not shown), which are usually well correlated in the worldwide oceans.

3.4.9 Eddy Vertical stability

In order to check the possible mechanism that leads to the aforementioned two regions’ high eddy frequency, the baroclinic instability is checked, which is believed to be the primary source of eddy energy in most of the ocean and boundary currents [Beckmann et al., 1994; Stammer, 1997]. The potential energy in the mean circulation could be converted into eddy energy by baroclinic instability. On the other hand, eddies can also feed kinetic energy back into mean flow and help to
change the circulation structure [Wang et al., 2012]. The baroclinic instability of the background mean circulation also influenced the seasonal mesoscale properties significantly [Halliwell et al., 1994; Qiu, 1999]. To examine how does it affect eddy activity, baroclinic instability is analyzed using WOA01 climatological data.

The Brunt–Väisälä frequency is defined as

$$N = \sqrt{-\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}},$$

where $\rho_0$ is the background density of seawater, $\rho$ is the seawater density, and $z$ is the vertical coordinate in depth.

The vertical current velocity shear is derived using the thermal wind balance as

$$\left| \frac{\partial u}{\partial z} \right| = \frac{g}{\rho_0 f} \sqrt{\left( \frac{\partial \rho}{\partial x} \right)^2 + \left( \frac{\partial \rho}{\partial y} \right)^2}.$$

Both $N$ and $\left| \frac{\partial u}{\partial z} \right|$ are averaged over the top 0-300m, seawater density is calculated by invoking the Gibbs-SeaWater software packages [McDougall, 2011].
Figure 3.14: Climatological monthly mean Brunt–Väisälä frequency, EKE and vertical shear over 18°N to 24°N of the Red Sea basin

Figure 3.14 shows the climatological monthly relationship among the Brunt–Väisälä frequency, the EKE and the vertical shear, averaged from 18°N to 24°N over the whole zonal range of the basin. Peaking from June to July, the Brunt–Väisälä frequency has an obvious seasonal cycle. It is mainly because the surface water is strongly heated during summer, which leads to a great vertical gradient in density. However, the peak of $N^2$ exhibits from June to July instead of from August to September (the most heated period for the Red Sea). One possible explanation is due to the eddy activity. AE (Seen from Figure 3.6(b), where positive polarity associates with higher AE frequency than that of CE) would deepen and thicken the thermocline, which contributes to weaker thermocline intensity and a smaller $N^2$. 
The seasonal cycle of stratification (indicated by $N^2$) is significantly correlated with EKE (correlation coefficient of -0.91).

EKE reaches its first peak in January up to $110\text{cm}^2\text{s}^{-2}$, and the second peak appears in August at around $90\text{cm}^2\text{s}^{-2}$, the later of which might be a result from the strong Tokar Jet. Strong vertical shear appears in February and September and reaches up to $\sim7 \times 10^{-3}\text{s}^{-1}$, while the minimum is found in July of $4.3 \times 10^{-3}\text{s}^{-1}$. There is an identical seasonal cycle between EKE and vertical shear throughout the year except for that in the autumn, which indicates that strong vertical shear would convert baroclinic instability into EKE\cite{Wang et al., 2012}. 
4. Model Validation

This chapter provides the validation between model outputs and observations.

4.1 Transport Through Bab el Mandeb

Figure 4.1: Meridinal flux through Bab el Mandeb (a) averaged between November of 2009 and May of 2010, and (b) between June and October 2010. Hovmöller diagram of (c) temperature and (d) salinity at 43.27°E 12.89°N in the strait.

Water exchange between Gulf of Aden and the Red Sea is important for the general circulation, eddy evolution, and water fluxes. As mentioned in section 1, a strong seasonal variation of the flow through the strait associated with the monsoons results in an annual cycle of the current pattern. A characteristic cross-section is
selected to demonstrate those two current structures. Figure 4.1(a) shows the mean meridinal flux from November of 2009 to May of 2010, with the zero-contour drawn as the black solid line. The SW in the upper layer deepens to ~100m flowing from the Gulf of Aden into the Red Sea, with an incline shallower at west and deeper at east. The RSOW of deep Red Sea is as strong as more than 1m/s. In Figure 4.1(b), the meridinal flux is averaged from June to October 2010. The surface layer (~30°C) shallows to ~40m or less with an upward convex shape. The GAIW (~21°C) layer intrudes into the Red Sea with a maximum speed reaching 0.2m/s at ~80m depth. The RSOW from the deep Red Sea flows into the Gulf of Aden with a weaker speed than that during winter. Time series of temperature and salinity vertical structures at the Bab el Mandeb is plotted in Figure 4.1(c) and Figure 4.1(d). The relatively cold water distinguishes GAIW during summer, while the salinity is more consistent than temperature. During summer, the isothermal line shallows and isohaline line deepens from June to October.

### 4.2 Model comparison With Cruise Cross-section

An oceanographic research cruise aboard the R/V Aegaeo was carried out in the Red Sea between 16 and 29 March 2010, conducting the first large-scale physical oceanographic survey of the eastern Red Sea. This cruise collected observations of top-to-bottom ocean currents and water properties such as temperature, salinity, dissolved oxygen, turbidity and fluorescence. The cruise plan called for nine
transects across the Red Sea focusing entirely on the northern half (from KAUST northward; 22°-28°N). A total of 111 casts were made during the cruise. The stations are shown in Figure 4.2.

Figure 4.2: Map of cruise stations (in black dots), the selected cross-sections from cruise observations (~23°N cross-section in red dots, along basin-axis cross-section in purple dots) and from the model (in blue dots)

Figure 4.3: Vertical distribution for the along basin-axis cross-section: (a) salinity from cruise observation, (b) salinity from model, (c) temperature from cruise observation and (d) temperature from model
Figure 4.3 shows the temperature and salinity at meridinal cross-section (the zonal cross-section ~23°N is shown in Figure A.3) from observation and model, respectively. The thermocline in both figures occurs at ~200m, below which water mass is quite uniform. While the vertical salinity gradient from the model is smaller than that from observations, with 0.2 Psu less in the deep water. Salinity flux scheme needs to be further modified to achieve better vertical structure.

4.3. Validation With SSH

Figure 4.4: (a) Monthly mean of sea surface geostrophic velocity derived from SSH for June 2010. (b) Monthly mean of sea surface velocity from model.

The eddy is often associated with highly nonlinear stochastic processes, so it is difficult to precisely simulate, both the eddies genesis or the evolution. However, the statistics of eddy properties is helpful to gain more knowledge of them, and some semi-stationary or consistent eddies could be simulated by the model because of the relatively high stability and linear composition. Figure 4.4 shows a snapshot of the
SSH-based geostrophic current and the simulated surface current by MITgcm, from which the main CEs centered at ~23°N and ~20°N match quite well.
5. Conclusions and future work

In this study, the merged satellite altimetry data over 1992-2012 are investigated to characterize the mesoscale eddy properties in the Red Sea. The seasonal fields of SSH show marked seasonality with a magnitude of 15 cm along some parts of the east coast, and variation in the autumn is stronger compared to in other seasons. One prominent feature that has not been previously studied is the spatial variation across the basin with the seasonal signal shown by an EOF analysis. The first EOF mode contributes 90.5% of the variation, and a significant impact is found between SSH variation and seasonal wind cycle.

We studied the analysis of mesoscale eddy features in the Red Sea regarding the mean properties and spatiotemporal variability. A winding-angle based eddy identification algorithm is employed to derive the mesoscale eddy information from SSH data. A total of 2742 AEs and 2583 CEs are identified, belonging to 1262 AE tracks and 1321 CE tracks. Statistics suggest that eddies generates over the entire Red Sea, with two regions of high eddy frequency in the central basin. Approximately 76% of the detected eddies have a radius ranging between 40 km and 70 km, of which both intensity and absolute vorticity decrease with eddy radius. The average eddy lifespan is about 5 weeks, and eddies with longer lifespan tend to have larger radius but less intensity. The eddy lifespan also depends on the location of the eddy, those generated within the region (18°N-24°N) of high eddy frequency have
longer lifespan than those generated further south or north. Eddies with more intensity appear to be less deformed and more circular, but different deformation rates exist between AEs and CEs.

More inspection of the long-lived 22 CEs and 26 AEs suggests their different propagation characteristics. With the absolute vorticity going rather stable, the AEs tend to move more northward than the CEs. After 3-4 weeks of growing phase, the characteristic radius for the long-lived eddies is around 60km-70km and EI ~0.02cm^2s^-2km^-2.

AEs generation during summer is obviously lower than that during other seasons, while CEs generation is higher during spring and summer. Other features of AEs and CEs are similar with both vorticity and intensity reaching the summer peaks in August and winter peaks in January. Inter-annual variability reveals that the eddies in the Red Sea, unlike most other eddies in the world ocean, is sort of isolated from the global El Niño/La Niña event. Regarding the entire Red Sea, no obvious correlation is detected between ENSO and eddies properties. The eddy property tendencies are different from the south and north basin, both of which exhibit a two-year cycle.

Hydrographic data is exploited to analyze the baroclinic instability of the eddies in the two regions with high eddy frequency. Showing the correlation coefficient of -0.91, Brunt–Väisälä frequency is negatively correlated with EKE, which results from
the AE activity in this region. Climatological vertical velocity shear variation is identical with EKE except in the autumn, suggesting the vertical shear could convert the energy from baroclinic instability into eddy variability.

Numerical simulation results from the MITgcm are validated with previous studies and observations. The vertical structure of the simulated flux through Bab el Mandeb is successfully reproduced with the annual alternation of two and three layers water exchange. Further validation with the 2010 cruise suggests that the thermocline occurs at ~200m, but the model vertical salinity gradient is lower than the observations. The model surface eddy variability is also examined, suggesting relatively good agreement with the observations.

The future work will involve using this high-resolution model with proper assimilation scheme that helps to improve the accuracy, which would provide more details on the eddies of either large or small size.
REFERENCES


Barenghi, C., D. Dritschel, and A. Gilbert (2009), Vortex Dynamics from Quantum to Geophysical Scales Introduction, Geophys Astro Fluid, 103(2-3), 111-111.


National Geophysical Data Center. (2001), ETOPO2 global 2* elevations, edited, pp. 1 CD-ROM, National Geophysical Data Center, [Boulder, Colo.].


APPENDIX

A.1 Concepts of satellite products

The Mean Dynamic Topography (MDT) is the permanent stationary component of ocean dynamic topography.

The marine Geoid is the shape of the sea surface assuming a complete absence of perturbing forces (tides, wind, currents, etc.).

The Mean Sea Surface (MSS) represents the sea level due to constant phenomena, which is computed from altimetry, averaging the data over several years.

\[ \text{MSS} = \text{Geoid} + \text{MDT} \]

Sea Level Anomalies (SLA) is the sea surface height with respect to a MSS.

Absolute dynamic topography (ADT) can be defined as sea surface height with respect to the geoid.

Sea Surface Height (SSH) is the sea surface height with respect to the Reference ellipsoid.

This mean circulation is not produced directly from altimetry data, which rather provide the MSS. We therefore have to combine altimetry data with other data (in-
situ, gravimetric satellites, etc), to determine the geoid precisely, and by subtracting it, compute the mean circulation.

So, SSH = (Altitude - Range - corrections) = MSS + SLA/SSHA = geoid + MDT + SLA/SSHA.

**A.2 Figures**

Figure A.1: Drifter track on top of eddy vorticity derived from SSH [Provided by Dr. Amy Bower]
Figure A.2: Eddy representation with the first mode of SSH EOF subtracted for 2010

Figure A.3: Vertical distribution for the ~23°N cross-section: (a) salinity from cruise observation, (b) temperature from cruise observation, (c) salinity from model and (d) temperature from model