Estimating Sea Level Change at the Egyptian Coasts Using Different Data Sources

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Abstract : The sea level has been rising over the past century, and the rate increased in recent decades. In urban areas along coastlines around the world, rising seas threaten infrastructure necessary for regional industries. There are two main reasons for sea level rising; glaciers and ice sheets are melting and adding water to the ocean and the volume of the ocean is expanding as the water warms. The main objective of this research is to determine the sea level change in the Mediterranean Sea and the Red Sea by using different data sources (tide gauge, Altimetry, and GRACE satellite data) for the period 2010-2015. The results show that the estimations obtained from satellite altimetry and tide gauges measurements have a better agreement.

Keywords
Tide Gauge, Satellite Altimetry, GRACE, Vertical Land Movement, Sea Level Change

I. Introduction

The Sea Level Change (SLC) is extracted from tide gauge data that referenced to the benchmark fixed coastal land. SLC can also be determined from satellite altimetry data reference to ellipsoid with reference to the earth's mass center in terrestrial references frame (Guo, J.Y., et al., 2016). In order to know how much of the increase in sea level is due to actual mass transfer, -the water movement from land to ocean- scientists depends on a multiple of direct measurements like; melt rate and glacier elevation made during field surveys, and satellite based measurements of tiny shifts in earth's gravity field. The increase in mass increases the strength of gravity, when water shifts from land to ocean, Scientists estimate the amount of added water based on these gravity shifts, (Merrifield M.A. et al., 2014, Pelto M.S. 2015). As global temperature gets warmer warm, sea level continues to rise. How much it will rise depends mostly on the rate of future carbon dioxide emissions and future global warming. The rising speed depends mostly on the rate of glacier and ice sheet melting. Sea level alteration has a non-uniform behavior around the world, it is discovered that some regional sea level variations are larger or smaller than the average global value, this is duo to climate variability and local environments (Douglas B.C. , 2001 , Peltier W.R. , 2004, Miller L. and Douglas B.C., 2004). During the twentieth century the rate of sea level rise had an average of 1.5-2.5 mm/year (IPCC., 2013, IOC, 2006). In 2012, as a request of the US Climate Change Science Program, NOAA scientists conducted a review of the research on global sea level rise projections, and conclude that there is a very high possibility that global mean sea level will rise at least 0.2 m but no more than 2.0 m by 2100 (Climate.gov , 2009).

In Egypt (Nassar M. et al., 2003) estimated that the sea level increased by 12 cm from 1906 to 1980, which means a rate of approximately 1.5 mm per year, and (Sharaf el Din S. et al., 1989) showed that the rate of sea level rise is 1.6 mm per year at Alexandria in the period from 1958 to 1988. Other studies stated that the sea level rising rate will be higher than it is now because of the global warming that causes thermal expansion of water input from the melting of continental ice sheets and land basins.

Tide gauge and satellite missions are the main techniques used to measure sea level variations. Tide gauge has been used to monitor sea level changes with reference to the TG land for the last two centuries with low spatial and high temporal resolution (Barnett T.P., 1984). Since 1993 with the appearance of satellite altimetry, it has been commonly used to monitor the absolute sea level changes with a suitable accuracy and high spatial and temporal resolution. The tide gauge will provide the absolute coastal sea level changes when the vertical land movements are precisely observed. The absolute sea level changes contain the steric and mass components. The steric sea level variations are produced by the temperature and salinity changes, and the mass sea level variations are resulting from fresh water input and output, which could be measured by the Gravity Recovery and Climate Experiment (GRACE) mission launched in August 2002 (Tapley B.D., et al. , 2004). Many factors affect the GRACE results; the first one is GRACE instruments noise and measurements errors, the second one is the errors from the atmosphere and ocean models, the third one is noises and correlated errors in the GRACE harmonic coefficients, and the fourth one is due mainly to the low resolution and land –ocean linkage effects (Swenson S.C. and Wahr J., 2006).

The main objective of this study is to estimate the sea level change (SLC) at the Egyptian coasts using different data sources. Accordingly, two study areas were chosen, the first along the northern Egyptian Coasts (Mediterranean Sea) and the second along eastern Egyptian Coasts (Red Sea). SLC are measured and analysed from (tide gauge, satellite altimetry, and GRACE) data sources, for the period 2010-2015.

II. Data Used

Generally, there are two main types of sea level observations that measure, the first is the direct measurements such as tide gauge and satellite mission; while, the second one is the indirect

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measurements as ocean temperature and ocean salinity measurements. Herein, three different data sources of sea level change are used (a) tide gauge measurements which in a few cases go back over 100 years, and satellite measurements, which are available only over two decades and consists of (b) satellite altimetry data and (c) GRACE data.

A. Tide gauge and vertical land movement data

For the Egyptian coasts, there is only one tide station on each coast (Alex station on the coast of Mediterranean Sea and Safaga station on the Red Sea Coast) as shown in Figure 1 provided from Survey Research Institute (SRI) in Egypt covering the time span from 2010 to 2015 in the form of average monthly observations.

Figure 1: Tide gauge stations along the Egyptian coasts

The vertical land movement and global isotactic adjustment (GIA) values at Alex and Safaga stations were obtained from time series GPS data of the station from this website (http://www.station-gps.cea.com.eg/Anglais/cadre_anglais.htm) over the same period of tide gauge data.

B. Satellite altimetry data

The altimetry observations from Jason-2 satellite altimeter (Level-2) were in the form of Geophysical Data Record (GDR) downloaded from the Archive, Validation and Interpretation of Satellite Oceanographic (AVISO) and can be obtained from the website (http:// www.aviso.oceanobs.com / en / news / ocean - indicators / mean - sea level / processing - corrections / index . html). It contains full accuracy altimeter data and sea surface height (SSH), with a high precision orbit (accuracy 1.5 cm), provided approximately 35 days after data collection. The instruments on Jason-2 make direct observations of the following quantities: altimeter range, significant wave height, ocean radar backscatter cross-section (a measure of wind speed), ionospheric electron content, tropospheric water content, mean sea surface, and position relative to the GPS satellite constellation with azimuth/range resolution: 11.2 km x 5.1 km. This data were downloaded so that they cover the same time span of the available tide gauge time series data.

C. GRACE data

The set of data provided by the GRACE project comprised of monthly sets of spherical harmonic geoid coefficients up to degree and order 60 for the time span starting in January 2009 and ending in December 2013. These coefficients, are derived from raw tracking measurements (GRACE consists of a pair of satellites whose mutual distance, absolute positions and velocities are continuously monitored), are computed by the Center for Space Research (CSR).

The Level-2 Release-05 (RL05) gravity coefficients computed at the Center for Space Research (CSR) were used to estimate global water mass variations with a spatial resolution of 1°×1°.

III. Methodology

Three different data sources of sea level observations are collected and processed in order to define a corrected sea level. In the next stage the sea level change and the trend of the study duration (2010 – 2015) are computed. Figure 2 shows the methodology used in this research.

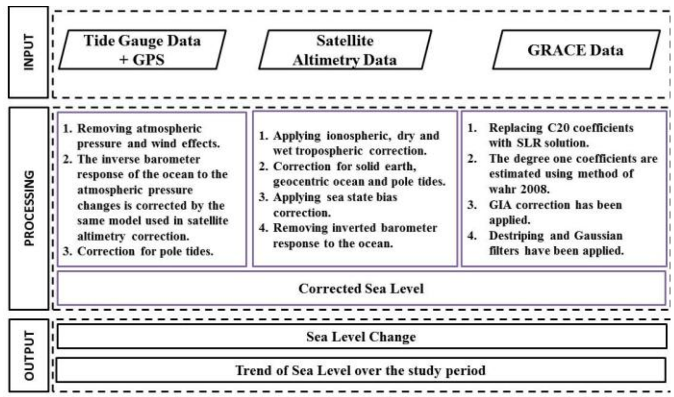

Figure 2: Research Methodology Flow Chart

A. Tide Gauge Measurements

Tide gauge measurements have been processed; the atmospherically-induced sea level caused by the action of atmospheric pressure and wind was removed from the tide gauge records. The same dynamic atmospheric correction as for altimetry was applied for the sake of consistency (Marcos M. et al., 2014). Also, the TG time series are corrected for pole tides (J. Wahr et al. , 1998) and for the inverse barometer response of the ocean to the atmospheric pressure changes (Carrere L., and Lyard F., 2003) by the same model used in satellite altimetry correction. Corrections for ocean and solid Earth tides are not applied due to the use of the monthly average records. After applying the above corrections on the sea level obtained from tide gauge observations the corrected sea level (SL) can be determined, then the annual sea level change over a specific period can be calculated by subtracting the corrected sea level of previous year from the next year

$$SLC_{TG} = Sl_{next\ year} - Sl_{previous\ year} \quad (1)$$

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The tide gauge (TG) at the coast areas determine a relative sea level change respecting to the coast benchmark (Woodworth P. L. and R. Player , 2003), So Vertical Land Movement (VLM) should be observed and added to get absolute sea level change which is regarded by the GPS at or near TG stations (Guiping Feng et al., 2012) . Also, the effect of the glacial isostatic adjustment (GIA) on the vertical land movement is corrected.

$$SLC_{abs\,TG} = SLC + VLM - GIA \tag{2}$$

The relative trend of sea level change ($T_{rl\ TG}$) was computed using liner regression model

$$T_{rl\,TG} = a * Sl + b \tag{3}$$

Equation (3) is repeated six times (the period of study) resulting in six equations in three unknowns solved by least squares method to obtain the trend of sea level change over the study period. Finally, the absolute trend of sea level change Tabs was calculated by adding vertical land movement rate (T_{VLM}) to the relative trend.

$$T_{abs\,TG} = T_{rl} + T_{VLM} \tag{4}$$

B. Satellite Altimetry Measurements

Altimeters on-board satellites practically determine the instantaneous height of the sea surface (h) from a reference ellipsoid by knowing the satellite height (h^*) and measuring the range (R) between the satellite and the sea surface. The observation equation for the altimetric measurements can be written as (Ducet, N. et al):

$$h - \Delta h = h^* - R_{corr} \tag{5}$$

where

$$\Delta h = T_S + T_G + T_p + IB$$

$$R_{corr} = R + \Delta R_{wet} + \Delta R_{dry} + \Delta R_{ion} + \Delta R_{ssb}$$

where

T_S, T_G, T_p and IB are solid earth tide, geocentric tide, pole tide and the inverse barometric effects, respectively.

$\Delta R_{wet}, \Delta R_{dry}, \Delta R_{ion}$ *and* ΔR_{ssb} are the wet, dry tropospheric correction, ionospheric correction and sea state bias, respectively.

The necessary geophysical and atmospheric corrections are applied to the data set, such as ionospheric delay, dry and wet tropospheric corrections, solid Earth corrections, geocentric ocean tide loading corrections, pole tide corrections, sea state bias corrections, and the Inverted Barometer (IB) response of the ocean.

After determining the corrected Sea Surface Height (SSH), the sea level change was computed by subtracting the SSH of the year from the previous one as

$$SLC_{alt} = SSH_{next\ year} - SSH_{previous\ year} \tag{6}$$

Then the rate of sea level change Talt was determined by using linear regression model

$$T_{alt} = a * SSH + b \tag{7}$$

By applying the least squares method, the trend of sea level change over the study period can be calculated.

C. GRACE Measurements

The degree 2 order 0 (C20) coefficients are replaced by Satellite Laser Ranging (SLR) solutions (Cheng M. and Tapley B., 2004); the degree 1 coefficients (C11, S11, and C10) are used from (Swenson S. et al., 2008); in order to minimize the effect of measurement and correlated errors, we use the 300 km width of Gaussian filter and de-striping filter (Swenson S.C. and Wahr J., 2006). The postglacial rebound signals in the data have been removed according to the GIA model of (Paulson A. et al., 2007). In order to compare the altimetric results, we have to add back the GAD coefficients to the GRACE GSM coefficients (Flechtner F. , 2007) and remove the time-variable mass of the atmosphere averaged over the global ocean (Willis, J.K. et al. 2008). Finally, we can calculate the mass-induced sea level changes with the gravity coefficients anomalies (Chambers D. P., 2006) as:

$$\Delta h(\varphi,\lambda) = a\frac{\rho_{ave}}{3\rho_w}\sum_{l=o}^{\infty}\sum_{n=0}^{l}\frac{2l+1}{1+k_l} \times W_n\, p_{lm}(\cos\varphi) \times [\Delta C_{lm}\cos(m\lambda) + \Delta S_{lm}\sin(m\lambda)] \tag{8}$$

where ρ_{ave} is the average density of the Earth (5517kg m^{-3}), ρ_w is the density of fresh water (1000 kg m^{-3}), a is the mean equatorial radius of the Earth, W_n is a Gaussian smoothing operator, P_{lm} are the fully-normalized Associated Legendre Polynomials of degree n and order m, φ is the geographic latitude, λ is the longitude, , and ΔC , ΔS are the Stockes Coefficients.

Sea level change can be obtained from GRACE by computing the sea level anomaly as:

$$SLC_{GRACE} = \Delta h_{next\ year} - \Delta h_{previous\ year} \tag{9}$$

After calculating the sea level anomaly Δh , the trend of sea level change over the time period was determined by linear regression model as follow:

$$T_{GRACE} = a * \Delta h + b \tag{10}$$

By applying the least squares method, the trend of sea level change over the study period can be calculated.

IV Results and Discussion

The monthly time series of sea level measurements from the satellite altimetry, 2 tide gauge stations and GRACE are used to estimate the sea level change along the Mediterranean Sea and Red Sea coast for the monitored six years (2010 – 2015). Then the trends of sea level at Alex and Safaga stations were computed using equations 3, 7 and 10 from Tide Gauge, Altimetry and GRACE Sea Level data respectively. In these equations there are three unknowns (T (the required trend), a and b (equation parameters)) and one known parameter (SL (sea level value at each year), these equations were solved for six years which give six equations in three unknowns using least squares solution.

A. Sea Level Change of Mediterranean Sea

Firstly, the sea level variation time series are calculated to the Mediterranean Sea using the available data.

1) Tide Gauge Results at Alex station

The sea level change (Table 1) was calculated from the average of monthly observations at Alex station.

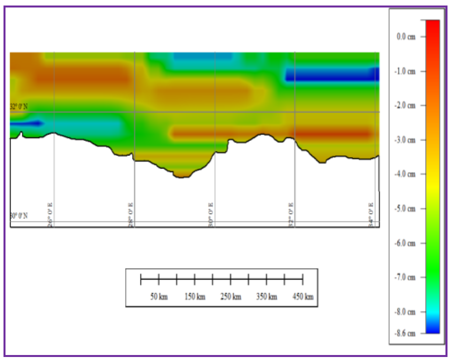
Table 1: Sea Level Change from Tide Gauge Data at Alex Station Corrected from Vertical Land Movement

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Change (mm)	-12.07±12.3	13.37±12.3	-5±12.3	2.83±12.3	-5.06±12.3

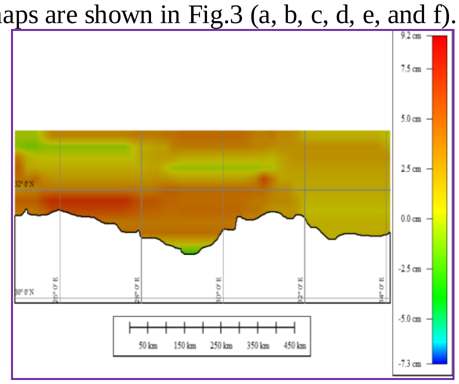
In Table 1, it is shown that the sea level of the Mediterranean Sea at Alex is oscillating between falling and rising year after year.

2) Altimetry Results

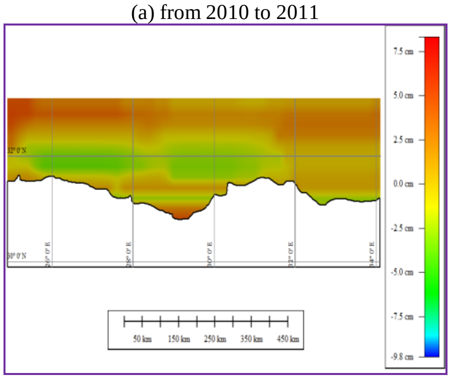
The sea level change maps were produced for time span from 2010 to 2015 as single years and for all period as whole. These maps are shown in Fig.3 (a, b, c, d, e, and f).



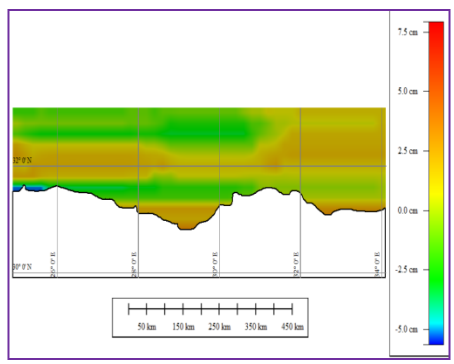
(a) from 2010 to 2011



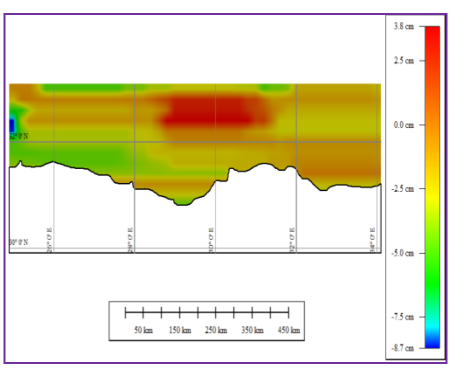
(b) from 2011 to 2012



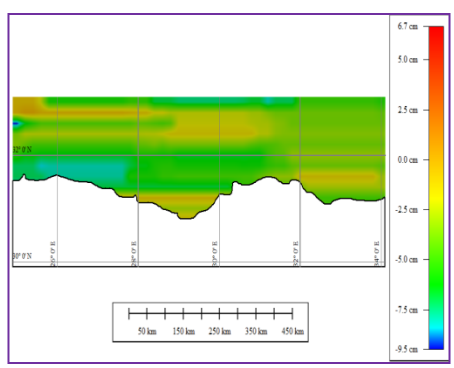
(c) from 2012 to 2013



(d) from 2013 to 2014



(e) from 2014 to 2015



(f) from 2010 to 2015

Figure 3: Map of Sea Level Change by Satellite Altimetry

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Figure 3 (a, b, c, d, e, and f) show the map of sea level change from 2010 to 2015. Figure 3a represents the results for year 2010 to 2011 in which the values of changes ranges between 0 and -8.6 cm where most of the area coloured in red that signify the values from 0 to -1 cm. In Figure 3b, the values of sea level change ranges from -7.3 to 9.2 cm along the coast of Mediterranean Sea where the values decrease from East to West in the period from 2011 to 2012. In year 2012 to 2013 (Figure 3c), the sea level rises in all the shown maps with small amount close to zero cm coloured in yellow to red.

Similarly, to figure 3c; figure 3d values of the sea level change ranges from zero to about 2.5 cm for the major of the map except in the east for areas coloured in blue the sea level falls to about 5 cm. In figure 3e, the sea level falls in the duration from 2014 to 2015 for areas coloured in green and blue, while it rises for others. Figure 3f shows the resultant change in the time span from 2010 to 2015 where the sea level change ranges from -9.5 (coloured in blue) to 6.7 cm, where the major of the map coloured in green except in the upper west area the sea level rise towards the orange colour, and the lower west area coloured in blue to represent lower sea level. The sea level change from altimetry maps at Alex station were obtained in (Table 2).

Table 2: Sea Level Change from Altimetry Data at Alex Station

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Change(mm)	-37.00 ± 22.9	41.00± 22.9	-26.00± 22.9	24.00± 22.9	-11.00± 22.9

The sea level at Alex is oscillating between falling and rising year after year, the same behavior from the results of the tide gauge data.

3) GRACE Results

GRACE data used to determine sea level change at Alex station from the density mass variation (Non-steric sea level change) for the same periods as tide gauge data and Altimetry data in (Table 3).

Table 3. Sea Level Change at Alex Station from GRACE from 2010 to 2015

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Change (mm)	6.83±11.3	-7.48±11.3	14.35±11.3	1.95±11.3	2.65±11.3

The sea level change showed in (Table 3) at Alex station along the Mediterranean Sea and the values proved that the sea level rises in all periods of study except the time span from 2011 to 2012.

The results of altimetry were compared to tide gauge results as shown in table 4, while table 5 represents the comparison between GRACE and tide gauge respectively.

Table 4. Differences between Sea Level Change from Altimetry and Tide Gauge at Alex Station

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	Min.	Max.	Mean
Absolute Difference (mm)	24.93	27.63	21.00	21.17	5.94	5.94	27.36	20.13

Table 5. Absolute Differences between Sea Level Change at Alex Station from GRACE and Tide Gauge

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	Min.	Max.	Mean
Absolute Difference (mm)	19.08	20.85	19.35	0.88	7.71	0.88	20.85	13.57

It can be observed that the mean difference of Altimetry and tide gauge was 20.13 mm the mean difference with respect to GRACE was 13.57 mm. Figure (4) shows the sea level change at Alex station from altimeter, tide gauge, and GRACE, respectively for 2010 to 2015.

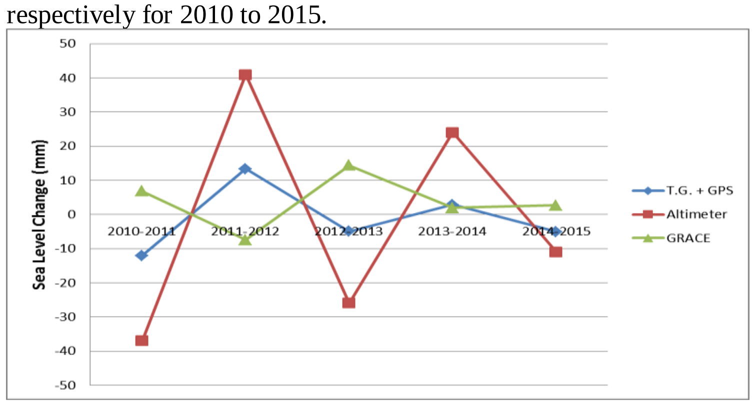


Figure 4. Sea Level Change at Alex Station from Altimetry, Tide Gauge, and GRACE from 2010 to 2015

B. Red Sea

1) Tide Gauge Results at SAFAGA station

At Safaga station, the computed sea level change (Table 6) was not corrected for vertical land movement due to lack of time series data.

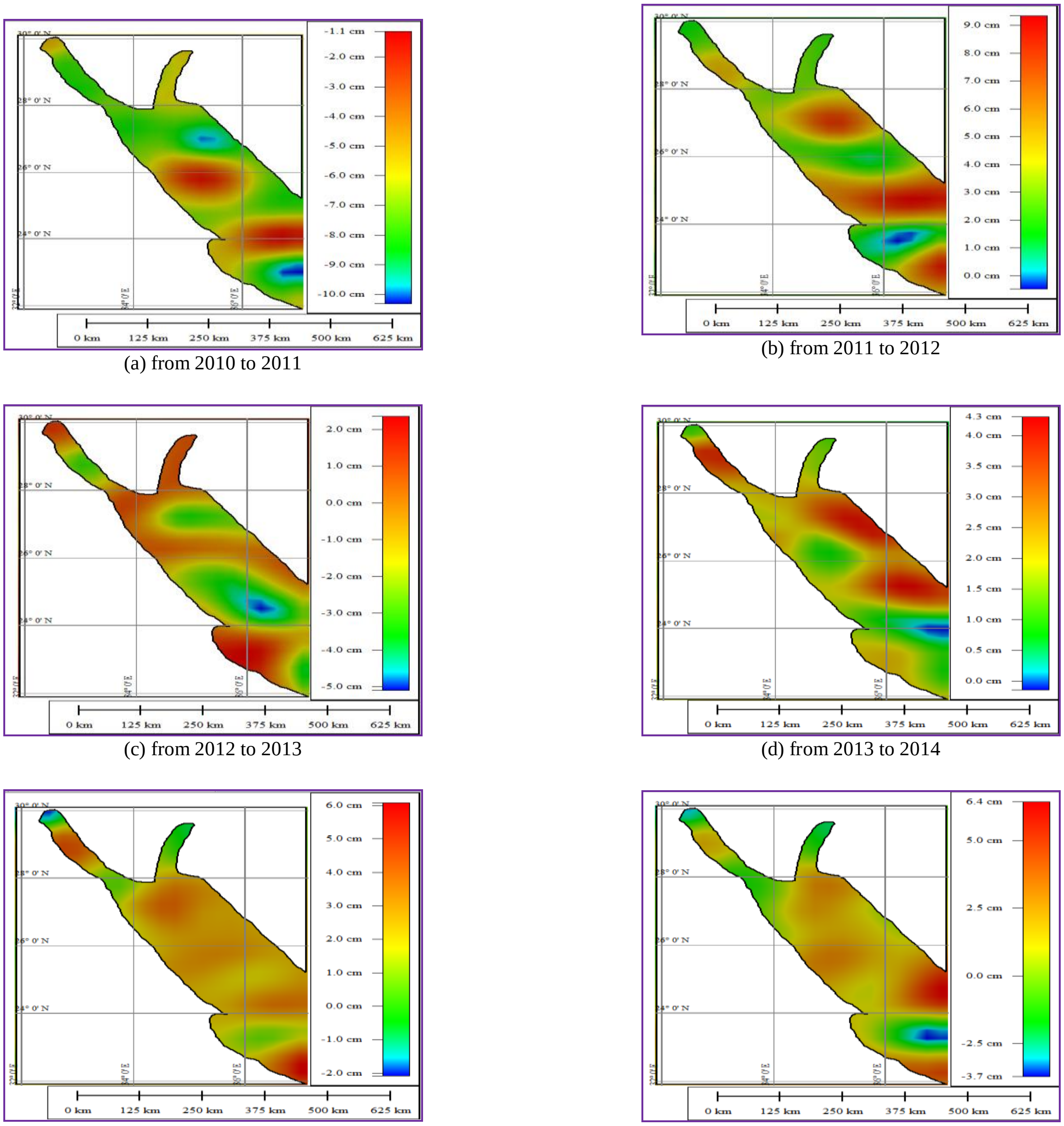
Table 6. Sea Level Change from Tide Gauge Data at SAFAGA Stations with Vertical Land Movement

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Change (mm)	8.17±15.9	9.2±15.9	4.95±15.9	5.34±15.9	0.47±15.9

The sea level of the Red Sea increases (Table 6) for all one year time periods from 2010 to 2015 and for the full period as well but it should be noted that these values are not corrected for vertical land movement.

2) Altimetry Results

The sea level change along Red Sea was mapped from 2010 to 2015 as shown in figure (5).



(a) from 2010 to 2011

(b) from 2011 to 2012

(c) from 2012 to 2013

(d) from 2013 to 2014

(e) from 2014 to 2015

(f) from 2010 to 2015

Figure 5. Sea Level Change from Altimetry along the Red Sea Coasts

Figure 5a represents year 2010 to 2011, the level change ranges between -1 to -10 cm which indicates that the sea level falls in this year. Figure 5b shows the change from 2011 to 2012 in which the sea level rises from 0 to 9 cm while most of areas along the coast are colored in green with average change of about 3 cm. From 2012 to 2013 (Figure 5c), the sea level rises with maximum value 2 cm and it continues to rise from 2013 to 2014 (Figure 5d), where the values ranges from 0 to 4.3, where the western coast of the red sea represent in green colour. From 2014 to 2015 (Figure 5e), the values ranges from -2.0 to 6.0 and do so for the full period from 2010 to 2015 (Figure 5f) that represent the sea level rise in the most of the map area. At Safaga station the sea level variation was deduced from sea level change maps (Table 7).

Table 7. Sea Level Change from Altimetry Data at Safaga Station

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Change(mm)	-74.7 ±38.8	32.1 ±38.8	2.1 ±38.8	24.8 ±38.8	6.1 ±38.8

The sea level is rising at Safaga station for all periods except from 2010 to 2011.

3) GRACE Results

The sea level variation computed at Safaga station from GRACE harmonic coefficients data (Table 8). GRACE computations declared that the sea level at Safaga rises in some periods (e.g. 2010-2011, 2012-2013 and 2014-2015) and falls in others (e.g. 2011-2012 and 2013-2014) while, it rises for the whole period from 2010 to 2015.

Table 8. Sea Level Change at Safaga Station from GRACE from 2010 to 2015

Period	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Change(mm)	12.1±7.8	-7.4±7.8	8.4±7.8	-3.5±7.8	4.1±7.8

The altimetry results cannot be correctly validated at Safaga station due to the anonymity of the vertical land movement at the study period. The previous values of sea level change from GRACE were validated (Table 9) using the tide gauge values at Safaga station resulting in a mean difference 7.3 mm.

Table 9. Absolute Differences between Sea Level Change at Safaga Station from GRACE and Tide Gauge

Period	2010 - 2011	2011 - 2012	2012 - 2013	2013 - 2014	2014 - 2015	Min.	Max.	Mean
Absolute Difference (mm)	4.07	16.6	3.49	8.87	3.64	3.49	16.6	7.3

Figure (6) shows the sea level change at Safaga station from altimeter, tide gauge, and GRACE, respectively for 2010 to 2015. It can be observed that the mean difference of tide gauge is close to GRACE results than Altimeter.

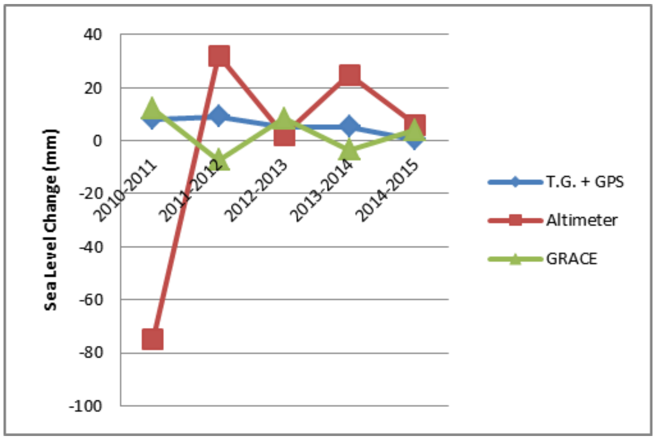


Figure 6. Sea Level Change at Safaga Station from Altimetry, Tide Gauge, and GRACE from 2010 to 2015

C. Trend of Sea Level Rise

Secondly, the results of tide gauge, altimetry and GRACE data processing along Mediterranean Sea at Alex station shows that the sea level rises with an average rate of 1.05 mm/yr for tide gauge and 1.30 mm/yr for altimetry while it is 3.70 mm/yr for GRACE data. Also, Safaga tide gauge station data processing showed that the level of the red sea rises with a rate of 5.8 mm/year, where altimetry and GRACE results declared that the red sea level does so with rates 3.8 mm/year and 2.00 mm/year respectively.

V. Conclusion

This research focused on the determination of the sea level change along the Egyptian coasts at two stations along Mediterranean Sea (Alex station) and Red Sea (Safaga station) using the tide gauge, Jason-2 altimetry and GRACE data sets. The tide gauge average monthly observations were available from 2010 to 2015 and the same time interval was considered in downloading Jason-2 altimetry geophysical data records and GRACE monthly spherical harmonic coefficients data.

For the annual changes of sea level, the TG+GPS, satellite altimetry and GRACE results showed that the sea level rises along Mediterranean Sea and The Red Sea with an average rate of 1.05 mm/yr for tide gauge and 1.30 mm/yr from altimetry while it is 3.70 mm/yr from GRACE data at Alex station and 5.8 mm/yr from tide gauge observation, 3.8 mm/yr from altimetry and 2 mm/yr from GRACE at Safaga station. When the vertical velocities from the GPS observations are added into TG results, the estimations obtained from satellite altimetry and tide gauges measurements have a better agreement. The mean difference between tide gauge results and altimetry results is 20.13 mm while GRACE satellite data represent an effective tool for detecting sea level change from density mass variations as the mean difference between its results and Tide Gauge results is 13.57 mm at Alex station.

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