Sea level variation in the Red Sea based on SODA data

By

Kamal Aldien Ibrahim Alawad Mohamad

A thesis submitted in partial fulfillment for the

degree of Master of Science

in the

Faculty of Mathematics and Natural Science

Geophysical Institute

Bergen University

October 2012

Abstract

In this study we investigate the sea level variation in the Red Sea focusing on wind stress setup. 50-years dataset from 1957 to 2007 of sea level and wind stress from Simple Ocean Data Assimilation (SODA) data version 2.0.2-4 are used, which are taken from Carton and Giese (2007). The Hanish Sill (located in 13.25ºN) represents the reference point, in which the sea level, wind stress and steric effect compare to this point. A correlation coefficient is used for the northern, central and southern Red Sea during three seasons: summer, early winter and late winter. A weak correlation between sea level and wind stress is observed in all periods and locations, except in the central basin where it records a correlation of -0.66 during the late winter.

The seasonal anomaly difference of sea level with reference to the Hanish Sill shows clearly an annual cycle, with the maximum is during August and September of about 5 cm, and the minimum is during February and March of about -5 cm. The mean sea level profile reflects a strong gradient from the south to the north, 0.13 to -0.04 m, respectively, with a bulge located in the central basin of about 0.16 m. The seasonal anomaly difference of wind setup compared to the Hanish Sill has a strong semi-annual cycle especially in the northern basin with range of about 14 cm. The seasonal anomaly difference of steric effect, which represents the residual term, also reflects a semi-annual cycle in the northern basin with 9 cm range. However, in the central and southern, the annual cycle appears the dominant one with 8 cm range.

Acknowledgments

First of all, I would like to express my gratitude to my advisor Knut Barthel who guided this thesis and correcting various document with attention and care, enabling me to develop and understand the subject. Deepest senses to him for the extra time he have spent on this thesis and for always keeping his door open in any time.

I am enormously grateful to the NORAD's Program for Master Studies (NOMA) for the funding and support this thesis during two years. I express my thanks to the Geophysical Institute (GFI)-Bergen University (UiB)-Norway where this work was undertaken, and Institute of Marine Research (IMR)-Red Sea University-Sudan for their cooperation with Geophysical Institute (GFI) to unable me to do this work. The thanks extend to the very helpful staff, researchers, and employee at those institutes for comfortable working environment and excellent facilities.

I am heartily thankful to the staff of the Sudan Meteorological Authority, especially Dr. Abdalla khiyar Abdalla and Maha Abdelrahman, without their help I couldn't be able to joint this scholarship.

I offer my regards and blessings to all of those who helped and supported me during this work, my neighbors in Fantoft, and all Sudanese friends studying or living in Bergen, especially Mohammed Alfaki.

Last but not least, I would like to thank my parents and my family members for their love, encouragement and prayers.

Dedications

To my

Parents Ibrahim and Ehlam,

My wife Safa,

And my daughter Saba

.

Contents

Abstract i

Acknowledgments iii

Dedication v

1 Introduction 1

1.1 Motivations 1

1.2 Description of the Red Sea 2

1.2.1 Geography 2

1.2.2 Climate 3

2 Literature review 6

2.1 Sea level 6

2.2 Wind stress 8

2.3 General circulations in the Red Sea 10

2.3.1 The currents and eddies 10

2.3.2 Water massess 13

2.4 Steric sea level 15

3 Theory and Method 17

3.1 Data 17

3.2 Method 17

3.3 Theory 18

4 Results 21

4.1 The north 22

4.2 The center......25
4.3 The south......28
5 Discussions......41
5.1 Sea Level......41
5.2 Wind Stress......42
5.3 Steric Variation......43
6. Conclusions and Recommendations......44
References......45

1 Introduction

1.1Motivations

The sea level in the Red Sea has a large seasonal variation. Generally the variations of sea level have three main reasons, geological effects, regional dynamics and the large scale dynamics, where the regional one divided into inverse barometric effect, fresh water input, and the local atmospheric and oceanic circulation (Cui et al. 1995). In this study we deal with the wind stress setup which is one of the atmospheric parameters, because the seasonal variations of wind stress, and combine effect of evaporations and water exchange through the Bab al-Mandab strait are mainly influences the sea level in the Red Sea (Edwards 1987) (Sultan et al. 1995) (Sultan et al. 1996).

50-years of SODA data of sea level and wind stress were used to investigate the variation of sea level in the Red Sea. The Red Sea is divided into three locations, north, center, and south, and into three seasons summer, early winter, and late winter. The data was grouped into 5 years for every season and location, and Hanish Sill was putted as reference point in which the sea level, wind setup compare to. Then a lot of calculations were made to investigate the wind setup contribution into sea level.

1.2 Description of the Red Sea

1.2.1 Geography

The Red Sea is a semi-enclosed marginal sea, its basin resulting from the separation of Africa and the Arabian Peninsula (see Figure 1.1). It extends from 12.5˚-30˚N with a distance of about 2000 km, and 280 km width (Morcos 1970). The surface area is $0.45*10^{12}m^2$ (Tragou et al. 1999) and the average depth is 450 m, but 2000 m was recorded in the center (Degens and Ross 1969). It is connected to the Arabian Sea and Indian Ocean through the narrow strait of the in the south, and to the Mediterranean Sea in the north through the Suez Canal. The shallowest depth in Bab al-Mandab is Hanish Sill, about 150 km north of strait, and 110 km width, where the greatest depth is 137 m (Werner and Lange 1975).

The Red Sea has hot brine pools found in the deepest parts (Degens and Ross 1969). The highest temperature and salinities that have been recorded are 58˚C and 320, respectively (Pickard and Emery 1990). The surface layer has high salinity of 38-40 both in summer and winter, but in the north it exceeds that, about 42.5. And the deep layer has salinity values of 40.5 to 40.6.

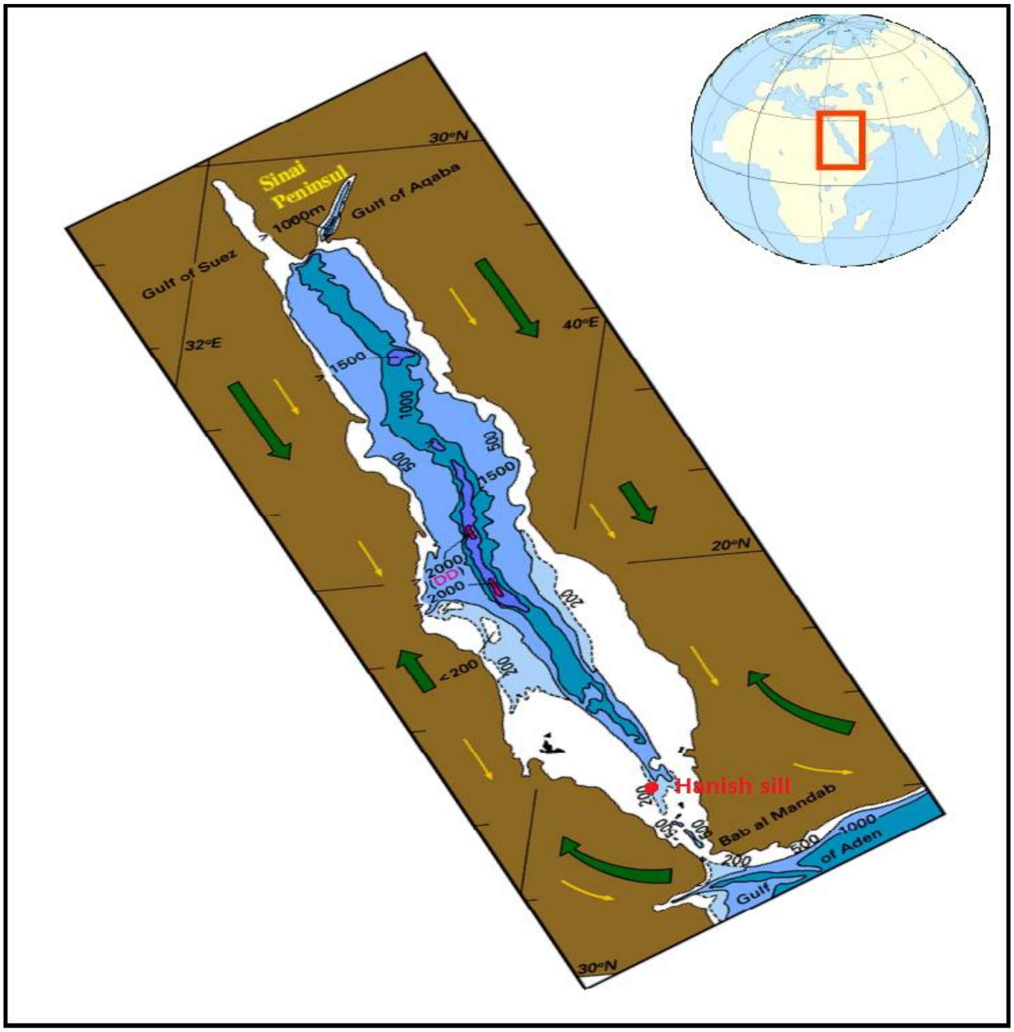


Figure 1.1: Bathymetric map of the Red Sea.

1.2.2 Climate

The Red Sea is characterized by high temperatures, in summer (June-September) the surface is 26-30˚C, and in winter (October-May) it is 24-28˚C. Due to high temperatures the Red Sea has the highest rate of evaporation (E) of some 200 $cmyear^{-1}$, while the precipitation average (P) is about 7 $cmyear^{-1}$ and there are no rivers flowing into it (Pickard and Emery, 1990). The recent study illustrate that the rate of E−P about 2.06 ± 0.22 $myear^{-1}$ (Sofianos and Johns 2002).

The surface wind is influenced by the high mountains and plateaus on both sides of the Red Sea. Direction and speed vary slightly laterally. North of 19˚N, the winds are from the north-northwest all the year, but south of 19˚N, it is controlled by the monsoon flow which changes their direction twice a year (Patzert 1974) (see Figure 1.2).

The winter season has northeast monsoon (October-May), and the wind in the southern Red Sea is from southeast to south-southeast. From October to December this south-southeast wind is relatively strong, about 6.7-9.3 ms^{-1}, while the north-northwest wind in the north is weak, about 2.4-4.4 ms^{-1}. The convergence zone is near 19˚N, and by time it moves southward until the wind becomes from north-northwest during June. The wind stress between 12 and 15˚N is quite strong, especially in November and December, 0.14 $dynescm^{-2}$ (0.014 Pa) (Patzert 1974).

The summer season has south-southwest monsoon (June-September), the wind is from northwest to north-northwest along the entire length of the basin, and the wind stress between 20 and 25˚N is 0.02 $dynescm^{-2}$ (0.002 Pa) (Patzert 1974).

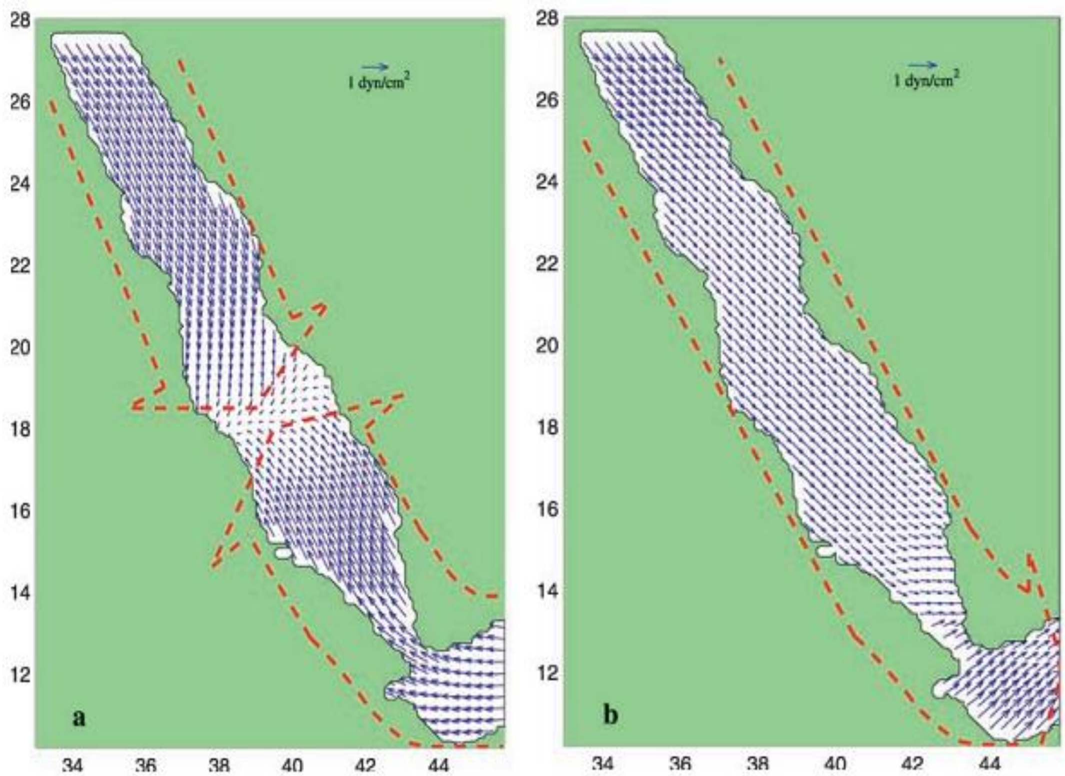
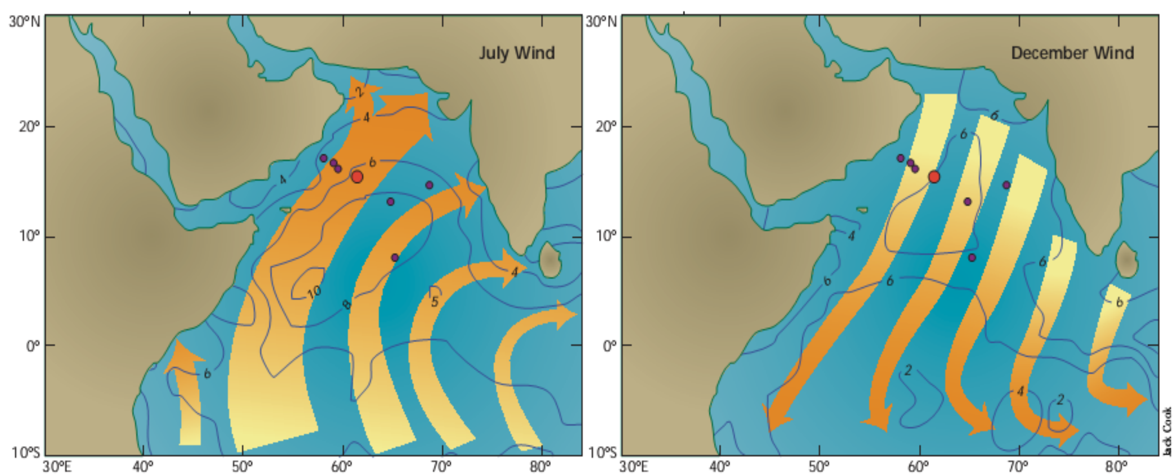


Figure 1.2: Wind stress regime for (a) January and (b) July (Sofianos and Johns 2003).



(a) (b)

Figure 1.3: Wind regime in the Arabian Sea (a) summer season represented by July (b) winter season represented by December (Honjo and Weller 1997).

2 Literature review

2.1 Sea level

The long-term sea level variations in the Red Sea are mainly influenced by the effect of wind stress and combined effect of evaporation and water exchange through the Bab al-Mandab (Edwards 1987; Sultan et al. 1995; Sultan et al. 1996; Sultan and Elghribi 2003). The sea level in the Red Sea has a seasonal change. It is high in winter and low in summer (Morcos 1970; Patzert 1974; Osman 1984; Osman 1985; Edwards 1987; Sultan et al. 1995; Sultan et al. 1996; Sofianos and Johns 2001; Sultan and Elghribi 2003; Manasrah et al. 2009).

The sea level in the Red Sea is characterized by two cycles, annual and semi-annual, where the annual cycle one appears the dominant (Abdallah and Eid 1989; Sultan et al. 1996; Abdelrahman 1997; Sultan and Elghribi 2003). The semi-annual cycle has relatively large amplitude during winter, where the peaks in April and it is decreases in February. The prevailing wind regime and atmospheric pressure may a possible cause of this oscillation (Sultan and Elghribi 2003).

Table 2.1: Annual and semi-annual cycle of sea level, (Abdallah and Eid 1989), except Jeddah is from Sultan and Elghribi (2003).

location	Annual (%)	Semi-annual (%)	Both (%)
Port Suez	84.0	12.4	96.0
Jeddah	77.3	21.0	98.0
Port Sudan	82.1	16.6	98.0
Perim	81.2	15.7	96.0

Manasrah et al. (2009) divided the climate in the Red Sea into four seasons, and the area into three regions, and investigated the sea level as spatial and temporal variations. The spatial variation indicates that the northern part has significantly low sea level during winter and spring seasons, about 12-15 cm when we compared it with the central and the southern parts. No significant variation in all locations during summer season. While during autumn season the sea level has a bulge in the central basin, about 4-6 cm when compared with northern and southern parts (Manasrah et al. 2009). This bulge is appears during summer and winter seasons, but it's slightly (Fig. 2.1). In general, most seasons shows that the mean sea level in the southern and central parts is permanently higher, than the northern part.

The temporal variation shows that during winter, the mean sea level is higher about 3-5 cm than summer and autumn and 1 cm than spring season in northern part. In the central Red Sea the winter and spring seasons are higher than summer and autumn season by about 11-16 cm. While in the south, it is higher than that, about 16-18 cm. Generally, during winter and spring seasons, the mean sea level was significantly higher, about 10-12 cm than summer and autumn seasons. Small difference was recorded between autumn and summer seasons in all locations (Manasrah et al. 2009).

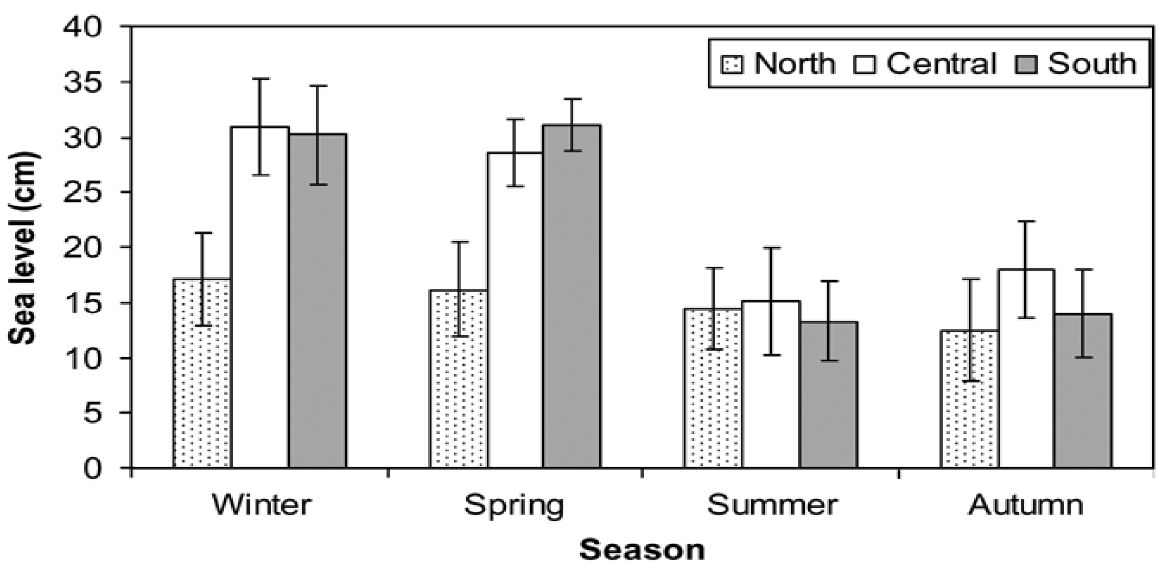


Figure 2.1: Seasonal average sea level (cm) at three locations in the Red Sea (north, central and southern) during the period 1958-2001 (Manasrah et al. 2009).

2.2 Wind stress

Two components of wind stress (cross and long-shore) at Jeddah and Port Sudan which lie at the eastern and western coast of the central Red Sea respectively are studied by Sultan et al. (1995) (see Figure 2.2). The regression analysis between the sea level and cross-shore component wind stress of Jeddah accounted for 11% of the sea level variation, with a correlation of 0.33. While the long-shore component accounted for 27%, with a correlation of 0.52. The regression equation of the sea level with both components of wind stress explained 51% of the sea level variations, and the correlation of 0.72. While at Port Sudan, the regression analysis between the sea level and wind stress accounted for 63% (cross-shore) and 25% (long-shore) of the sea level changes, while the correlation of 0.79 and 0.5 respectively. The regression equation of both components wind stress explained 63% of the sea level changes, with a correlation of 0.79.

Sultan et al. (1995) conclude that the seasonal variation of the sea level in Jeddah is mainly governed by the long-shore wind stress, but the two components explained the sea level variation to a greater degree. Also he found that the mean value of the long-shore component of wind stress in the summer season (April - September) is twice that of the winter season. Because it is enhanced by NNW wind which influences the entire Red Sea in summer. While in winter the long-shore component of wind stress is reduced by the NE monsoon and the wind is from SSE. This oscillation of wind stress led to decrease the sea level in summer and rise in winter. But in Port Sudan the reverse is true; the major cause of sea level variations is cross-shore wind stress, which has the same value of regression and correlation coefficient when the analysis is made by both components.

But also Sultan et al. (1996) found that the variance of annual cycle of long shore wind stress in Port Sudan was 50%, while for the cross-shore about 6%. There is a weak indication of a semi-annual component of wind stress. He concluded that the any points which lies north of the convergence zone of wind in the Red Sea is not controlled by wind stress, but it is associated with southern part of the basin. This is because the long-shore component wind stress in winter is greater than summer, where this situation is concurrent with increases of sea level in winter and decreases in summer. Another indication of semi-annual cycle was found in Jeddah by Sultan and Elghribi (2003). It is dominants in the long-shore wind stress, and constitutes 50% of the variance, while the annual one was 22%. In contrast the annual cycle is the major portion of variance in cross-shore wind stress of about 68%, while the semi-annual is 26%. The expected reasons for the annual cycle was the southwest monsoon which has the annual change in their speed and directions, while for those of semi-annual one is not yet clear (Sultan and Elghribi 2003). Also he found a strong correlation between wind stress and sea level in Jeddah of about 0.69, with 95% confidence limits for 10 degree of freedom.

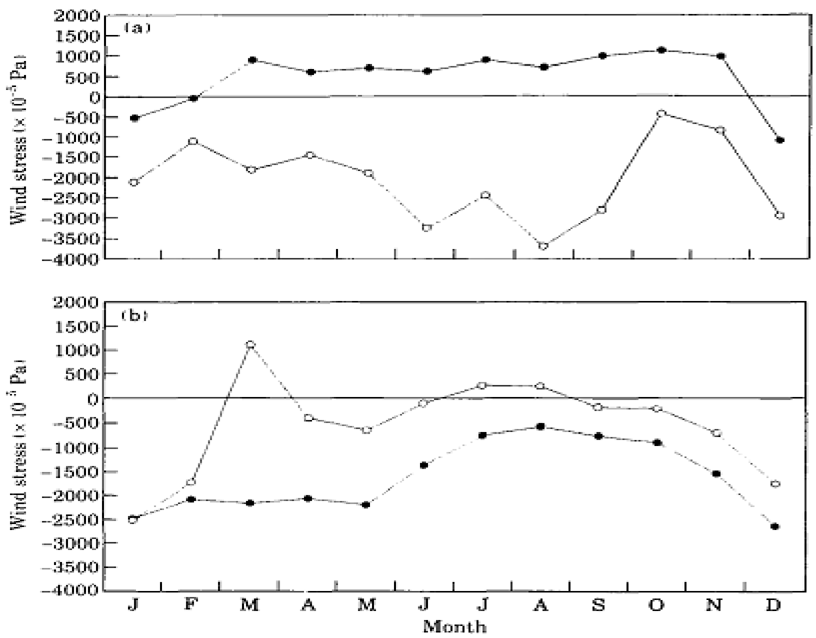


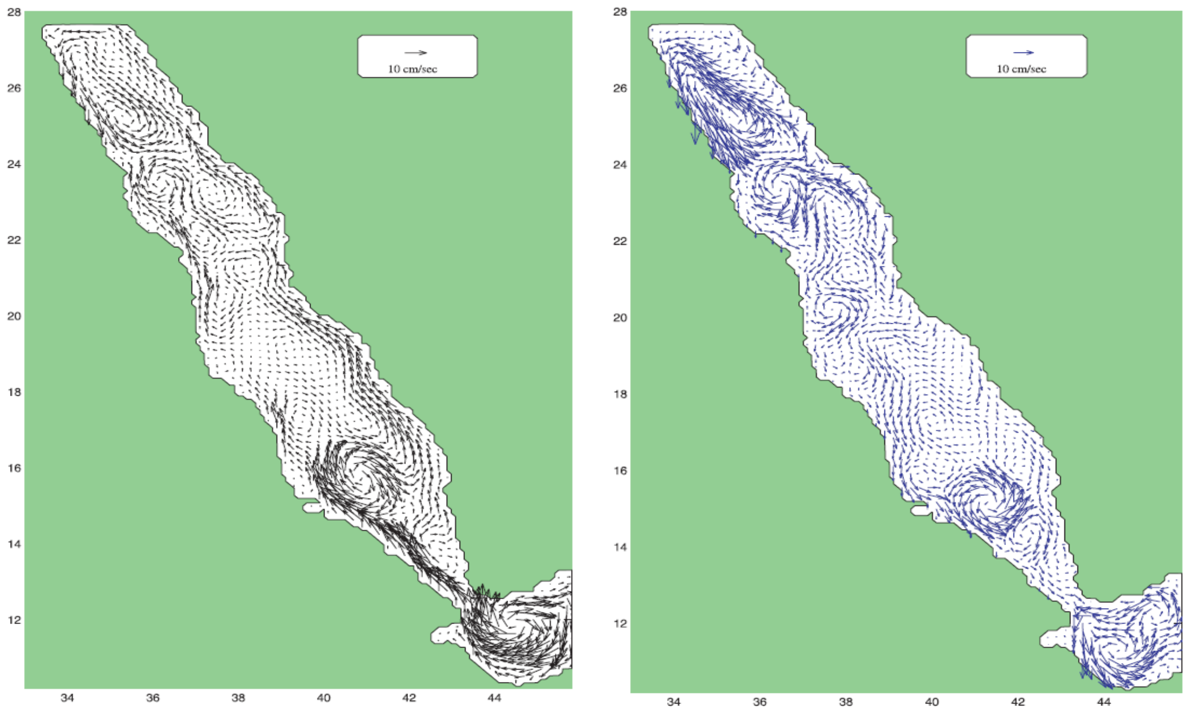
Figure 2.2: Monthly means of both components of wind stress cross-shore (-●-) and long shore(-o-) during 1991 at (a) Jeddah (x10^{-5}) and (b) Port Sudan (x10^{5}) (Sultan et al. 1995).

2.3 General circulations in the Red Sea

2.3.1 The currents and eddies

In the central channel of the Bab-el-Mandab strait, and during the northeast Indian monsoon (October-May), these wind is induced the surface water of Gulf of Aden into the Red Sea. When mean vector wind is become 6.7-9.3 ms^{-1} in the strait, concurrent with a strong mean surface current of 15-20 cms^{-1} following north-northwest. Where it is direction is against the wind regime between 19° and 25°N (Barlow 1934; KNMI 1949; Boisvert 1966).

During the southwest monsoon (June-September), all the Red Sea is dominant by the north-northwest wind, which are driven the mean surface south-southeast currents toward the Gulf of Aden through the strait of Bab-el-Mandab. In this time the Arabian Sea is relatively low and become as a sink to the Gulf of Aden water due to monsoonal wind. Thus the Red Sea and Gulf of Aden water were joint together until reach the Arabian Sea (Patzert 1974). The strong north-northwest wind during summer in the northern Red Sea increases the speed of the south-southeast currents north of 26°N. Then a strong surface outflow currents of about 15 cms^{-1} between 18° and 20°N were observed, while the strongest one occurs during July, it exceed 20 cms^{-1} in the strait of Bab-el-Mandab. During early June in the southern Red Sea, the wind change their direction from the south-southeast to north-northwest, and the currents change the direction approximately in the same phase of wind shift, while in early September of south-southeast wind, the change in current direction have the time lags by approximately one month (Barlow 1934; KNMI 1949; Boisvert 1966)

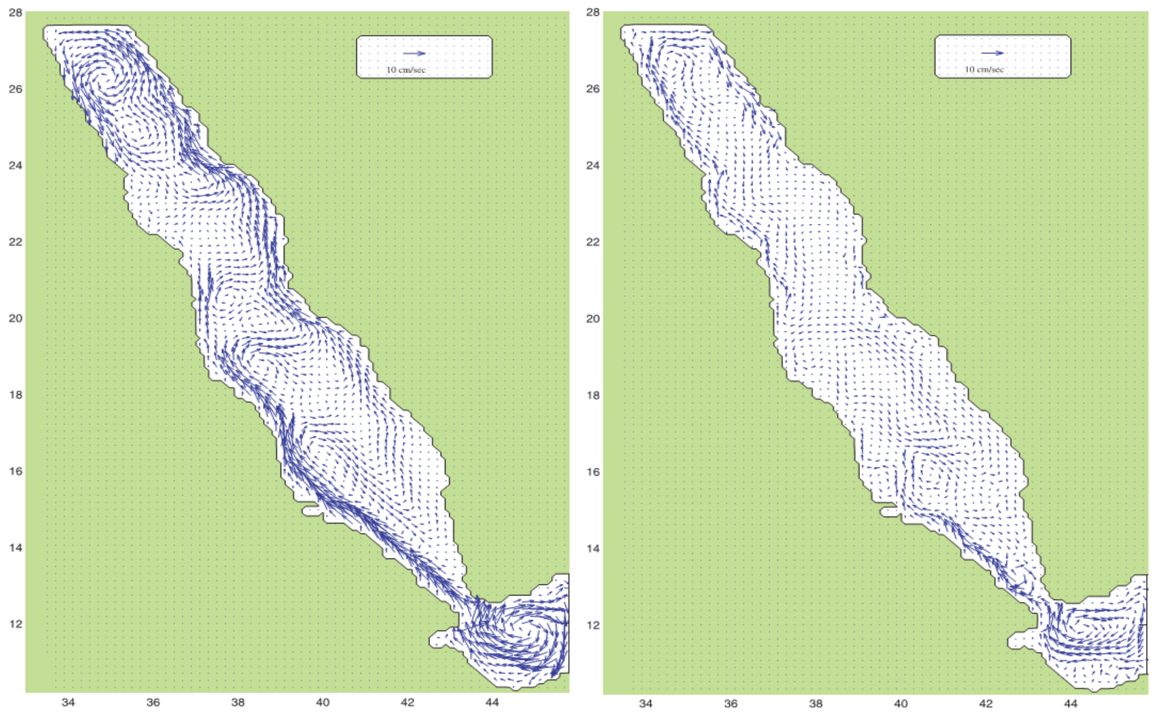


(a) (b)

Figure 2.3: The mean surface current, (a) winter season, and (b) summer season (Sofianos and Johns 2003).

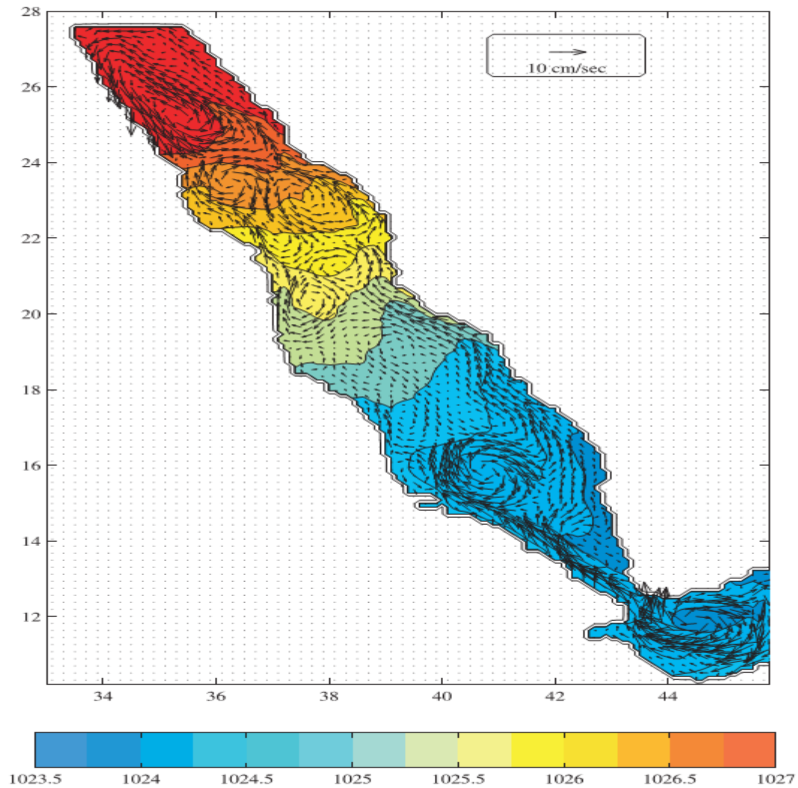
Sofianos and Johns (2003) notice that there is a strong surface and westerly inflow during winter in the strait of Bab-al-Mandab (Figure 2.3a). These currents produced a mesoscale anticyclonic gyre located between 15° and 16°N, and it is velocity exceed 50 cms^{-1}. Near 16°N the currents were ceases by the north-northwest wind along the western boundary during summer (Figure 2.4b), and easterly boundary current was observed following the northward, but it is weaker than the southern one. Generally the main feature of summer season is irregular and the circulation is weaker than winter. The mesoscale gyre is become cyclonic rotation and another one was observed in the north, and in the south the westerly boundary current is disappears.

When he separates the effects of wind stress in the general circulation from the thermohaline one, Sofianos and Johns (2003) found that the thermohaline effects is the dominants forcing mechanism in the Red Sea. This is clearly appears from a comparison between Figure 2.4a with Figure 2.4b. In the northern Red Sea the thermohaline has a strong cyclonic eddy, which is the dominant feature of the general circulation, while the wind stress has a weak anticyclonic eddy. But around 22ºN, it is clearly that the western boundary current which is present in the combine forces in Figure 2.5 are appears only in wind stress driven circulations.



(a) (b)

Figure 2.4: Sea surface velocity driven by (a) thermohaline effect (b) wind stress effect (Sofianos and Johns 2003).



.

Figure 2.5: Annual mean surface circulation driven by combine forcing on the mixed layer density (Sofianos and Johns 2003).

2.3.2 Water Masses

The Red Sea is characterized by two dominant water masses, surface water (SW), and Red Sea outflow water (RSOW). These masses are affected by Gulf of Aden water masses, surface water (SW) and Gulf of Aden intermediate water (GAIW). Two layer system occurring during winter season. The Gulf of Aden surface water (SW) was observed as inflow in the Red Sea with deepens to a depth of ~100 m (Figure 2.6), this inflow is balanced simply by Red Sea outflow water (RSOW) (Cromwell and Smeed 1998). The volume flux of inflow water is about 0.38 sv and for outflow of about 0.352 sv with an evaporation rate of about 0.025 sv (Souvermezoglou et al. 1989). In summer season, three layer system were observed, outflow of the Red Sea surface layer (SW), which distinguished by high temperature (>30˚ C), and about 50m depth in both the Red Sea and Gulf of Aden.

The second layer is Gulf of Aden intermediate water (GAIW) which intrudes through the strait into the Red Sea at depth centered of about ~100 m. It is temperature is different, relatively cold in the Gulf of Aden (15˚ -17˚ C), saltier and relatively warm in the Red Sea (~22˚ C). While the third layer is Red Sea outflow water (RSOW) which is dominant outflow layer throughout the year (Figure 2.6), but in summer it is much smaller than winter (Cromwell and Smeed 1998). With 0.035 sv evaporation rate, Souvermezoglou et al. (1989) found that the volume transport are 0.1 sv and 0.06 sv for the Red Sea surface and deep outflow layer respectively, and o.19 sv for intermediate inflow layer.

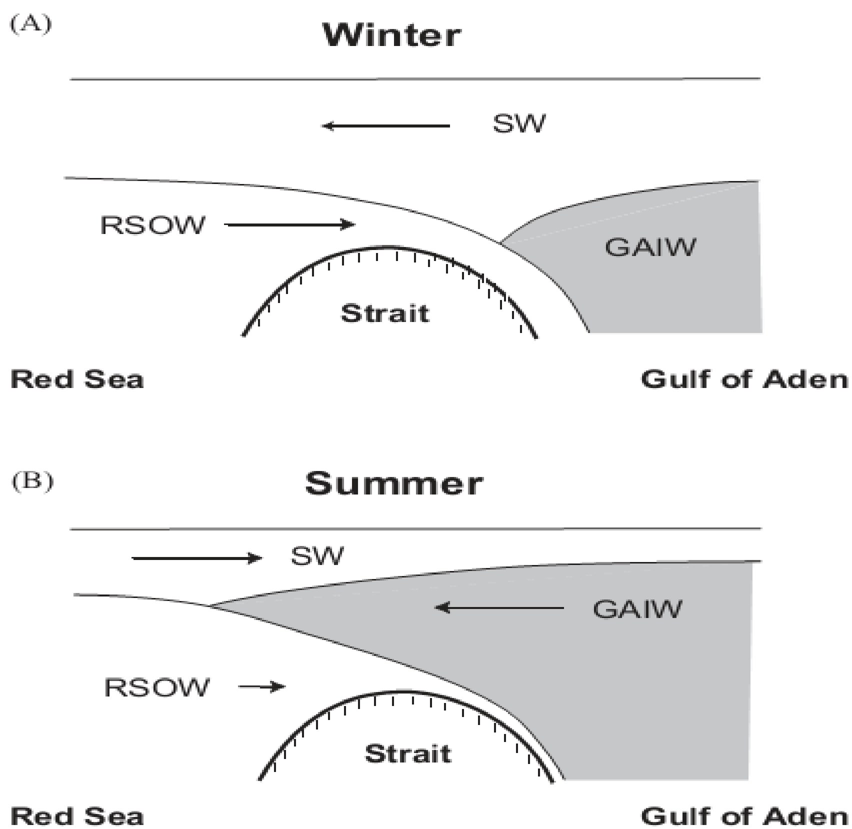


Figure 2.6: Exchange of water masses in the Bab el-Mandab strait, (A) winter and (B) summer season, where SW=surface water, GAIW= Gulf of Aden intermediate water and RSOW=Red Sea outflow water (Smeed 2004).

2.4 Steric sea level

The steric sea level is defined as the variations of specific volume of sea water. It is depend upon the thermal and haline effects to create the variation of density within the water column. That means the steric sea level is high, when the water is warm and/or less saline, and it is low when the water is cold and/or more saline (Patzert 1974). The steric variations of sea level in upper 300 m near Aden and Perim in the southern Red Sea and the sea level at shore station have the same phase and similar range. In the northwest Gulf of Aden, the upwelling of cool and less saline water is caused the steric variation with range larger by approximation 8 cm. Patzert (1974) found that in upper 200 m of the water column in Port Sudan in the central Red Sea, and upper 50 m in the Gulf of Suez in northern Red Sea, the steric sea level is raised in summer, and lowered in winter, but the mean sea level is reverse, thus the steric effect is not control the mean sea level in Port Sudan and Gulf of Suez.

The correction of Gulf of Aden and Perim mean sea level with both steric effect and atmospheric pressure yield unexplained drops in mean sea level in Aden during June, and in Perim during April, these drops are probably within the data variability range, that means the conditions which control the mean sea level vary from one set of data to another. The atmospheric pressure and steric variations were corrected to the Port Sudan and Port Sues mean sea level, yield the same phase, but the range of mean sea level is increases by 13 and 20 cm in Port Sues and Port Sudan respectively (Patzert 1974). Thus the total effect of both atmospheric pressure and steric variations is to diminish the rise and fall of mean sea level in the Northern and central basin. Then the exchange of water masses in the southern end and the wind setup of north-northwest wind are responsible for sea level variations in the northern and central Red Sea.

As found by Sofianos and Johns (2001), in the southern Red Sea, the steric variations has the largest reading, about 15 cm. It is reaching their maximum at the end of winter, while their minimum during the end of summer. In contrast, in the central and northern Red Sea the water is heated from above during the summer, thus, the steric variations have the maximum level about 7 cm. That means it is acts opposite to wind setup in summer season by increasing the total sea level.

Eid and KAMEL (2004) are investigates the variation of total steric sea level in the Red Sea during different seasons. The steric effect in the north has a negative value all the year due to low temperature and/or high salinity, which are increases the density. The thermal effect is seen the main factor during winter and spring seasons in the north, while the haline is main during autumn and summer seasons. In other hand the southern basin has a positive steric effect in all season, due to inflow of relatively warm and less saline water in to the Red Sea, which decreases the density. In this region the haline effect is seem to be the major factor during all the seasons, more detail is found in table 2.2.

Table 2.2: Spatial and temporal distributions of the steric sea level in the Red Sea (Eid and KAMEL 2004).

Component	Region	Seasons				
		Winter	Spring	Summer	Autumn	Year
Thermal (Zt)	23-28ºN	–9.07	–6.17	0.27	–3.17	–4.53
	20-23ºN	–2.49	–1.08	5.88	4.58	1.72
	17-20ºN	0.56	2.89	8.26	7.95	4.92
	13.17ºN	–3.30	0.15	6.47	1.70	1.26
	Red Sea	–4.15	–1.68	4.60	2.28	–
Haline (Zs)	23-28ºN	–5.09	–6.44	–8.53	–5.55	–6.15
	20-23ºN	1.22	0.86	–3.05	–1.44	–0.60
	17-20ºN	0.26	4.64	2.55	5.70	3.29
	13-17ºN	6.07	13.94	10.09	9.35	9.86
	Red Sea	–0.50	1.56	–1.60	0.52	–
Total steric (Zα)	23-28ºN	–14.15	–11.60	–8.27	–8.72	–10.69
	20-23ºN	–1.27	–0.22	2.83	3.14	1.12
	17-20ºN	0.62	7.53	10.82	13.65	8.21
	13-17ºN	2.76	14.10	16.56	11.05	11.12
	Red Sea	–4.65	–0.12	3.00	2.80	–

3 Theory and Method

3.1 Data

The sea level and wind stress data for 50-years of the Red Sea from 1 January 1958 to 31 December 2007 were obtained from Carton and Giese (2008) dataset version 2.0.2-4. The data cover the area from 10.25ºN to 28.25ºN and from 33.75ºE to 43.75ºE. The reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA) effort began at the University of Maryland in the 1990s to reconstruct the changing physical climate of the global ocean.

SODA data was produced by an Ocean General Circulation Model (OGCM), with an average horizontal resolution of 0.25°×0.4°, and 40 vertical levels with 10-m spacing near the surface. The numerical model results were corrected every 10 days by a vast set of observations, which include hydrographical data from both ship intake and moored station, and remotely sensed SST**.** The SODA data used here is monthly averages mapped on a horizontal 0.5°latitude × 0.5° longitude grid, which is conveniently uniform.

3.2 Method

Monthly mean values of sea level and wind stress for 50-years of the Red Sea were divided into three seasons, summer (June to September), early winter (October to January), and late winter (February to May). The reason of this grouping is to monsoonal wind which divided the climate in the Red Sea into summer (June-September), and winter (October-May) (Patzert 1974). Eid and KAMEL (2004) illustrate that the (April-May) and (October-November) are transitional period representing spring and autumn seasons respectively, but really they are not exist in the southern and central Red Sea. That is because they are disappears by tropical climate. The Red Sea was divided into three locations, Northern (26.75ºN and 34.75ºE), Middle (19.75ºN and 38.75ºE) and Southern (14.25ºN and 42.75ºE). The Hanish Sill which is located in the southern Red Sea at 13.25ºN was the origin and the reference point to which sea level, wind setup, and steric effects were compared to. Also the data were grouped into 5 year periods, as example the group named 6F refers to the first five years of the 1961-1970 decade, and 6S refers to the second five years of that decades. The group 5S represents three years only, because the data begins from January 1958, and the group 0S represents two years only, because the data ends on December 2007.

The calculations of the wind setup contribution to sea level variations were made. In these calculations it was convenient to consider a northwest directed wind stress as positive, while a southeast directed is negative. Various matlab programs were used to analyze the data, and to calculate the components of wind setup and steric effect of the sea level variations.

3.3 Theory

The SODA data are monthly mean values, and on that time scale it is fair to assume that the upper layer is in a static balance between wind stress and horizontal pressure force along the Red Sea axis (neglecting rotational effects):

Integrated vertically from z=-H, where $\tau = 0$ (no effect of wind there) to z=0

$$\frac{1}{\rho^\circ}\int_{-H}^{0}\frac{\partial p}{\partial x}dz = \frac{\tau}{\rho^\circ} \qquad (1)$$

Where p is hydrostatic pressure, τ is the along-axis wind stress, $\tau > 0$ when it is to North westward, ρ° is the density of the sea water, and x is the along-axis direction.

The hydrostatic pressure is

$$P = \rho^\circ g\eta + \int_{z}^{0}\rho g dz' \qquad (2)$$

Derivation of Equation (2) w.r.t x yields

$$\frac{\partial p}{\partial x} = \rho^{\circ}\mathrm{g}\frac{\partial \eta}{\partial x} + \frac{\partial}{\partial x}\left(\int_{z}^{0} \rho \mathrm{g} dz'\right) \tag{3}$$

Insert it in Equation (1) and solve for the sea surface slope gives

$$\frac{\partial \eta}{\partial x} = \frac{\tau}{\rho^{\circ}\mathrm{g}H} - \frac{\partial}{\partial x}\left(\frac{1}{H}\int_{-H}^{0} (\int_{z}^{0} \frac{\rho}{\rho^{\circ}}\, dz')dz\right) \tag{4}$$

Where η is the sea level height. Integrate Equation (4) from any point in the Northern Red Sea x'=x to the Hanish Sill x'=0 yields

$$\int_{0}^{x} \frac{\partial \eta}{\partial x} dx' = \eta(x) - \eta(0)$$
$$= \int_{0}^{x} \frac{\tau}{\rho^{\circ}\mathrm{g}H} dx' - \int_{0}^{x} \frac{\partial}{\partial x}\left[\frac{1}{H}\int_{-H}^{0}\left(\int_{z}^{0} \frac{\rho}{\rho^{\circ}}\, dz'\right)\right] dx' \tag{5}$$

$$\eta(x) - \eta(0) = +\frac{1}{\rho^{\circ}\mathrm{gH}}\int_{0}^{x} \tau dx'$$
$$-\frac{1}{\rho^{\circ}H}\left[\int_{-H}^{0}\left(\int_{z}^{0} \rho(x) dz'\right) dz - \int_{-H}^{0}\left(\int_{z}^{0} \rho(0) dz'\right) dz\right] \tag{6}$$

Where η(0) represents any non-steric sea level.

Equation (6) tells that the sea level at some position *x* along the Red Sea axis is given as the sea level at Hanish Sill (*x*=0) plus the wind stress setup plus the difference in steric effects at position *x* and at Hanish Sill.

If the Soda data doesn't include the effect of atmospheric pressure (P'_a) to sea level Height, then

$$\frac{\partial u}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g\frac{\partial \eta'}{\partial x} + \frac{1}{\rho}\frac{\partial \tau}{\partial z} \tag{7}$$

$$\eta_a = -\frac{P'_a}{\rho g}$$

Where η_a represent the surface elevation of an inverse barometer.

$$P = \rho^\circ g\eta' + \int_z^0 \rho g dz' \tag{8}$$

Where η' is sea level height given by

$$\eta' = \eta - \eta_a$$

Then Equation (6) becomes

$$\eta(x) = \eta(0) + \eta'_a(x) - \eta'_a(0) + \frac{1}{\rho^\circ g H}\int_0^x \tau dx' - \frac{1}{\rho^\circ H}\int_{-H}^0 \left(\int_z^0 \rho(x) dz'\right) dz + \frac{1}{\rho^\circ H}\int_{-H}^0 \left(\int_z^0 \rho(0) dz'\right) dz \tag{9}$$

The left hand side represents the sea level, the first term in the right hand side is any non steric effect at the southern basin, the second and the third are atmospheric variation, the fourth is wind setup and the fifth and sixth are the steric effect, which represent the residual term. As SODA model didn't include the atmospheric pressure, then we neglect it.

From Equation (6) we derive the seasonal anomaly.

$$\eta'(x) = \eta'(0) + \frac{1}{\rho^\circ \mathrm{gH}} \int_0^x \tau' dx' - \frac{1}{\rho^\circ H} \int_{-H}^0 \left(\int_z^0 \rho'(x) dz' \right) dz + \frac{1}{\rho^\circ H} \int_{-H}^0 \left(\int_z^0 \rho'(0) dz' \right) dz \qquad (10)$$

Where $\eta' = \eta - \bar{\eta}$, $\tau' = \tau - \bar{\tau}$, and $\rho' = \rho - \bar{\rho}$, the bar is annual mean, and primes represents the deviation from the annual mean value.

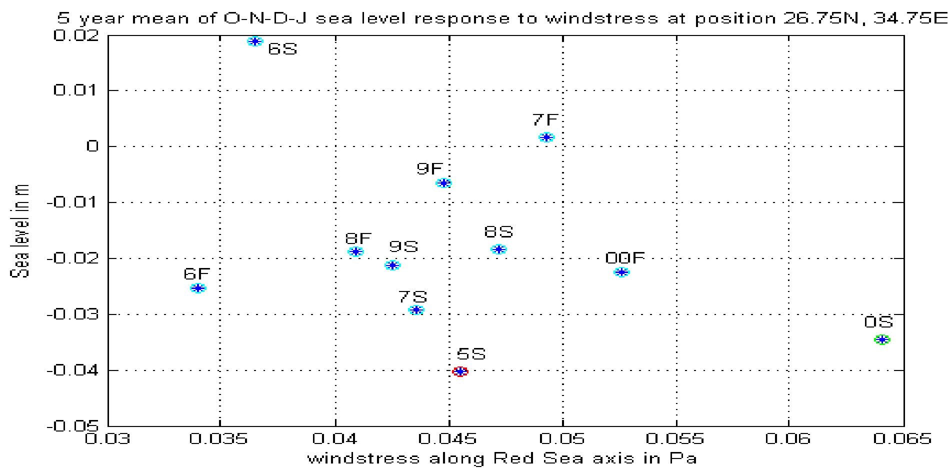
4 Results

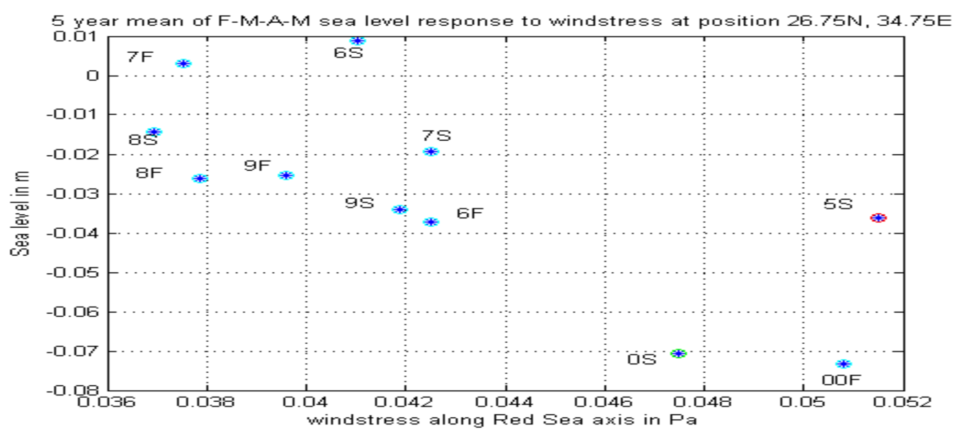
4.1 Sea level response to the local wind stress

4.1.1 The northern Red sea

The 5 year mean of sea level response to the wind stress in the northern Red Sea is displayed in Figure 4.1. Note that in these calculations a southeast directed wind stress is considered positive. The wind stress has a relatively high value, and it is from the northwest all the year. There is no significant seasonal variation in wind stress; the values fluctuate between 0.035 to 0.055 Pa during all seasons. Generally slight difference of sea level was recorded between early and late winter, they fluctuate between 0.02 and 0.01 to -0.04 m respectively, except (00F) and (0S) on the late winter, which recorded the lowest value of sea level about -0.07 m for both, and high values of wind stress about 0.051 and 0.047 Pa, respectively, where the most period around 0.04 Pa. The sea level in summer is lower than early and late winter, it fluctuates between -0.04 to -0.1 m. The late winter season has the strongest response of sea level to local wind stress. The 00F (2001-2005) February-May sea level is the lowest one, -.073 m, concurrent with a strong wind stress directed to the southeast, while the 6S (1966-1970) sea level is the highest one, 0.01 m concurrent with a weak wind stress (see mid panel of figure 4.1).

This is also revealed by the data for each year shown in Figure 4.2.The correlation coefficient between the wind stress and sea level is always has a negative value, because the wind is from the northwest all the time. That means when the wind is blowing from the north, then it is inversely proportional to the sea level (strong and positive southwest directed wind stress together with low sea level yield negative correlation coefficient). The value of correlation coefficient is small in the summer and early winter seasons, it recorded -0.30 and -0.34 respectively, while the anticorrelation in late winter is about -0.48. That means the local wind stress is not playing a major role in the seasonal variation of sea level in the northern Red Sea, and other parameters may influence the sea level rather than local wind stress.





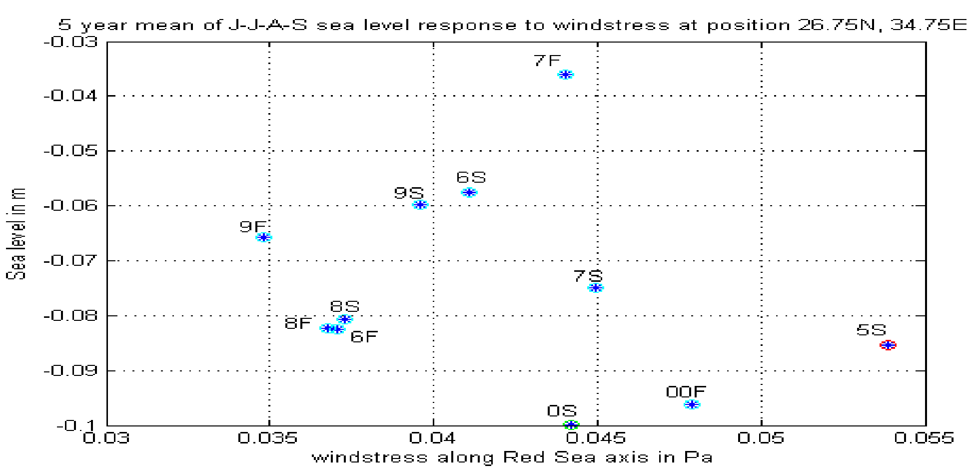


Figure 4.1: 5 years mean of early winter (O_N_D_J) (upper panel), late winter (F_M_A_M) (mid panel), and summer (J_J_A_S) (lower panel) sea level response to wind stress in the northern Red Sea.

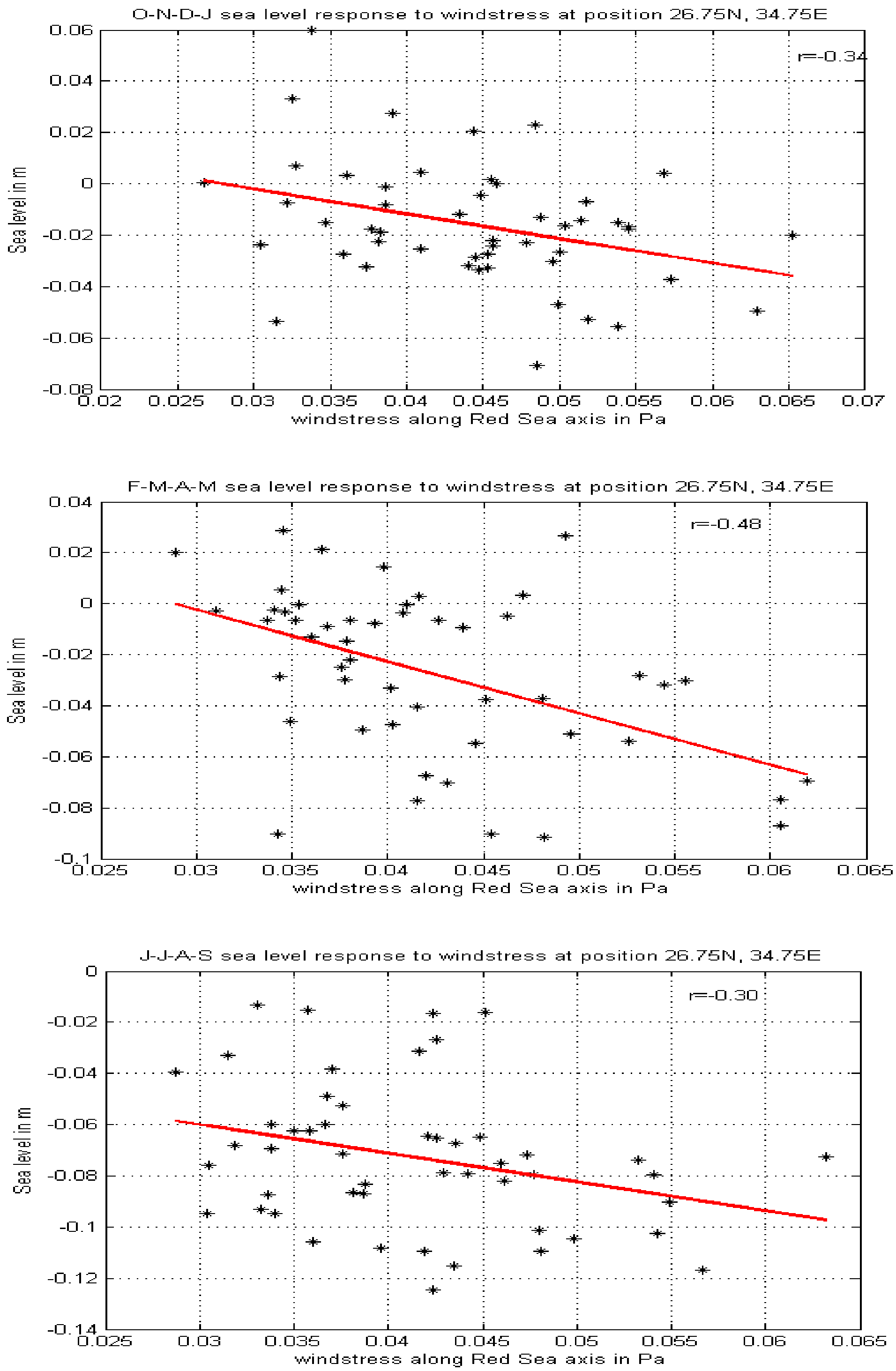


Figure 4.2: Correlation between the sea level and local wind stress of early winter (O_N_D_J) (upper panel), late winter (F_M_A_M) (mid panel), and summer (J_J_A_S) (lower panel) in the northern Red Sea.

4.1.2 The central Red Sea

Generally the sea level in early and late winter in the central Red Sea is almost the same Sea (Fig. 4.3). It fluctuates between 0.1 to 0.12 m in both, except 0S during early winter was recorded 0.09 m (upper panel), and also during late winter (mid panel) 00F and 0S were recorded 0.067 and 0.076 m respectively. The direction of wind stress is positive because it is from the northwest, and its value in late winter is almost twice that of early winter, the most points are between 0.2 to 0.4, and 0.1 to 0.2 Pa respectively. The sea level in summer is lower than that of early and late winter; it is between 0.06 to 0.08 m, and the wind stress is relatively weak and variable, but mostly from the northwest.

As we noted in the northern Red Sea, 00F and 0S has the highest wind stress and lowest sea level during the late winter. They are continuing the same behavior, mostly during all seasons. In other hand, 6S during early winter and summer seasons, and 7F during the late winter were recorded high sea level when the wind stress is weak and/or variable.

The correlation coefficient between the sea level and wind stress on the late winter has a negative value -0.66, while on early winter and summer it is negative and weak -0.31 and -0.13 respectively (Fig. 4.4). That means the variations of sea level in the late winter is relatively controlled by wind stress, and the reverse is true in other seasons. Strong northwestern wind stress is inversely proportional to the sea level in late winter.

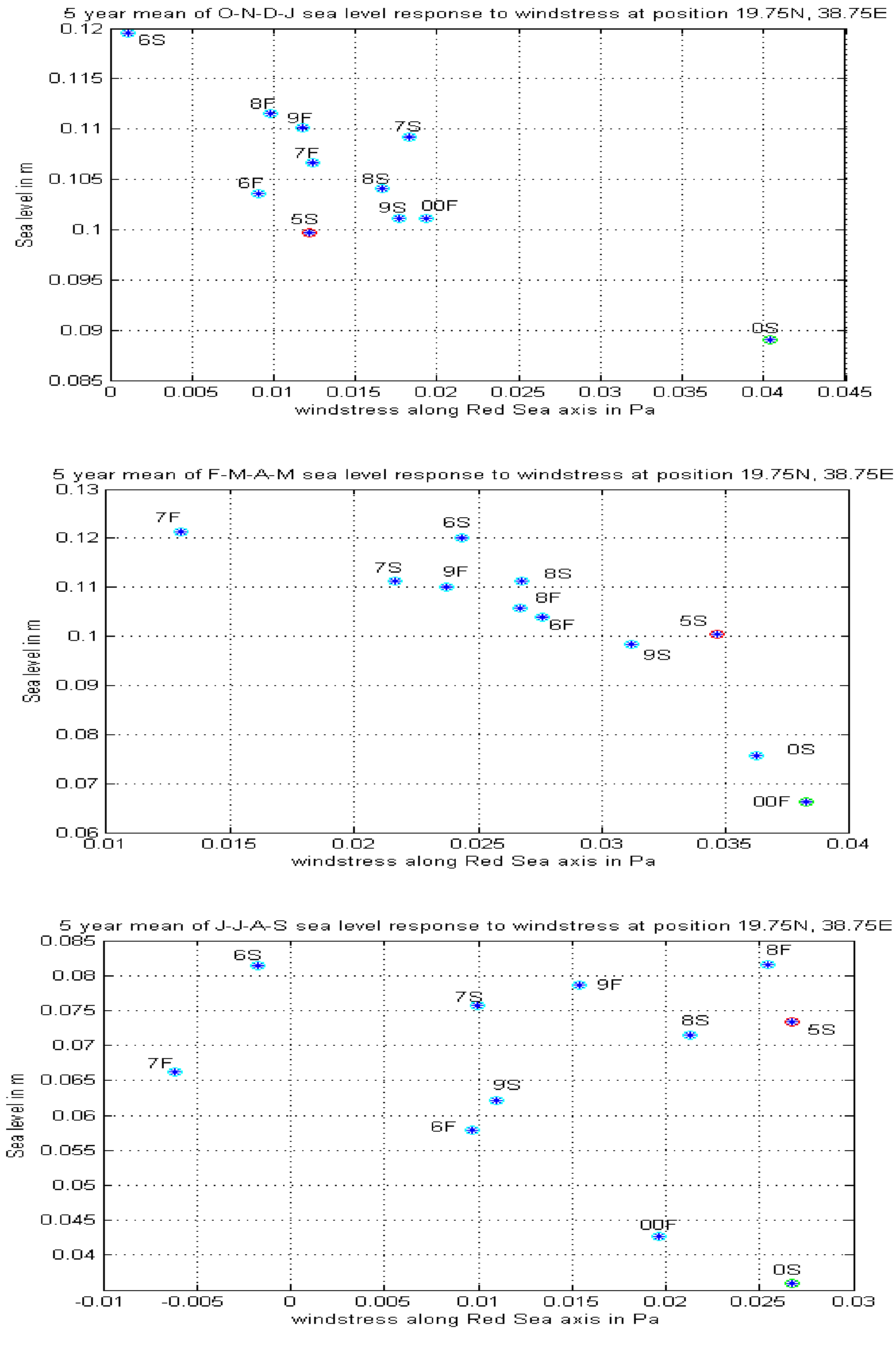


Figure 4.3: 5 years mean of early winter (O_N_D_J) (upper panel), late winter (F_M_A_M) (mid panel), and summer (J_J_A_S) (lower panel) sea level response to wind stress in the central Red Sea.

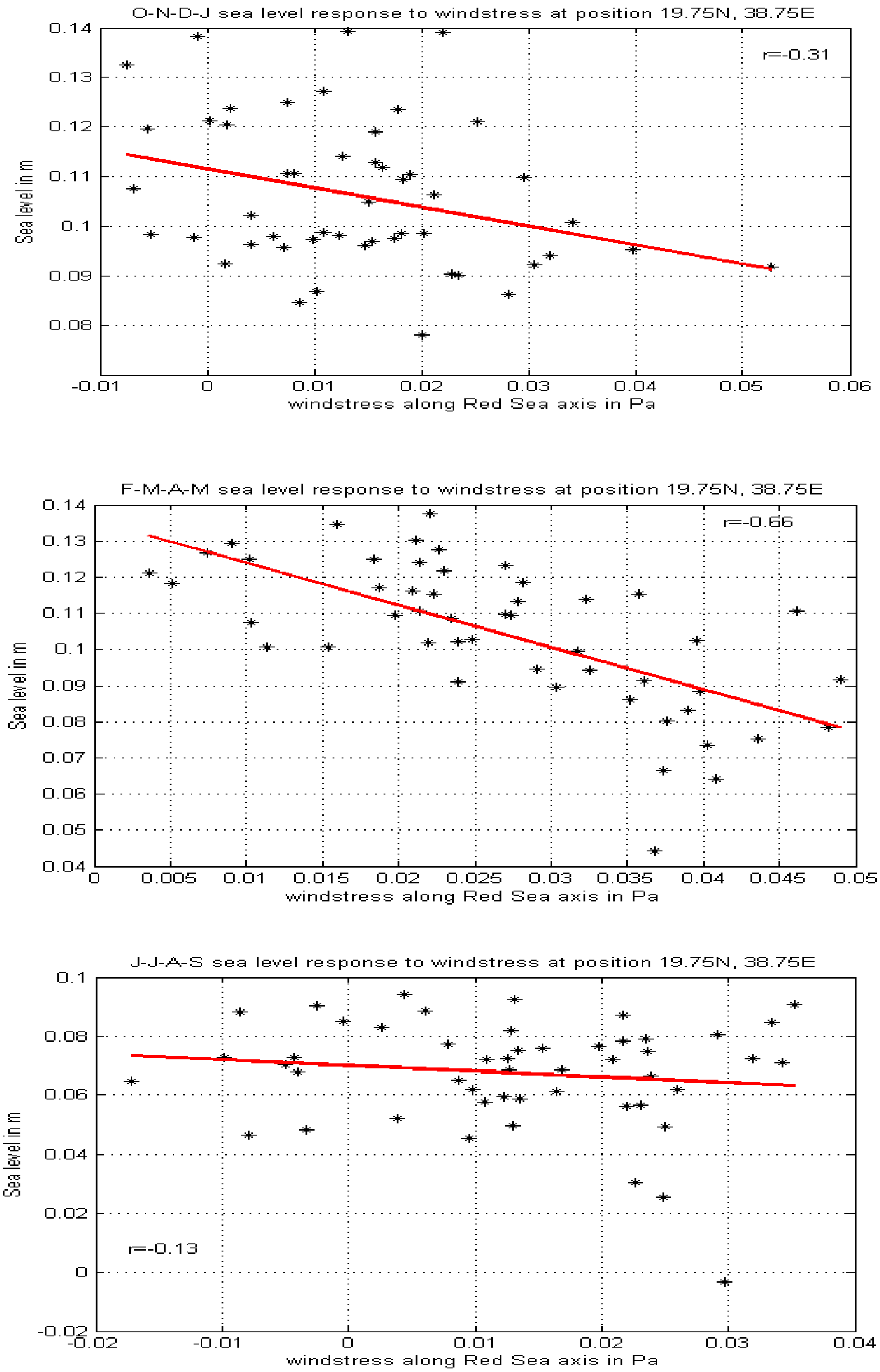


Figure 4.4: Correlation between the sea level and local wind stress of early winter (O_N_D_J) (upper panel), late winter (F_M_A_M) (mid panel), and summer (J_J_A_S) (lower panel) in the central Red Sea.

4.1.3 The southern Red Sea

The sea level in the late winter is greater than early winter and summer, but generally it is value in all winter is higher than summer. It is fluctuates between 0.17 to 0.25, 0.15 to 0.19, and 0.075 to 0.12 m respectively. While the reverse is true in wind stress during winter, the early winter is greater than late winter wind stress. The most periods are fluctuates between -0.015 to -0.065 Pa, and from -0.004 to -0.016 Pa respectively, except 7F which is recorded -0.024 Pa. The summer season wind stress is lower than all winter. The direction of wind stress in all winter is from the south, while in summer, the most periods were recorded the northern wind except 7F, 7S, 00F, and 00S has the southern wind and it is relatively weak. This indicates that the Red Sea is under the influences of northern wind stress in summer season,

Also this figure appears that there is a change in behavior of sea level on the early winter. 00F and 0S has about 0.15 m of sea level and about -0.065 Pa of wind stress in both, while the mean sea level of the other periods are almost 0.18 m and the maximum value of wind stresses are less than -0.025 Pa. This indicates that we have increases in wind stress and decreases in sea level. Also this situation is continues during late winter, but the wind stress is relatively normal. In summer season 00F and 00S also are recorded lower sea level, but with southern wind stress.

The correlation coefficient between the sea level and wind stress during early winter is about 0.45, while during late winter has a negative correlation of about -0.02. And it is value during summer is about 0.34.

This result indicates that the wind stress is not playing a major role in seasonal variation of sea level in the southern Red Sea.

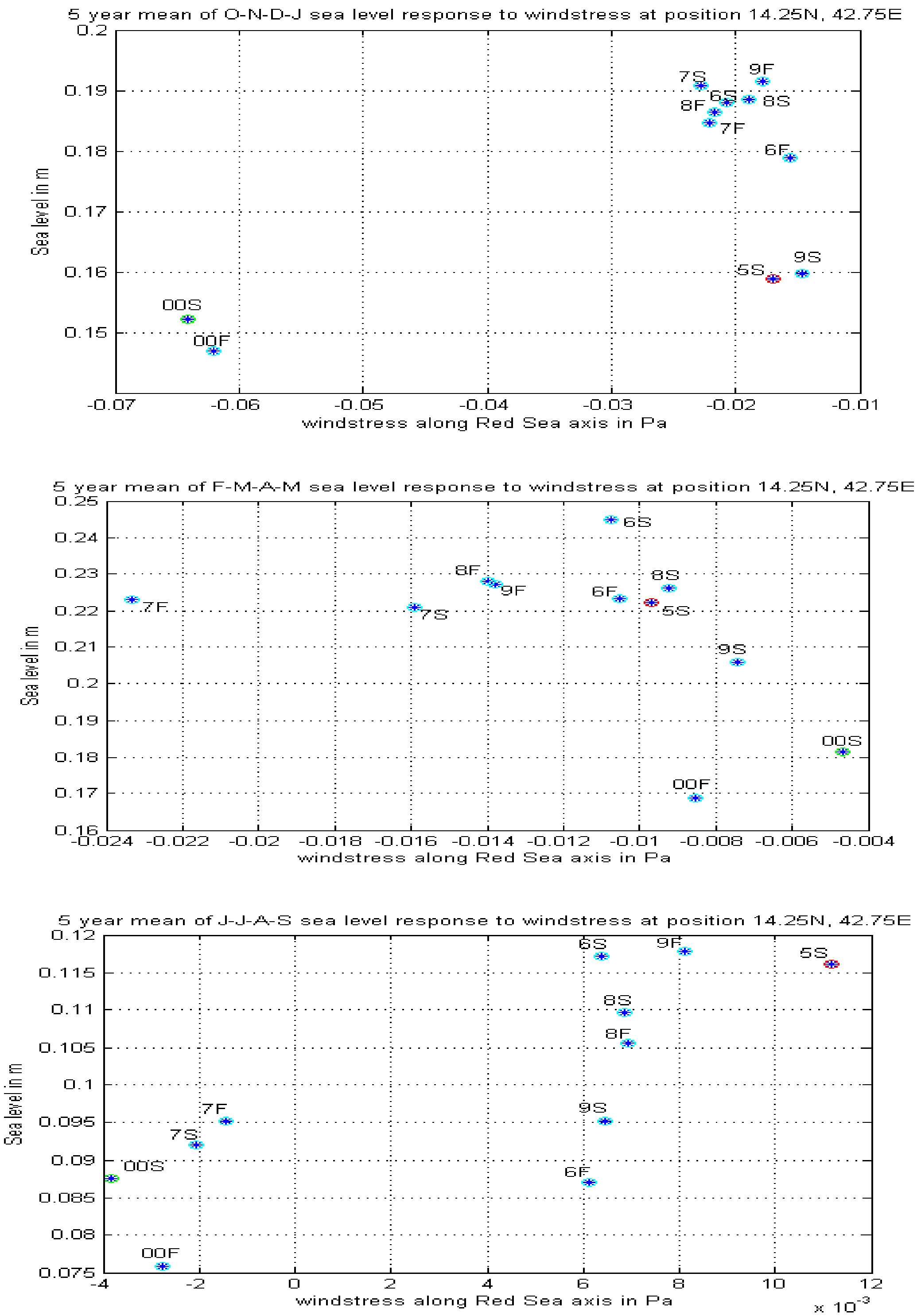


Figure 4.5: 5 years mean of early winter (O_N_D_J) (upper panel), late winter (F_M_A_M) (mid panel), and summer (J_J_A_S) (lower panel) sea level response to wind stress in the southern Red Sea.

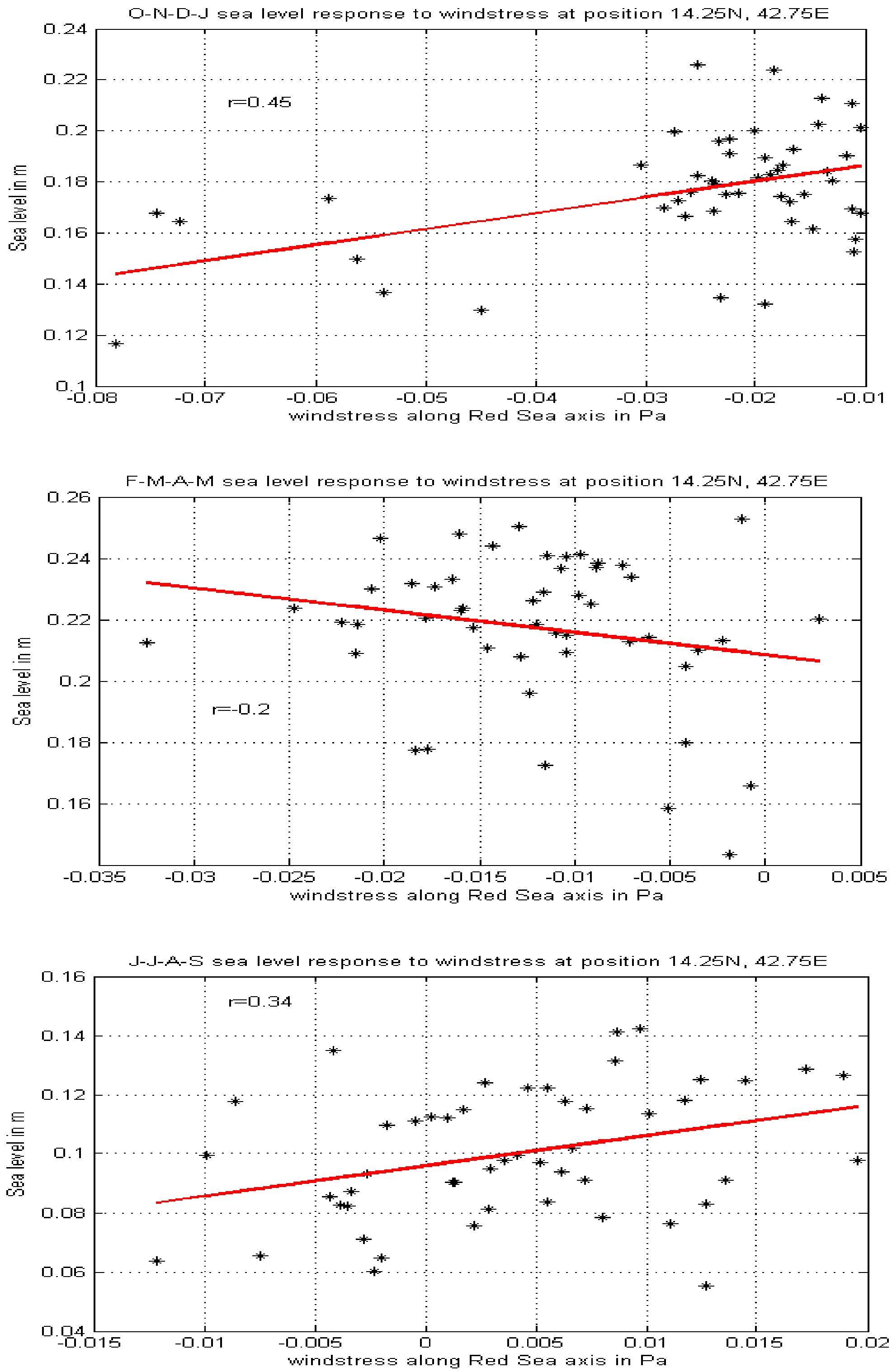


Figure 4.6: Correlation between the sea level and local wind stress of early winter (O_N_D_J) (upper panel), late winter (F_M_A_M) (mid panel), and summer (J_J_A_S) (lower panel) in the southern Red Sea.

4.2 Sea level and wind setup Seasonal anomaly difference with Hanish Sill

Figure 4.7 shows the difference in sea level anomalies between any points along the Red Sea and Hanish Sill. The sea level reflects clear annual variation in the Red Sea, and there is no any indication of semi-annual one. During Late winter, the anomalies difference of sea level has a negative value along the entire basin, reaching it is highest level in the central basin of about -5 cm, exactly during February and March. The reverse is true during summer and early winter, the anomalies difference has a positive value of about 5 cm, with maximum value during September in the central basin also. The sea level difference anomalies have two peaks located in the central Red Sea, one during late winter and the other during summer season. These variations are illustrate more clearly in figure 4.8, where the March and August Months (upper Panel), and December and May months (lower panel) compare with the annual mean sea level profile along the entire basin.

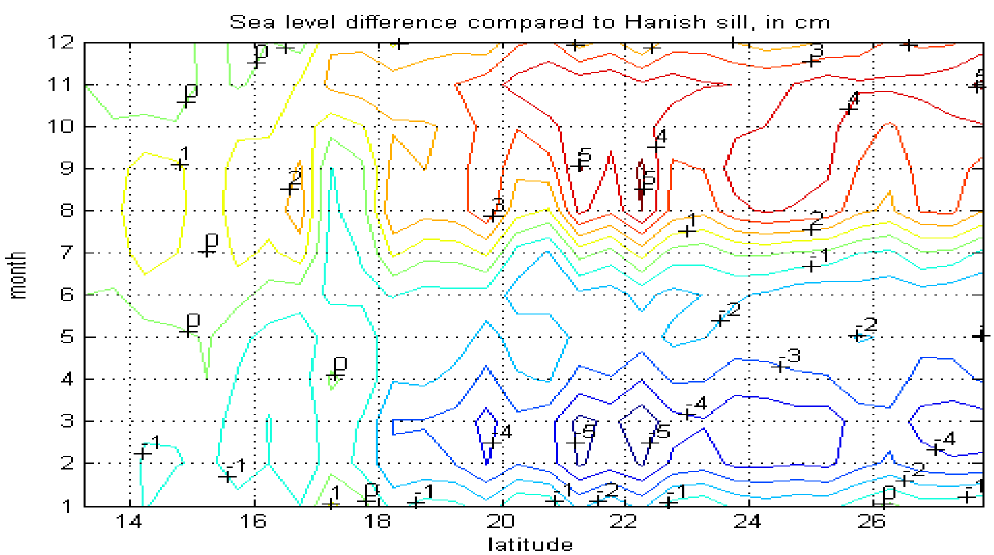


Figure 4.7: Seasonal anomaly difference of the total sea level with reference to Hanish Sill, in cm.

Notice that the sea level during March month is higher than annual mean, reaching it is maximum difference in the central and southern basin. Where during August the sea level is lower than the mean, reaching it is maximum difference in the northern and southern basin. Where the sea level during December and May months it is higher than the annual mean.

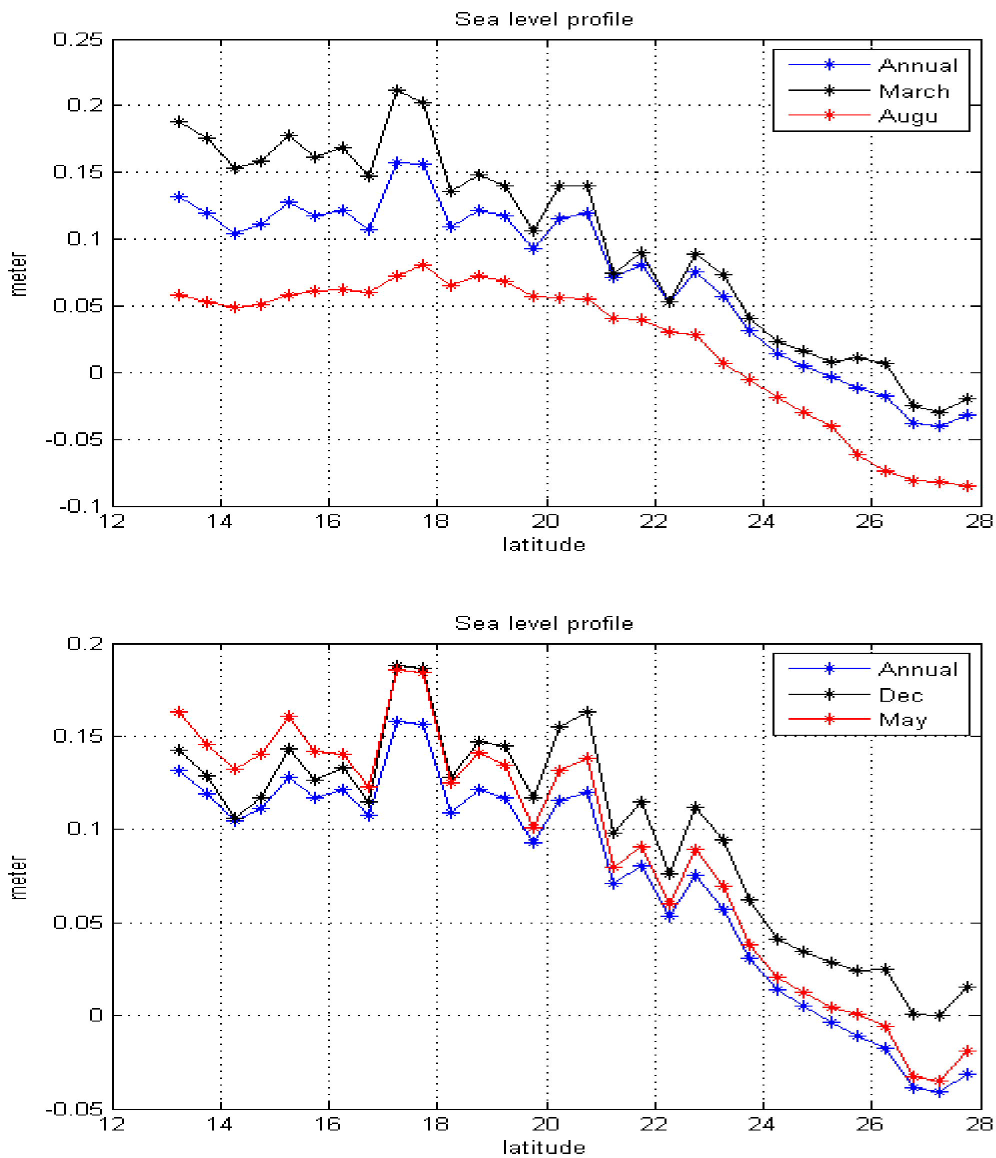


Figure 4.8: Sea level profile along the Red Sea. The blue line is annual. The black is March month. And the red is August month (upper panel), the blue line is annual, the black is December month. And the red is May month (lower panel).

The northern and central Red Sea has a semiannual variation of wind setup with range of about 14 cm (Figure 4. 9). these wind setup anomalies have two peaks, the biggest one is in the beginning of early winter (October) about 8 cm, and the other in the end of late winter (April) about 2 cm. The variations is decrease gradually until they reach zero in the southern end of the basin at Hanish Sill, which we use it as the reference point (x=0). (Note that in these calculations we define the x-axis positive northwestward, and the wind stress is defined accordingly positive when directed northwestward). The wind setup in the northern and central basin during late winter and summer seasons give negative anomalies of about -6 cm, while during early winter it is opposite, with positive sea level anomalies of over 6 cm. Figure 4.10 shows the wind setup anomalies, and it is contributions in sea level more clearly.

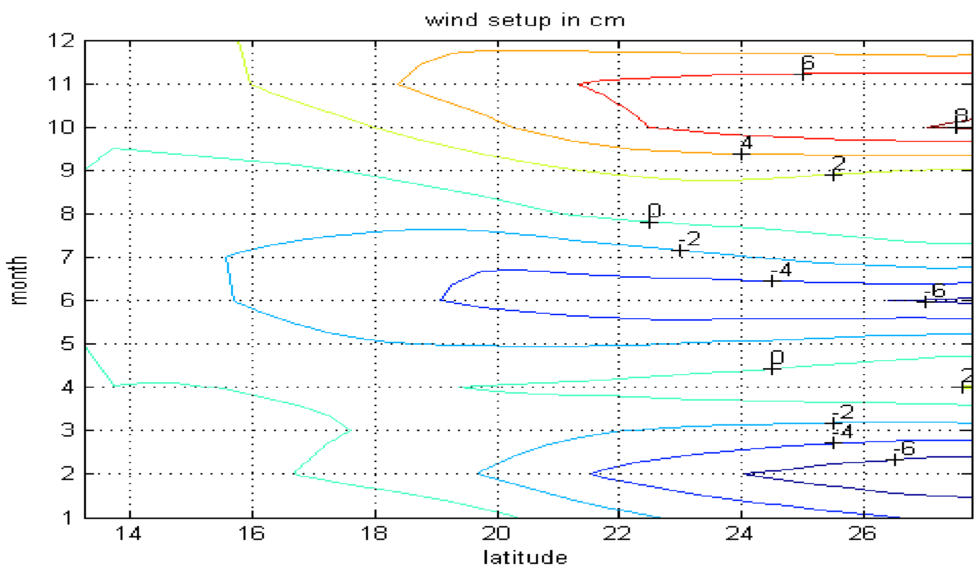


Figure 4.9: Seasonal anomaly difference of wind setup with reference to Hanish Sill, in cm.

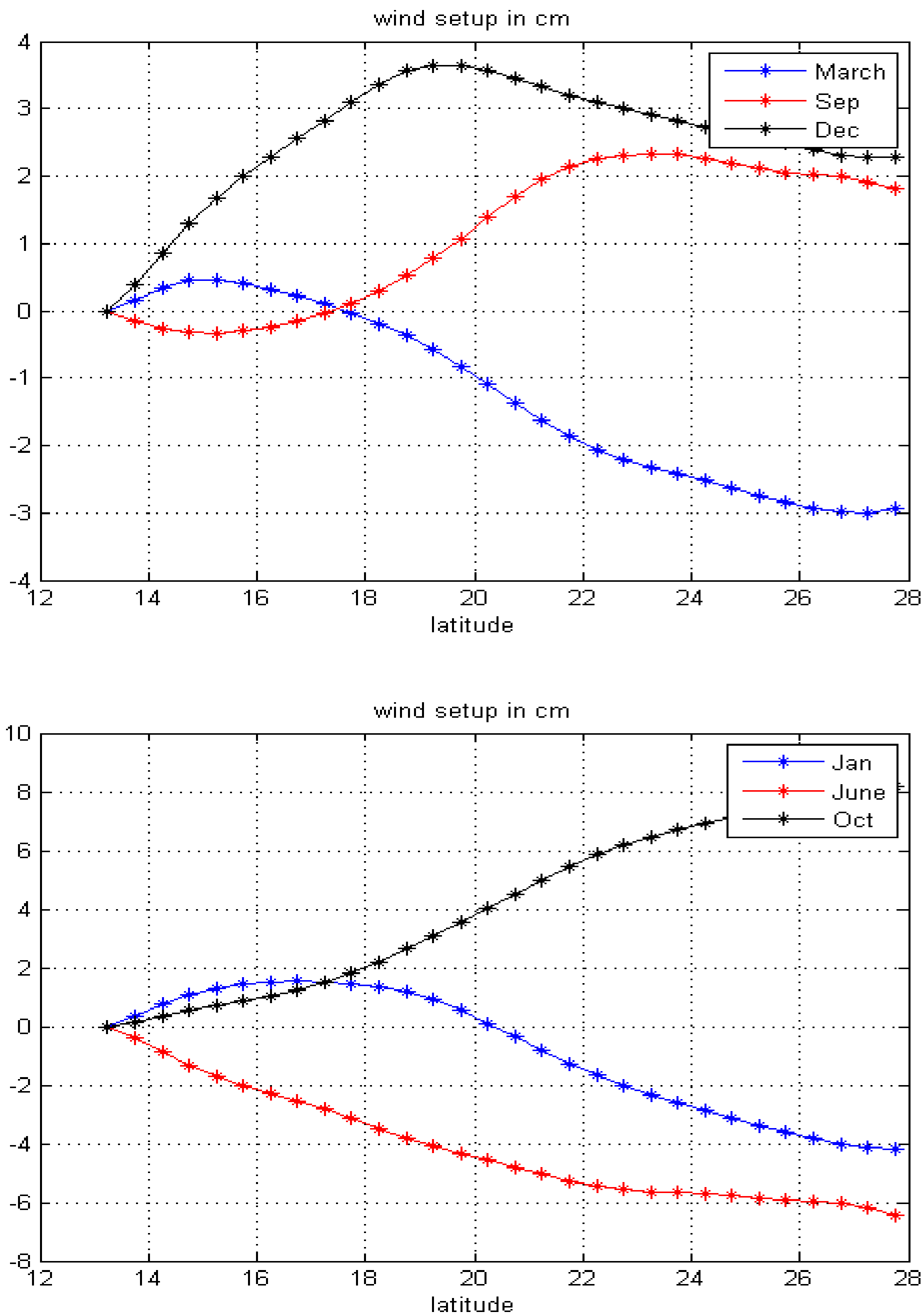


Figure 4.10: The wind setup anomalies for March, September and December (upper panel), and January, June and October (lower panel).

Figure 4.11 illustrates the seasonal anomaly difference of steric sea level along the Red Sea with reference to Hanish Sill, which represents the residual part of equation (10). The steric variation anomaly has a strong semi-annual cycle in the north. While in the central and southern basin, the annual cycle is appears the dominant one. It has a negative value during early and late winter along the entire basin, except during January and February it has a positive value in the Northern part. The negative anomaly indicates that the steric variation in any point along the Red Sea is less than Hanish Sill, and vise versa for a positive one. In summer season the anomaly is positive with maximum in the central basin of about 5 cm during July month. While in early and late winter, -4 cm during October and -5 cm during April respectively located in the northern part.

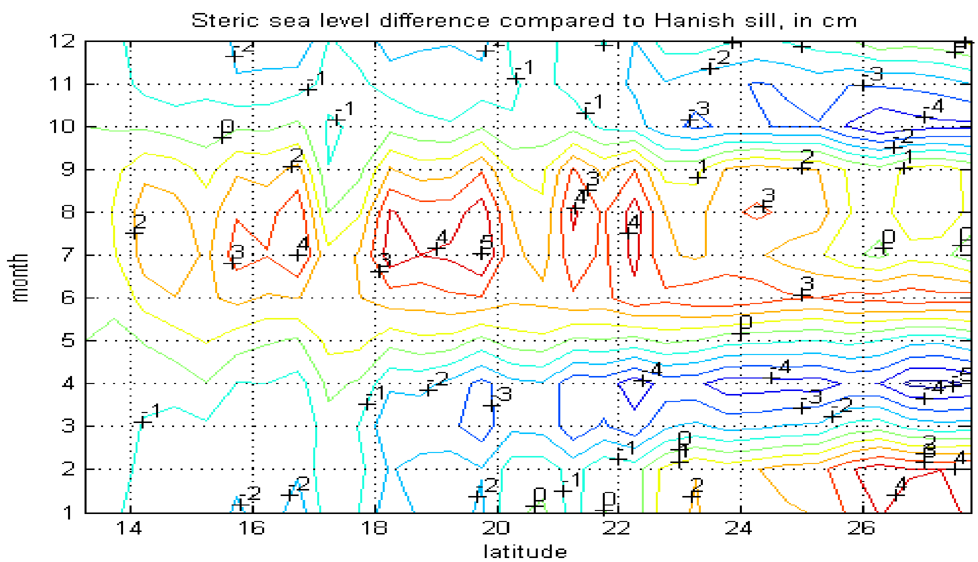


Figure 4.11: Seasonal anomaly difference of steric sea level with reference to Hanish Sill, in cm.

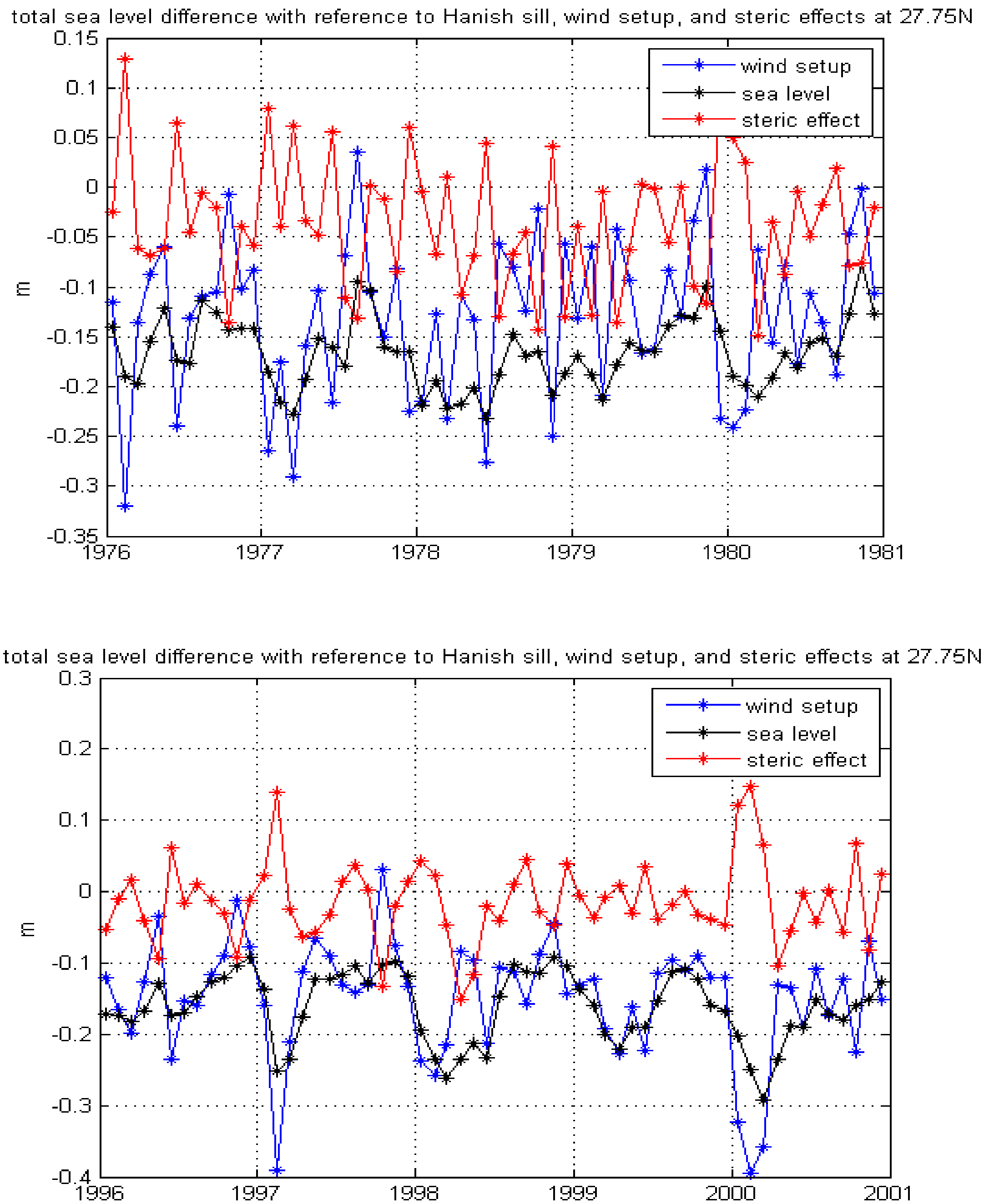


Figure 4.12: Total sea level difference with reference to Hanish Sill, wind setup, and steric effects at 27.75ºN, from 1976 – 1980 (upper panel), and from 1996 – 2000 (lower panel).

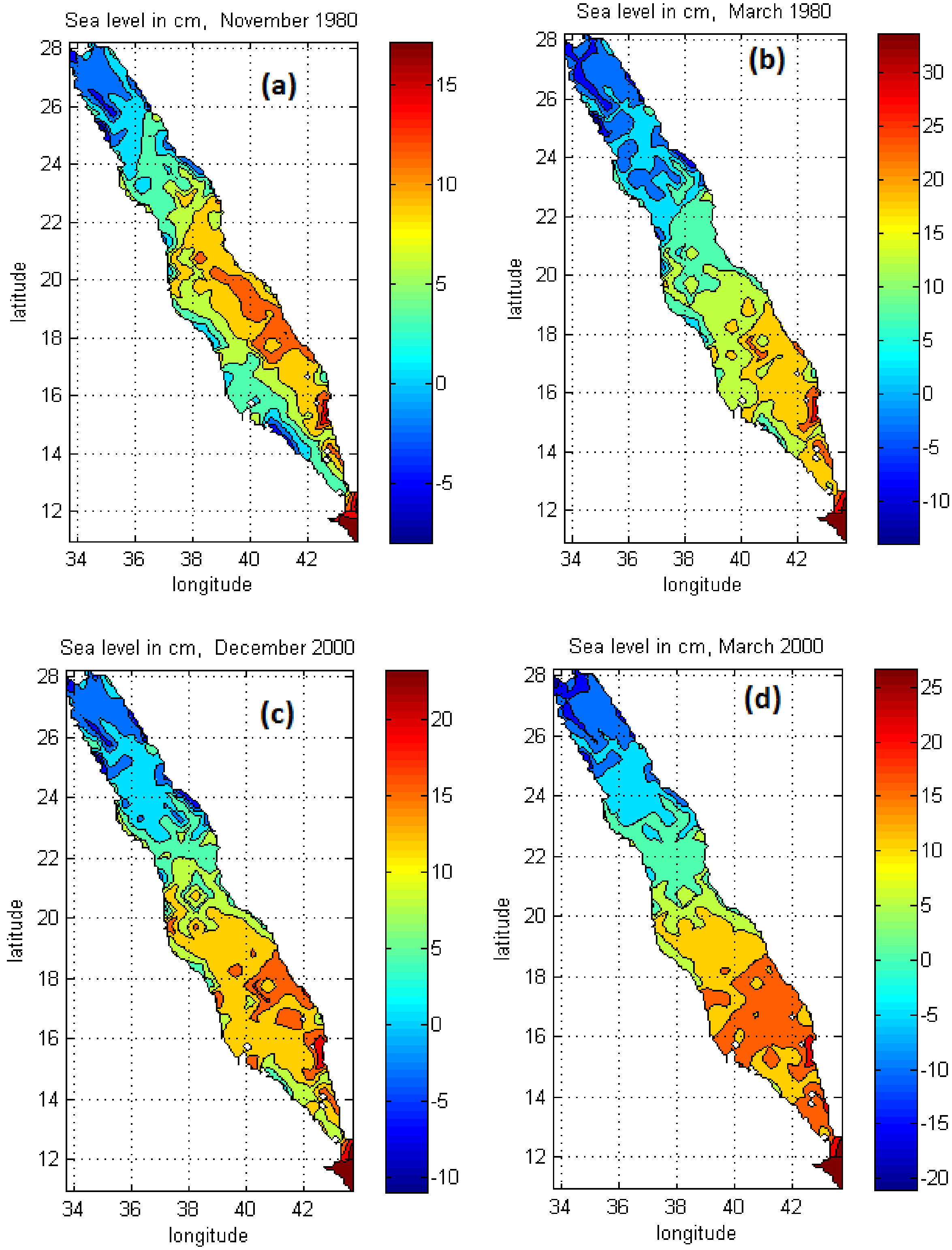


Figure 4.13: Sea level along the Red Sea plotted by using local fitt function, (a) and (b) are November and March1980, (c) and (d) are December and March 2000 respectively.

In Figure 4.12 we represent time series of total sea level difference to Hanish Sill, wind setup, and steric effects at 27.75ºN. This figure show that the steric effect is resulting from direct difference between the sea level and wind. As example the value of steric effect during February 1976 (upper panel) is approximately equal to 0.13 m, which is represent the direct difference between the sea level and wind setup, -0.19 and -0.32 m respectively during the same month. In this calculation the steric effect is represent a residual part of Equation (10). The sea level has an annual variations, reaching it is minimum difference to Hanish Sill during the early winter, and it is maximum difference during the late winter, mostly during February and March. Figure 4.13,a,c illustrate this feature where the November and December month in 1980 and 2000 are represent the minimum difference, while Figure 4.13,b,d are represent the Maximum difference during March 1980, and 2000. The sea level has a maximum difference when the wind setup is strong, and from the north, where the reverse is true.

On the other hand, the feature of maximum difference of sea level is shifted to May instead of February and March for 6 years, from 2002 to the last of data 2007; see Figure 4.14, and also this period was recorded relatively high wind setup during May and August Months. Figure 4.15 illustrate more clearly the shift of maximum difference of sea level, when we compare (a) with (b) which represent the sea level of February and March for 2002, we see that the sea level is increases in the entrance of the Red Sea at Hanish Sill, and decreases in the end of the basin around 27.75ºN during May. And also this feature are found during 2005 in the same periods and locations, see Figure 4.15 (c) and (d).

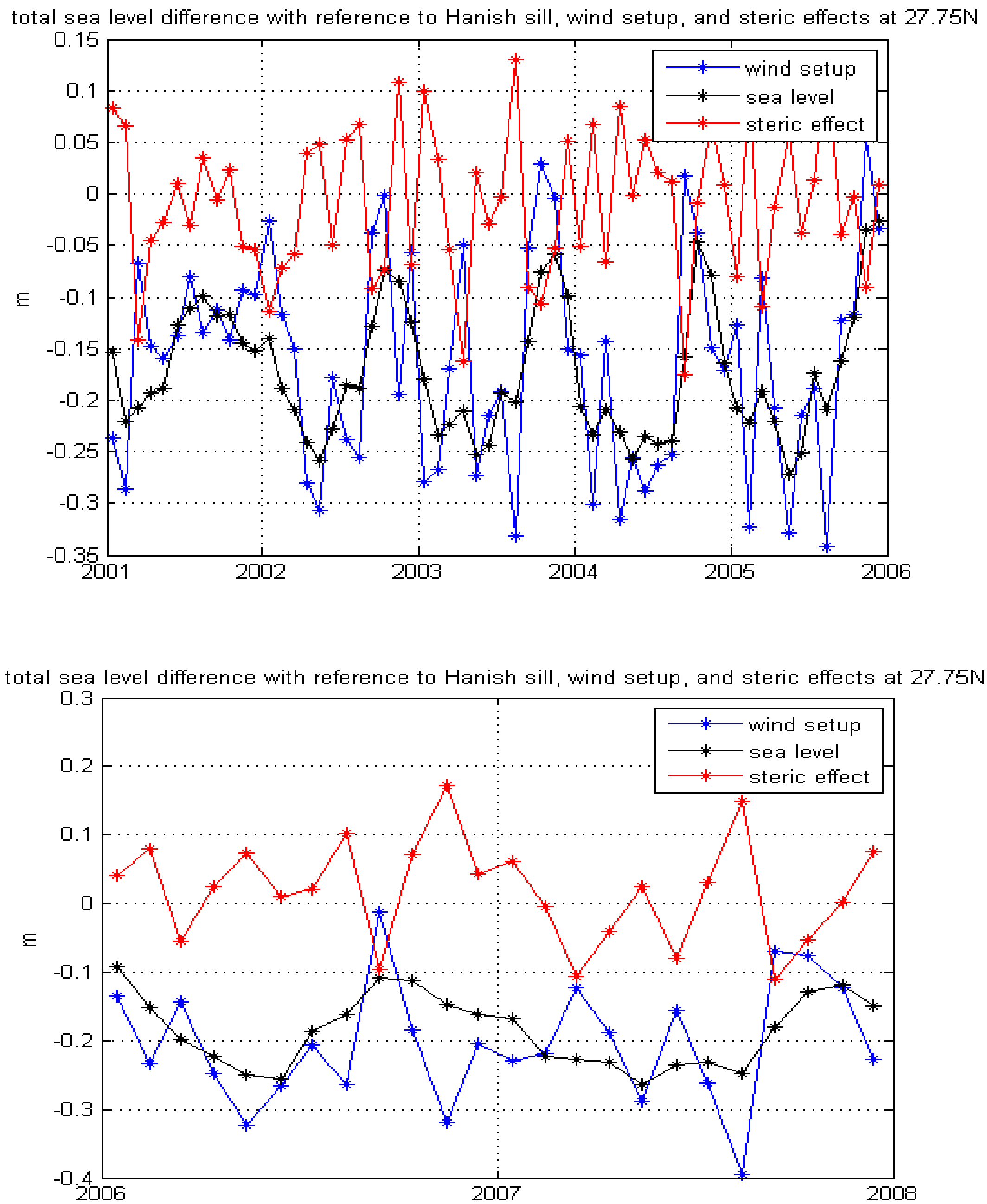


Figure 4.14: Total sea level difference with reference to Hanish Sill, wind setup, and steric effects at 27.75ºN, from 2001 – 2005 (upper panel), and from 2006 – 2007 (lower panel).

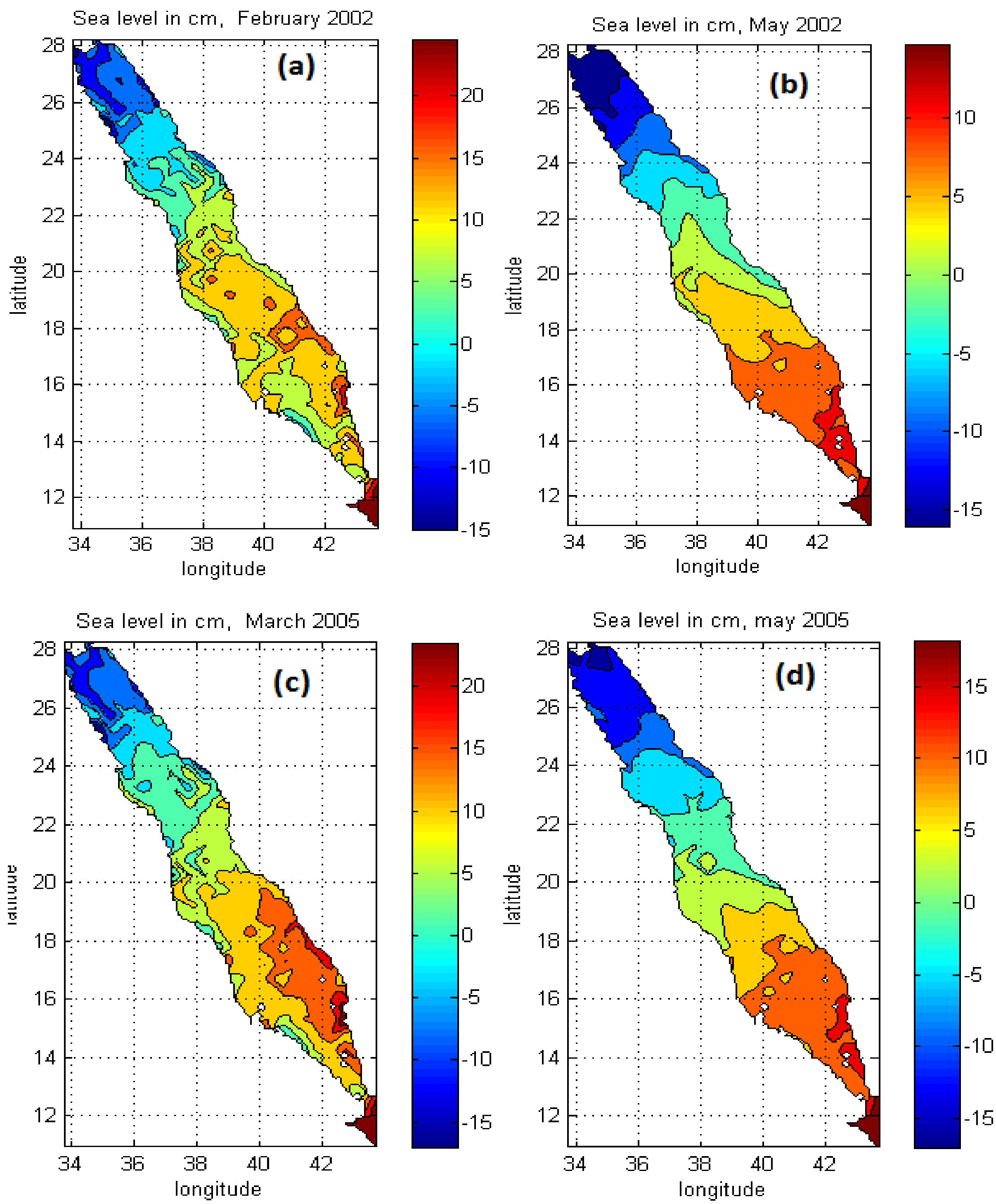


Figure 4.15: Sea level along the Red Sea plotted by using local fitt function, (a) and (b) are February and May 2002, (c) and (d) are March and May 2005 respectively.

5 Discussions

5.1 Sea Level

In this thesis, the sea level data were correlated with wind stress in the Red Sea to investigate the effects of the wind stress on sea level fluctuations. Figures 4.2 and 4.6 show a weak correlation during all seasons in the northern and central basin, respectively. But the late winter in the center yields a negative correlation of about -o.66 (see Figure 4.4 (mid panel)). The wind stress during this period is from the north, thus strong and northern wind stress decreases the sea level in the central Red Sea. As Patzert (1974) mentions, the sea level in the Red Sea is mainly affected by two factors during summer season, north-northwest wind stress, and the decrease of the Arabian Sea during summer season due to the Southwest monsoon, which creates sea level slope from the northern Red Sea until the Arabian Sea (see Figure 1.3). Then it is clearly that the wind is not control the sea level during summer directly, but the outflow water during summer due to the sink of Arabian Sea may the major factor in this period.

Another indication of weakness contributions of wind stress on the sea level variations were made by Sofianos and Johns (2003), who clarify the three dimensional circulations of the Red Sea by MICOM Model. They found that the general circulations are governed mainly by thermohaline effect, and the effect of wind stress is very weak. This appears clearly by comparing Figure 2.4 with Figure 2.5, the cyclonic gyre is appeared in the thermohaline one, where it is dominant feature in the combined forces experiment in the northern basin, while the wind stress experiment is anticyclonic circulation in that location.

The seasonal anomaly difference of sea level with reference to the Hanish Sill is revealing the annual cycle only (Figure 4.7). This result confirms with previous study which found that the sea level has the annual variations (Abdallah and Eid 1989; Sultan et al. 1996; Abdelrahman 1997; Sultan and Elghribi 2003).

Figure 4.8 shows that the mean sea level profile in the Red Sea has slope with a strong gradient from the south to the north, 0.13 to – 0.04 m, respectively, it highest in all winter months than summer. This result agrees with previous study

(Morcos 1970; Patzert 1974; Osman 1984; Osman 1985; Edwards 1987; Sultan et al. 1995; Sultan et al. 1996; Sofianos and Johns 2001; Sultan and Elghribi 2003; Manasrah et al. 2009). That is due to the inflow of Gulf of Aden surface water (SW) into the Red Sea during winter season (Cromwell and Smeed 1998), with 0.38 sv volume flux (Souvermezoglou et al. 1989), reaching the maximum especially during February and March months. The outflow of surface and deep Red Sea water into Gulf of Aden during summer season reaches the maximum during August month. Another thing is a bulge in the center basin with the maximum value of about 0.16 m between 17-18ºN. That is because the wind is converge in this area, and it is induced the sea level from both side when it reverses the direction during winter monsoon. Also this Figure reveals difference in the mean sea level value and the result of Figure 2.1 which made by Manasrah et al. (2009). My result is lower than Figure 2.1 of over 15 cm in the north and over 10 cm in the south. This may be due to the old version of (SODA1.2) data which Manasrah et al. (2009) used.

5.2 Wind Stress

Figures 4.1 and 4.5 of 5 years mean of sea level response to the wind stress in the northern and southern basins, respectively, which illustrate that the wind stress in the north is much greater than the south. The reverse has been observed by Patzert (1974) and Sultan et al. (1996). Where the wind stress in the south is stronger than the north during winter, especially during November and December where the wind stress between 12º-15ºN is 1.4 dynescm^{-1} (0.014 Pa) and 0.2 dynescm^{-1} (0.002 Pa) for the area between 20º-25ºN (Patzert 1974). Figure 4.9 of seasonal anomaly difference of wind setup to the Hanish Sill reflects a strong semi-annual variation. The previous study not found the mechanisms of this variation, but it is probably due to reversal of wind direction in the southern Red Sea.

The periods 00F and 00S in all seasons and locations have recorded some changes in their behavior. The wind stress increases concurrently with the decrease in the sea level, see Figures 4.1 to 4.6, and sometimes these periods change their directions totally, as in the southern basin during summer season (lower panel).

5.3 Steric Variation

Figure 4.11 illustrates the steric sea level effect which represents the residual part of equation (10). It clarifies the semi-annual cycle, which is the dominant feature in the northern Red Sea. While in the central and southern basin, the annual cycle appears dominantly. In summer season, the steric effect has a positive value, that mean it is higher than the Hanish Sill, which is totally corresponded with (Eid and Kamel, 2004), who found that the steric effect is rising, mainly due to the higher temperature that lowered the density. In contrast, the steric effect in northern and central is lower than the Hanish Sill during winter season, that is because a strong winter inflow of relatively warm and less saline water through the strait of Bab-el Mandab, which rise the steric effect in the south. Another reason is to existence of low temperature in the north, which increased the density and decreased the steric effect (Eid and Kamel, 2004).

An unexpected result was found in the northern part during the late winter, where about 4 cm was recorded in 26ºN. It is very difficult to explain this result, because as I mentioned above, the steric effect is produced as a residual term in the equation (10).

6. Conclusions and Recommendations

Long term sea level variations in the Red Sea were studied by using wind stress field from 1957 to 2007. Many calculations were used to investigate the effect of wind stress on the sea level. The correlation analysis yields a weak relation and indicates that the wind stress is not the main factor that controls the sea level in the Red Sea during all seasons, but it contributes on it. The effect of wind stress appears only in the central basin during the late winter. It tends to decrease the sea level, because it has a negative correlation of about -0.66. Therefore, other parameters may influence the sea level rather than the local wind stress. The sea level during 00F (2001-2005) and 00S (2006-2007) seems to decrease, concurrent with increased of wind stress. Exactly in the northern and central basin, more studies about this behavior are recommended.

The mean sea level profile along the Red sea showed a strong gradient between the south and north of about 13 to -0.04 cm, respectively, with the bulge in the central basin of 16 cm. The seasonal anomaly difference of sea level with Hanish Sill clarify a strong annual cycle, with maximum of 5 cm during August and September, and minimum of -5 cm during February and March in the central basin. When the same method was applied for wind stress, the semi-annual cycle were seen the dominant one, with maximum during April and October, 2 and 8 cm respectively, and minimum during February and June -6 cm for both.

In addition to wind stress, the steric effect has a semi-annual cycle, but they seen to be opposite with each other, except during the crest and trough of sea level, they are build up. Exceptional result of steric effect were recorded in the northern Red Sea during January and February of about 4 cm, thus a complete view of temperature, salinity and density within the water column were needed to investigate the real effect of steric variation in the sea level.

References

Abdallah, A. and F. Eid (1989). "On the steric sea level in the Red Sea." Int. Hydrograph. Review, Monaco **66**(1): 115-124.

Abdelrahman, S. M. (1997). "Seasonal fluctuations of mean sea level at Gizan, Red Sea." Journal of coastal research **13**(4): 1166-1172.

Barlow, E. (1934). "Currents of the Red Sea and part of the Indian ocean north of Australia." Marine Observer **110**: 150-154.

Boisvert, W. W. (1966). "Ocean currents in the Arabian Sea and northeast Indian Ocean." Naval Oceanographic Office **Sp-92**: 12 charts.

Carton, J. A. and B. S. Giese (2008). "A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA)." Monthly Weather Review **136**(8): 2999-3017.

Cromwell, D. and D. Smeed (1998). "Altimetric observations of sea level cycles near the strait of Bab al-Mandab." International Journal of Remote Sensing **19**(8): 1561-1578.

Cui, M., H. V. O. N. Storch and E. Zorita (1995). "Coastal sea level and the large-scale climate state A downscaling exercise for the Japanese Islands." Tellus A **47**(1): 132-144.

Degens, E. T. and D. A. Ross (1969). "Hot brines and recent heavy metal deposits in the Red Sea." New York, Springer.

Edwards, F. (1987). "Climate and oceanography." Red Sea, Pergamon Press, Oxford: 45-69.

Eid, F. and M. KAMEL (2004). "Contribution of Water Density to Sea Level Fluctuations in Red Sea." Marine Scienes **15**(1): 113-138.

Honjo, S. and R. A. Weller (1997). "Monsoon winds and carbon cycles in the Arabian Sea." Oceanus -Woods Hole Mass **40**: 24-28.

KNMI (1949). Red Sea and Gulf of Aden oceanographic and meteorological data publication, Koninklijk Nederlands Meteorologisch Instituut. **129:** 26.

Manasrah, R., H. Hasanean and S. Al-Rousan (2009). "Spatial and seasonal variations of sea level in the Red Sea, 1958–2001." Ocean Science Journal **44**(3): 145-159.

Margins, C. (1983). "306 D A. ROSS." Estuaries and enclosed seas **26**: 305.

Morcos, S. A. (1970). "Physical and chemical oceanography of the Red Sea." Oceanography and Marine Biology: an annual review **8**: 73-202.

Osman, M. (1984). " Variation of sea level at Port-Sudan." Int Hydrogr Rev Monaco **61**: 137-144.

Osman, M. M. (1985). " Seasonal and secular variations of sea level at Port-Sudan." J. Fac. of Mar. Sci **4**: 15-25.

Patzert, W. C. (1974). "Wind-induced reversal in Red Sea circulation." Deep Sea Research **21**: 109-121.

Pickard, G. L. and W. J. Emery (1990). Descriptive Physical Oceanography, An Introduction, Pergamon Press.

Smeed, D. A. (2004). "Exchange through the Bab el-Mandab." Deep Sea Research Part II: Topical Studies in Oceanography **51**(4): 455-474.

Sofianos, S. S. and W. E. Johns (2001). "Wind induced sea level variability in the Red Sea." Geophys. Res. Lett **28**(16): 3175-3178.

Sofianos, S. S. and W. E. Johns (2002). "An Oceanic General Circulation Model (OGCM) investigation of the Red Sea circulation, 1. Exchange between the Red Sea and the Indian Ocean." Journal of geophysical research **107**(C11): 3196.

Sofianos, S. S. and W. E. Johns (2003). "An oceanic general circulation model (OGCM) investigation of the Red Sea circulation: 2. Three-dimensional circulation in the Red Sea." J. Geophys. Res **108**(C3): 3066.

Souvermezoglou, E., N. Metzl and A. Poisson (1989). "Red Sea budgets of salinity, nutrients and carbon calculated in the Strait of Bab-El-Mandab during the summer and winter seasons." Journal of Marine Research **47**(2): 441-456.

Sultan, S., F. Ahmad and A. El-Hassan (1995). "Seasonal variations of the sea level in the central part of the Red Sea." Estuarine, Coastal and Shelf Science **40**(1): 1-8.

Sultan, S., F. Ahmad and D. Nassar (1996). "Relative contribution of external sources of mean sea-level variations at Port Sudan, Red Sea." Estuarine, Coastal and Shelf Science **42**(1): 19-30.

Sultan, S. and N. Elghribi (2003). "Sea level changes in the central part of the Red Sea." Indian journal of marine sciences **32**(2): 114-122.

Tragou, E., C. Garrett, R. Outerbridge and C. Gilman (1999). "The heat and freshwater budgets of the Red Sea." Journal of physical oceanography **29**(10): 2504-2522.
Werner, F. and K. Lange (1975). A bathymetric survey of the sill area between the Red Sea and the Gulf of Aden. Geologisches Jahrbuch D 13, 125-130.