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Gravity Observation and Crustal Deformation at Cairo Region and its Geodynamical Implications

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Abstract: Seismic activities in and around Cairo region suggest interested geodynamic behavior of this region due to the existence of local seismo-active tectonics from one side. On the other side, its location indicates the effect of the regional tectonic between the African plate and both the Eurasian and Arabian plates on it. Thus, Crustal deformation study was carried out in Cairo region after the October 12, 1992 earthquake that occurred at Dahshour region 35 km southwest the center of Cairo with a magnitude of 5.9. The main objective of this study was to delineate the crustal stress and strain field in Cairo region using GPS measurements. The calculated deformation analysis shows accumulated stress and strain covered the south and southeast of the area under investigation. Thus, it was important to determine subsurface structures attributed to the stress-strain accumulation and its relation to the earthquake occurrence. Therefore, spatial gravity map of the selected region deduced from satellite altimeter data was figured out. The gravity indicated important mass discontinuities zones which were well correlated with the seismological and deformation activities. The complete figure of the gravity map indicated that the tectonic settings of Cairo region obey the regional tectonic between the African plate and both the Eurasian and Arabian plates. The Gravity Recovery and Climates Experiment (GRACE) have been monitoring time-varying changes of the earth's gravitational field on a near global scale since 2002. Thus, data from GRACE has been used to determine the regional trends of the gravity variation along Cairo region. Locations of the anomalous gravity region shown to be comparable with locations of active crustal deformation deduced for GPS observations and seismological studies. This might be due to the restraining and releasing of stress in those areas. The final compiled output from the gravity, geodetic and seismic analysis will focus on the geodynamical regime of the seismo-active region and it is an attempt to delineate the crustal stress and strain fields.

Key words: Cairo · GPS · Satellite Altimeter and Gravity

INTRODUCTION

In Egypt, earthquake activities have been observed in various regions. The north-eastern part of Egypt with the capital Cairo plays an important role in both historical and recent seismicity. This area has an interesting tectonic features, as it is dominated by the relative movements of major plates (Africa, Arabia and Eurasia) and a relatively aseismic small plates from one side. On the other side, most destructive earthquakes occurred at Cairo are located on the southeastern part and attributed with two local active faults. Thus, Cairo is affected by both regional and local tectonic settings [1]. Significant crustal deformation obtained from GPS observation suggest the importance of the determination of any spatial or temporal mass variations attributed with its neo-tectonics. On the Other hand, repeated seismic activity suggests significant mass redistribution attributed with its neo-tectonics. The main outcome of the tectonic and seismological studies of Cairo is that it is affected by both regional and local tectonics. Therefore, revealing the tectonic effects of Cairo and its relation to the seismicity is of great interest [2].

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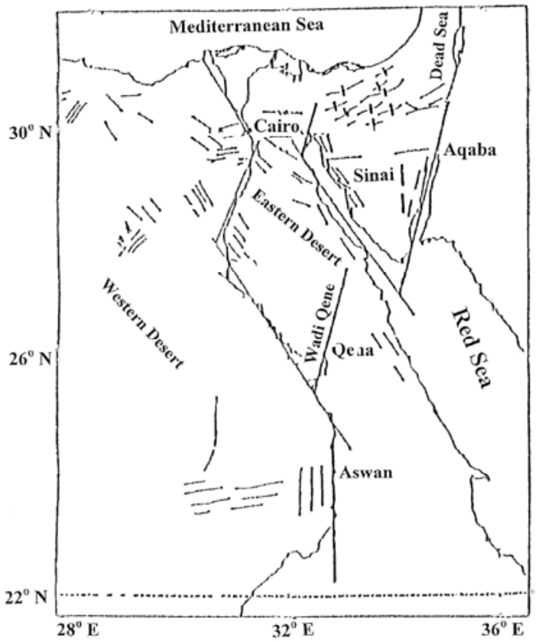

Fig. 1: The main tectonics and structural pattern of Egypt (Youssef, 1986) [2].

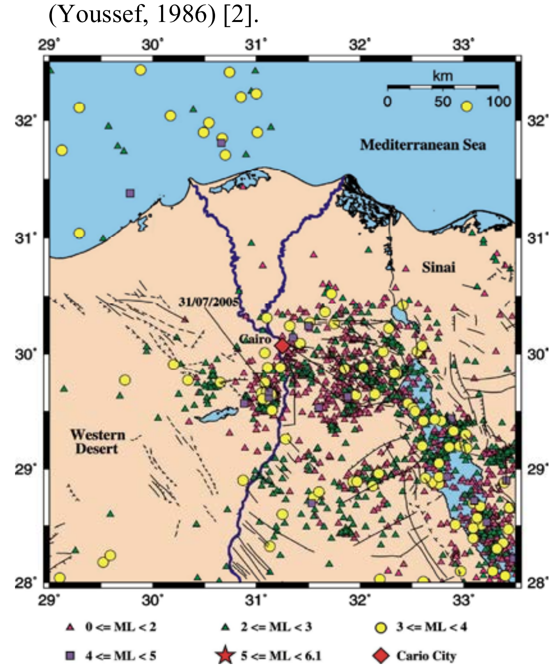

Fig. 2: Seismicity in and around Cairo.

Tectonics and seismological studies of Cairo indicate that, it is an ideal test-bed for the development of hypotheses for fundamental tectonic processes. Thus, linking modern observations to the neo-tectonics of this region with its previous tectonic evolution would provide a more complete picture of the evolution of the orogen.

Tectonic Settings and Seismicity of Cairo: Egypt is located in the northeastern part of Africa and extends beyond the Gulf of Suez and the Suez Canal into Asia. The tectonic evolution of Egypt is characterized by a number of stages since Precambrian. According to Said [3], Youssef [4] and Smith [5], Egypt is classified into three major geological provinces. The greater part of northern Egypt belongs to the unstable shelf which lies between foreland and geosynclines (Figure 1). Most of the area was covered by the principal marine transgressions at least since Paleozoic time. Cairo is located at the northeastern part of Egypt and belongs to this province. The main types of macrostructures in this province are monoclines and faults. Moustafa *et al*. [6] concluded that, the main structural features controlling the study area are the faults. Most of these faults have a Post Eocene age of deformation. The major faults that affect the study area have the N-W, E-W and N-E directions. The N-W trending faults are the most predominant ones. Analysis of these faults indicates that the main stress regime is the tensile stress, [7]. These tensile stresses are created from right lateral divergent strike slip movement on a deep seated of faults. All solutions in Cairo region showed normal faulting mechanism with a strike-slip component. Tectonically, Cairo is dominated by the relative movements of major plates (Africa, Arabia and Eurasia) and relatively aseismic small plates.

Egypt has long history in reporting earthquake activity; information on historical earthquakes is documented in the annals of ancient Egyptian history and Arabic literature. About 83 events were reported to have occurred in and around Egypt which have caused damage of variable degrees in different localities [6, 7]. Among them 12 events were reported to have caused significant damage in the today densely populated area of the north of Egypt [8].

The general distribution of earthquakes epicenters (historical and recent) in Egypt falls along three major trends [9], (Figure 2). The first major trend extends from the northern Red Sea area and along the Gulf of Suez, through the cities of Cairo and Alexandria. The activity along this trend has increased in recent years and is attributed to Red Sea rifting as well as several active faults [11]. The second trend extends from the eastern Mediterranean to East of the Nile Delta to Cairo and Fayum region. The first trend intersects the second one in the Cairo city [9]. Within this intersection the moderate earthquake of October 12, 1992 (Mb=5.9) occurred. Along the third trend (Dead Sea-Aqaba trend), the seismic activity is large (Fig. 2). This is may be related to the active sinistral movement along the Dead Sea Fault system and the Gulf of Aqaba [11, 12]. The Cairo region has been the focus of intense geological and geophysical investigations since the occurrence of the 12th October 1992 earthquake (Mb=5.9). The shallow earthquake occurred on 12th October 1992, was felt in much of Egypt from Alexandria to Aswan causing widespread damage and was reported in the Mediterranean-Cairo-Fayum belt. Its magnitude was 5.9. This earthquake occurred at about 25 km south-west of Cairo City, Dahshour area. Many aftershocks followed the main shock. The focal mechanisms of earthquakes located on the west bank of the Nile represent reverse faulting mechanism with strike-slip component, while normal faulting occurs in the eastern bank.

Method: The main objective of this study was to delineate the crustal stress and strain field in Cairo region, which has been done using GPS measurements. However, it was important to determine subsurface structures attributed to the stress-strain accumulation and its relation to the earthquake occurrence. Therefore, spatial gravity map of the selected region deduced from satellite altimeter data was figured out. The Gravity Recovery and Climates Experiment (GRACE) have been monitoring time-varying changes of the earth's gravitational field on a near global scale since 2002. Thus, data from GRACE has been used to determine the regional trends of the gravity variation along Cairo region.

Crustal Deformation of Cairo Region Deduced from GPS: Monitoring recent crustal movements has become one of the major and important tasks facing geodesists, since it has vital consequences for human safety and economic achievements. Different methodologies and techniques have been developed for monitoring crustal deformation where the focal mechanisms solutions for the analyzed seismological data and analyses of GPS data were combined and integrated to throw lights upon the geodynamic regime of the study area. The Global positioning system (GPS) considers as one of the most applicable tools for monitoring crustal deformation along the plate boundaries of regional and local scale. The interested tectonic settings of Cairo have met the successful development of GPS as a recent crustal deformation monitoring tool. The main objective is to study neo-tectonic features by combining previous tectonic studies and GPS crustal deformation. This also enables the determination of the evaluation of active tectonics of the selected region [2].

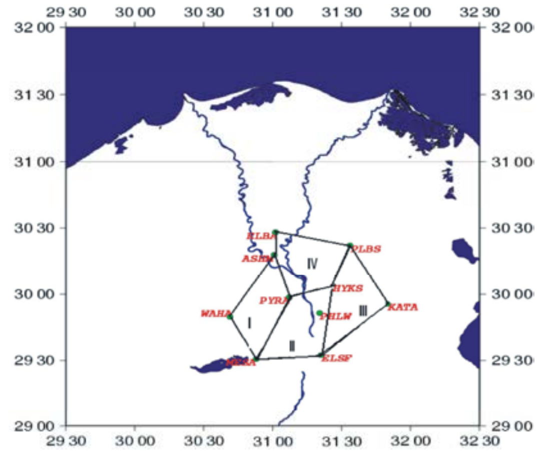

Fig. 3: Four blocks of Greater Cairo geodetic network.

GPS Data Observation: GPS Network consists of 10 geodetic benchmarks was established in 2004 in and around Cairo region (Fig. 3). The Nile River runs in the middle of this network and the northern part of the GPS network covers the southern part of Nile Delta, whereas its eastern and western parts are deserts. The initial measurements were carried out in May 2005 and were repeated successively till September 2009. Observation time for the whole campaigns was carried out 24 hours for a period of 3 days at all stations including the Permanent Helwan station to facilitate the combination of the data with some of the surrounding IGS sites. The data were processed using Bernese 5.0. [14], with the constrained condition used for such analyses to produce precise coordinates and associated covariance matrix of station position for each station. Combined solution of coordinates and velocity vectors at each site has been obtained to the ITRF2005 reference frame. The horizontal component of the velocity vectors with 95% confidence error ellipses. The horizontal components of these velocity vectors are further used to estimate the strain field.

Marine Gravity from Satellite Altimeter: The availability of altimeter data from satellite observations, such as data collected by the European Space Agency ERS-1, 2 and data from the US Navy Geosat, have opened new perspectives in the Earth sciences. One of the most important applications of these data is that they provide scientists with an unprecedented view of the Earth's interior and its gravity field over the marine regions, Sandwell and McAdoo [15].

The surface of the marine region can be, with some limitations, considered as an equipotential surface of the gravity field, or the so-called geoid surface. The actual geoid surface deviates up to 100 m from the ideal ellipsoid. Deviations of geoid surface obey to a great extent the topography of the marine floor and reflect the tectonic settings and the subsurface structures. Small deviations in the geoid height, which take a form of tiny bumps and dips, can be measured using precise radar mounted on a satellite such as ERS-1 and Geosat. One of the main applications of collecting gravity data on land is the determination of the geoid height. However, in marine regions the observed geoid can be converted into gravity anomaly or the so-called satellite altimeter gravity. The advantages of this conversion are that it makes it possible to figure out the gravity field over marine regions. In addition, converted gravity anomalies from the precise geoid can enhance the determination of small-scale geological features.

In satellite altimetry, two precise distance measurements are needed to derive the geoid. First, the ellipsoid height is measured by tracking the satellite over globally distributed control stations. Second, the height of the satellite above the ocean surface is measured with a microwave radar altimeter. The difference between these two heights is simply the geoid undulation.

The geoid can be transformed into gravity anomaly by using inverse Stoke's formula or by taking the derivatives of the geoid using Laplace's equation [16].

Li and Goetze [17] give a simple relation between the gravity anomaly and the geoid undulation. Gravity anomaly Δg associated with geoid height N with a wavelength λ is given by

$$\Delta g = 2\pi\gamma\ N/\lambda \quad (1)$$

where γ = 980,000 mGal is the average gravity of the Earth. This equation indicates that the gravity anomaly of 10 mGal and a wavelength of 10 km is associated with geoid undulation of 16 mm. This shows the precision needed for the geoid determination in order to compute gravity anomalies useful for geophysical applications. Green *et al.* [18] show that satellite altimeter gravity has an accuracy of about 5 mGal and a resolution of about 20 km. Zahran and Saleh [19] evaluated gravity satellite altimeter to the tectonic of the Red Sea.

The location of Cairo region, as it is pounded by the Mediterranean Sea from the north and the Gulf of Suez from the east made it possible to determine the regional spatial gravity field on a basis of satellite altimeter data. The interest of such computations is to evaluate the tectonic setting of this region regarding to the mass discontinuities. In addition, it is of great interest to determine the plate margins form of the gravity anomaly. Finally, neo-tectonics of this region can be evaluated considering the amplitude of the gravity anomaly.

The satellite altimeter free air gravity anomaly in and around Cairo is given in Figure 7 as computed by Sandwell and Smith [19].

Temporal Gravity Variation from GRACE: The presented spatial gravity anomalies and its tectonic evidences, together with the GPS deduced crustal deformation in and around Cairo region suggests significant mass redistributions during the neo-tectonic activities. Moreover, distributions of seismic activities at the southern eastern part of Cairo indicate the continuous activities of these zones. Temporal gravity variation could deliver important information about the mass redistribution attributed to the seismological activities and can be considered as important integration of the geodynamic studies of this region.

Until recent, it was not possible to monitor on a regional scale. The Gravity Recovery and Climate Experiment (GRACE) satellite mission was launched in March 2002 to map the temporal variations in the Earth's global gravity field on a monthly basis, [21]. The variability in these gravity field solutions represents geophysical responses associated with redistribution of mass at or near the Earth's surface, where mass variations are likely to occur on the time scales examined by GRACE measurements. Generally, the largest time-variable gravity signals observable in GRACE data are expected to come from changes in the distribution of water and snow stored on land, [22]. However, Geodynamic processes such as changes in the Earth's topography or mass distribution as a result of lithosphere plate interactions (collision, subduction, rifting), postglacial rebound, mantle convection, earthquakes, sedimentation and erosion, should also contribute to temporal variations of the Earth gravity field. Mikhailov *et al*. [23] investigated whether temporal variations of the gravity field caused by tectonic processes can be recognized in GRACE satellites. They demonstrated that new satellite gravity data can be used to detect and discriminate geodynamic signals generated by subduction zone.

We used 71 monthly gravity field solutions (RL04 unconstrained solutions) for the Period 2003 to 2009 from the GRACE database provided by the Center of Space Research of the University of Texas. The gravity field solutions were processed as follows: (1) The temporal mean was removed; (2) Correlated errors were reduced by applying destriping methods developed by Swenson and Wahr [23], (3) Spherical harmonic coefficients were converted to grids (0.5° × 0.5°) of equivalent temporal gravity using a Gaussian smoothing function with a radius of 300 km.

RESULTS

GPS Results: Horizontal displacements rates as deduced from GPS are given on figure 4. The maximum observed displacement in the period from 2005 to 2009 is distinguished in the Southern part, especially the Southwestern of the study area, whereas the displacement rates at these stations are 16.9, 13.8 and 11.8 mm/ye, respectively while the minimum observed displacement was found at the rest of the study area. The direction of horizontal displacements trends mostly to the eastern and southern directions. This suggested that the local deformation at Cairo could have an interrelationship with the eastern regional deformation or it can be triggered under the effect of Gulf of Suez neo-tectonics.

The horizontal components of the displacement vectors were used to estimate the dilatations and maximum shear strains within the observation periods. The area under study has been divided into four blocks, Figure (2). The strain parameters for each block have been calculated to determine possible regional pattern for the horizontal deformation of the selected region. Moreover, this computation enable the determination of the horizontal deformation, whether compression or dilatation and locating the distribution of the maximum shear within the selected region.

The dilatation for the period from 2005 to 2009 was represented (Fig. 5). We can observe that all the study area is suffering from compression forces except block II which is suffering from extensional forces. The maximum compression force rate amounting-0.42 μs is found at block I, the Southwestern region, while the maximum extensional rate is 0.31 μs at block II, the Southeastern part.

Maximum Shear Strain For the period from 2005 to 2009 is shown in Fig. 6. The highest value, 0.44 μs, is found at the Southwestern zone especially at block I and also the lowest one, 0.1 μs, is found at the Northeastern zone especially at block III.

Obtained Horizontal Displacement Rates reflect to great extent the repeated seismological activities on the southern eastern part of Cairo. However, directions of the displacement rates follow the counter-clockwise movement of the movements of the eastern Mediterranean plate and the Arabian plate. On the other hand, dilatation rates and maximum shear strain show the anomalous behavior of the southern eastern part of Cairo from one hand. On the other hand, general pattern reflect the tectonic pattern of regional tectonic between the African plate and both the Eurasian and Arabian plates.

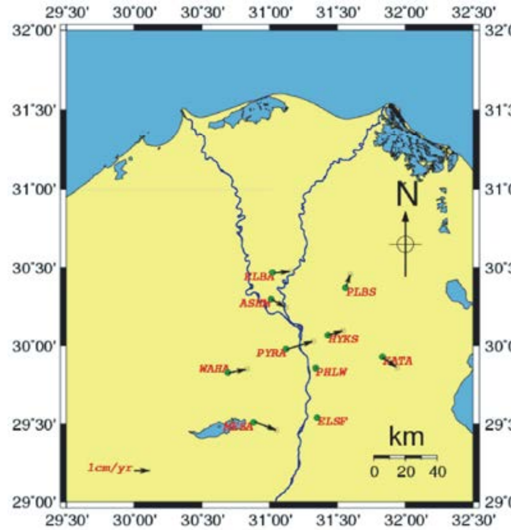

Fig. 4: The Horizontal Displacement Rates of the study area from 2005 to 2009.

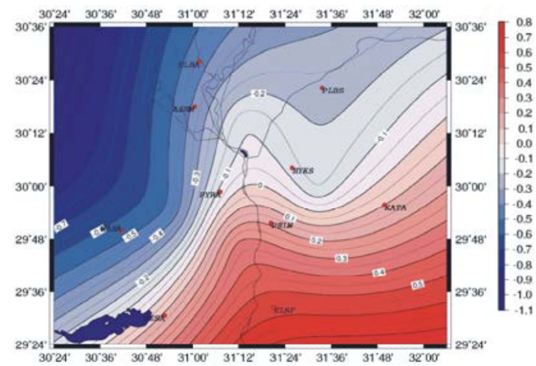

Fig. 5: Dilatation Rates of the study area from 2005 to 2009.

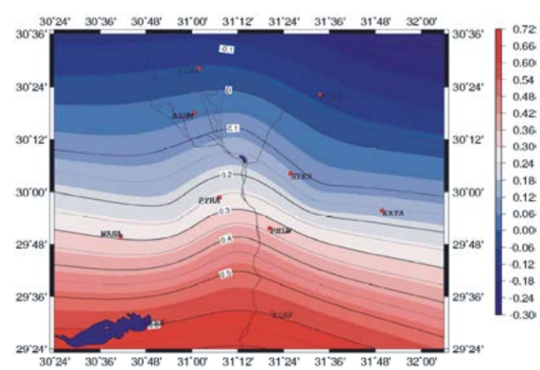

Fig. 6: Maximum Shear Strain Rates of the study area from 2005 to 2009.

Satellite Altimeter Gravity of Cairo: The gravity map figures out the regional tectonic settings around Cairo region clearly. Interpretation of the spatial gravity field variation can be done utilizing the tectonic map of the region, Figure 1, as follow:

- Three significant high positive gravity anomalies of the order of about 150 mGal pound Cairo from north, north east and eastern directions. These gravity zones represent African-Eurasian interaction on the north, relative movement of the eastern Mediterranean on the north east and the Arabian plate on the east. This indicates that, these regional tectonic settings play the main rule on the tectonic of Cairo.
- High negative anomaly on the order of-60 mGal can be seen along the Gulf of Suez eastern Cairo. This anomaly is parallel by positive anomaly located at the seismological and deformation active zone at the southern eastern part of Cairo. The whole gravity pattern at this region appears to be a right lateral thrust fault. This indicates that, activity of the Gulf of Suez plays an important rule on the recorded activity at the south eastern part.
- Northern Cairo is characterized by slight positive gravity anomaly increase northward under the effect of the northern Mediterranean tectonic settings.
- Central and western Cairo shows almost zero gravity anomalies reflecting the low reported seismicity on these areas.

Obtained horizontal displacement rates at the southern eastern part of Cairo and the counterclockwise rotation, as deduced from GPS, seen to be attributed with mass discontinuities and the amplitude of the gravity anomaly correlated well with the plate velocities obtained from GPS data analysis.

Temporal Gravity Variation of Cairo from GRACE: Figure 8 displays GRACE temporal gravity variation of Cairo region from 2004 to 2009. The figure includes earthquakes with magnitude more than 3. Remarkable pattern of temporal gravity variation has been indicated. This pattern shows high temporal gravity variation at the eastern part toward the Arabian plate and it goes down on the western direction reaching its minima at the western part of Cairo. The figure shows high correlation between the seismological activities and the temporal gravity variation. The significant temporal gravity variation indicates that the seismic activities attributed to

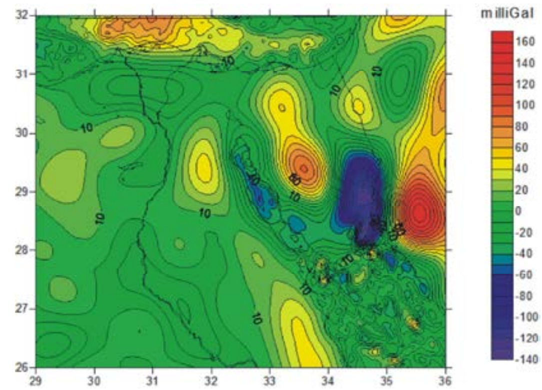

Fig.7: Satellite altimeter free air gravity map of Cairo region (after Sandwell and Smith) [19].

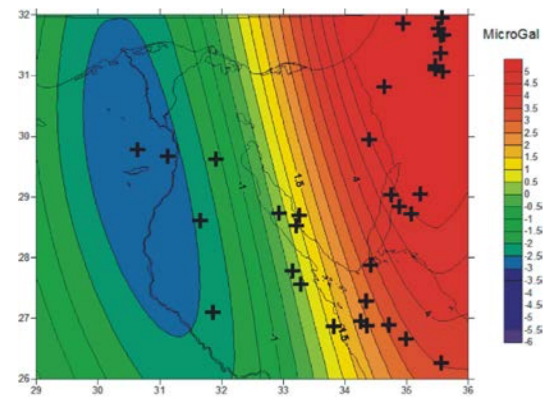

Fig. 8: GRACE temporal gravity variation of Cairo region from 2004 to 2009.

a significant mass redistribution around the seismo-active zones. Although, most of Cairo region located at a negative temporal gravity variation zone, the eastern seismically active zone is located at the zero level between the east and west. This indicates that, even the local seimic activity at the southern part of Cairo is triggered under the effect of the regional tectonic setting around Cairo especially from the Gulf of Suez at the East and slightly from the northern Mediterranean. In order to evaluate the neo-tectonics in and around Cairo in terms of the temporal gravity field variation, the mean annual values have been computed using GRACE data from 2004 to 2009 and are given in figure 9. Vectors have been added to the temporal gravity variation to delineate the direction of mass redistribution and to figure out plates and sub-plates margins in term of mass discontinuities. The figure shows significant annual temporal gravity variations and the gravity anomaly patterns figured out precisely the neo-tectonic deformation of the studied region. It reported again the north eastern part as a main source of mass redistribution around d Cairo. Vectors of

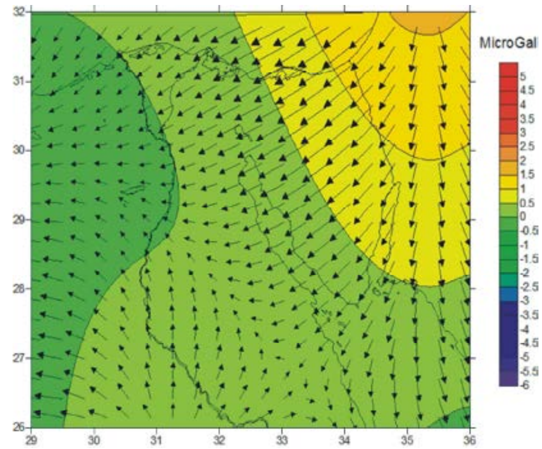

Fig. 9: GRACE annual temporal gravity Variation of Cairo region from 2004 to 2009.

the seismically active region at the southern eastern part of Cairo indicated beside its locality it is affected by the regional tectonic settings around Cairo.

DISSCUSSION

The location of Cairo region between the African plate and both the Eurasian and Arabian plates indicates interested regional tectonic settings accompanied by seimic activity from its north and east limits [3]. On the other hand, local seismic activity on the southern eastern part of Cairo region refers to continuous neo-tectonic [1]. Abdel-Monem *et al*. [2] suggest the seismological activities around Cairo are of local origin. Moreover, ISSAWY *et al*. [25] deduced that seismological activities around Cairo are accompanied by local mass distribution. On the other hand, Abo Elenean [26] suggests that seismological activities in and around Cairo triggered through its regional tectonic settings. This raise the question, whether local and regional tectonic activities occurred separately or regional tectonic affects its local one. On the current research modern Earth observing tools have been dedicated to shed more light on the geodynamic behavior of regional and local tectonics of Cairo.

Obtained GPS deformation rates show significant rate of deformation along the southern eastern part of Cairo. On the other hand, dilatation rates and maximum shear strain show the anomalous behavior of the southern eastern part of Cairo from one hand. On the other hand, general pattern reflect the tectonic pattern of regional tectonic between the African plate and both the Eurasian and Arabian plates. This suggested possible interrelationship between both local and regional tectonics. It is thus important to evaluate the tectonic setting of this region regarding to the mass discontinuities. On the current research this has been made using gravity-based satellite altimeter data. The gravity map shows important zones of mass discontinuities along the eastern and northern limits of Cairo representing the regional tectonics. Existence of high positive anomaly at the seismological and deformation active zone at the southern eastern part of Cairo parallel to the eastern zone suggests the effect of the tectonic activity of the Gulf of Suez on the local south eastern part tectonic activity.

Temporal gravity variation from GRACE has been used to detect a possible mass re-distribution along plates boundaries attributed to the neo-tectonics. Temporal gravity variation indicates that the seismic activities on this region are attributed to a significant mass redistribution around the seismo-active zones. In addition, it gives important information about mass sources responsible for neo-tectonics. The rates of temporal gravity variation correlated well with tectonics of the region and rates of the GPS recent crustal deformations. Due to spatial limitations of GRACE, it is not possible to reveal minor tectonics within Cairo region.

The study indicates the importance of considering spatial and temporal gravity to the deformation and tectonic studies for completeness of the geodynamic studies. Generally, it can be stated that the satellite data offer additional and complementary data sets to help the geoscientists to determine the Earth's internal structure and tectonics. Determination of spatial and temporal earth's gravity field from satellite opened new perspectives on earth sciences and provides valuable information of the geodynamic studies. However, vectors of the annual temporal gravity variations detect again the dependence of the local seismic activity of the regional tectonic activity on the east and north.

Integrating used modern earth observing techniques demonstrate that local seismic activity is a part of regional tectonic activity geodynamic regime.

CONCLUSION

According to the obtained results, it can be concluded that the active seismicity of Cairo is of local origin, but it triggered through its regional tectonic settings. In addition, observed crustal deformation is accompanied by mass redistribution on the active tectonic zones.

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