Analysis of Regional Time-Variable Gravity Using GRACE's 10-day Solutions

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Key words: Geoid, GRACE, satellite to satellite tracking, time-variable gravity

SUMMARY

Temporal and spatial variations occur in the Earth's gravity field continuously. The investigation of these variations provides information about the natural mass transportation and re-distribution of these masses (surface and interior) in the Earth. Seasonal groundwater storage changes, water circulation between the oceans and continents, melting glaciers, pressure changes in the depths of the oceans, sea level rise, geological processes of the Earth, tectonic plate and continental movements related with the isostatic equilibrium, and the other effects like atmospheric events are some examples of the dynamic Earth system. To be informed about all of them requires being able to understand the physical reasons of these events, to estimate their changes and effects in future, and to analyze the dynamic process of the Earth's system. The Earth's gravity field and its reference equipotential surface, the geoid undergo in response to all of these temporal changes at the different scales regionally. The changes in the large-scale regional gravity field can be detected by Low Earth Orbiter (LEO) satellites or terrestrial techniques measuring gravitational signals induced mass density variation of the Earth.

In determining of changes of the Earth's gravity field, GRACE (Gravity Recovery and Climate Experiment) satellites launched on March 17, 2002 play a different role compared to the other dedicated satellite missions. GRACE observes the effects of total mass changes that have the different periodic behaviors and occur due to various geophysical events, on the Earth's gravity field. The accurate analysis and modeling of these factors can be improved with the GRACE observations, filtered by a convenient method. In this context, the monthly (or more short-term) global gravity field models (derived from GRACE data) are utilized for representing temporal variation of gravity field.

In this study, time-dependent changes of gravity were investigated for Turkey and its near neighborhood (25°<φ<50° northern latitude and 10°<λ<60° eastern longitude) using GRACE data. The annual variations were computed for the height and gravity anomalies by using 10-day gravity field solutions released by CNES/GRGS (French Space Agency/Space Geodesy Research Group). The results indicate a downward trend for the study area. A significant decline is observed in the coast of the Caspian Sea. The velocities of variations range from -1.4 mm/year to -0.3 mm/year and from -1.2 μGal/year to +0.1 μGal/year for the height and gravity anomalies, respectively.

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1. INTRODUCTION

The Earth's global gravity field can be defined from the tracking LEO satellites. Passing over the mass anomalies, the LEO satellite is attracted by them, which results in disturbances of the satellite's orbit. In this context, Gravity Recovery And Climate Experiment (GRACE) which is a joint partnership between the National Aeronautics and Space Administration (NASA) and Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR), was launched on March 17th, 2002 from the Plesetsk Cosmodrome in Russia under the NASA Earth System Science Pathfinder Program (ESSP). The principal objective of GRACE mission is to monitor the temporal variations of the Earth's gravity field. Moreover, the mission contributes to improve mean (static) models of the gravity field and geoid with unprecedented accuracy and spatial resolution up to date (Tapley and Reighber 2001).

The GRACE mission consists of two identical satellites separated by about 220 km from each other in coplanar (near-circular polar orbit) at about 500 km initial altitude in tandem. As the satellites orbit the Earth (~15 times/day), the distance between the satellites changes because of fluctuations in the Earth's gravity field. Thanks to K-band microwave ranging system equipped to the satellites, the changes in the satellites' speeds and inter-satellite distances are continuously measured with micrometer-level accuracy (Watkins and Bettadpur 2000; Dunn et al. 2003; Tapley et al. 2004a). Furthermore, on-board GPS (Global Positioning System) receivers are operated to determine the satellites' locations and to synchronize the time tags of range measurements of the two satellites. Additionally, the high accuracy accelerometers measure non-gravitational accelerations; two star cameras provide the satellites' attitudes and orbits control by determining each satellite's orientation; the laser retro-reflectors are responsible for tracking the satellites from ground stations (Dunn et al. 2003).

The GRACE satellite system is based on the principle of satellite-to-satellite tracking (SST), both in the high–low mode (SST-hl) and low–low mode (SST-ll) (Figure 1) (Balmino 2001; Rummel et al. 2002). The accuracy of the gravity field is dramatically improved by a combined processing of the SST-ll and SST-hl data. Furthermore, the SST-ll provides not only the static gravity field with higher resolution but also its temporal variations with adequate resolutions. In other words, the K-band data which combined with GPS data are used to produce a detailed map of the Earth's gravity field (Liu 2008).

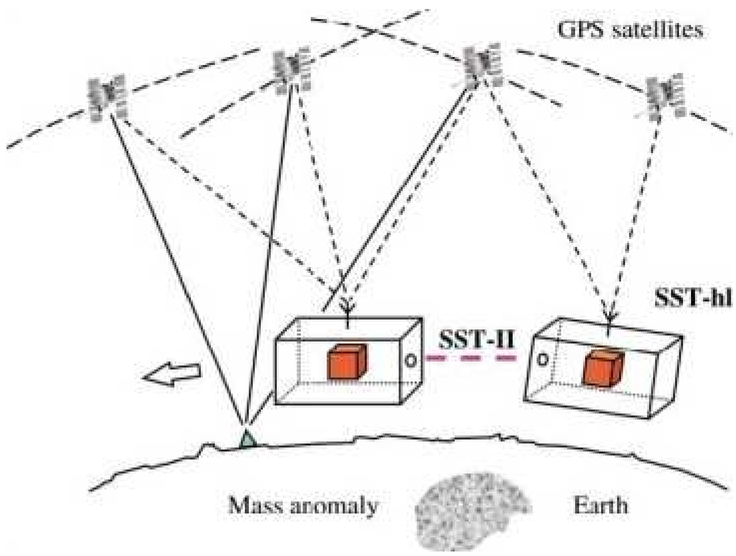

Figure 1. Satellite to satellite tracking (Balmino 2001).

The GRACE data are processed by a shared system called as GRACE Science Data System which is between Jet Propulsion Laboratory (JPL), University of Texas Center for Space Research (CSR) and Deutsches GeoForschungsZentrum (GFZ). Then, the level-1B data (calibrated instrument data) are generated and the level-2 datasets are released from them. These datasets are a series of the Earth's gravity field, provided in the form of truncated sets of harmonic coefficients at approximately monthly intervals (or shorter). Time variations in these coefficients can be used to estimate changes in the distribution of mass in the Earth system.

The initial GRACE gravity models were GGM01S (Tapley et al. 2003) and EIGEN_GRACE01S (Reigber et al. 2003) developed from first GRACE science data. These models were a five times as precise as pre-GRACE models for long and medium wavelength components of the Earth's gravity field and so they were a strong affirmation of GRACE mission (Tapley et al. 2004a). Afterwards, many new satellite-only and combined models have been released depend on the improvements of the processing methods, updated software and increasing data (ICGEM, 2012). For instance; the static gravity field models were comprised, such as GGM02 (Tapley et al. 2005), EIGEN-GL04C (Förste et al. 2008) and EGM2008 (Pavlis et al. 2008). Additionally, models of temporal gravity field variations are routinely produced from the GRACE data (generally, interval of one month) (Luthcke et al. 2006; Lemoine et al. 2007; Flechtner et al. 2010; Bruinsma et al. 2010, Liu et al. 2010).

For a better understanding the interior structure of the Earth and its temporal evolution, for studying the dynamics of the oceans and their interaction with meteorological and climate changes, for modeling the ice caps–oceans–continents relationships and for predicting the long term evolution of the mean sea level, also for unifying vertical reference systems and for the precise determination of satellite orbits in space, it is necessary to analyze the Earth's static and temporal gravity field (Balmino 2001). Besides, the determination of geoid which represents the real physical shape of the Earth is based on the Earth's gravity field. The irregularities of the geoid with respect to an ellipsoid of revolution which approximates the Earth's shape, characterize the density variations. The gravity field and its spatial and temporal variations reflect the Earth's density structure. Accordingly, the global gravity field determination is a fundamental aim of geodesy. Furthermore, the determination of this field with high precision plays an important role in the Earth sciences such as geophysics, oceanography, hydrology, glaciology etc.

In this paper, we start with a brief review of temporal variations of the Earth's gravity field via the GRACE mission. Then, we discuss the errors of GRACE estimations. In this context, it is demonstrated how the mass variations are represented with spherical harmonic coefficients. In the numerical investigation, it is evaluated the gravity changes in Turkey and its near neighborhood for the period 2003-2010 by using the GRACE data.

2. TIME-VARIABLE GRAVITY

The Earth's gravity field is not constant. It changes with location and depends on the distribution of mass in the Earth, which can undergo the changes in time due to dynamic processes in the Earth's interior or on or above its surface. The dynamic processes refer to the mass transportation between of continental water storages, oceans, atmosphere, ice sheets and glaciers, and also post-glacial rebound, tectonic motions and mantle dynamics within the Earth. The temporal variations of the Earth's gravity field resulting from these physical phenomena range in size from 10 to 100 parts per million (variation from the mean) and occur on a variety of time scales (from minutes to secular). Most of the time-variable signal comes from the Earth's fluid envelope: the oceans, atmosphere, ice sheets and continental glaciers and storage of water and snow on land. This is because water (and also gas) are much more mobile than rock (Wahr et al. 1998; Tapley et al. 2004a).

2.1 Grace Measurements for Time-Variable Gravity

The detection of global mass transport in the Earth's system by observing the associated temporal gravity field variations provides unique knowledge on mass redistribution. The GRACE mission is distinctively responsible for measuring temporal variations of the gravity field. The time series of gravity variations obtained by differencing the GRACE gravity fields provide information about changes in the distribution of mass (Tapley et al. 2004a). Until the launch of GRACE satellites, especially, Satellite Laser Ranging (SLR) was used to determine the very long wavelength mass variations (Nerem et al. 2000; Zhang et al. 2005).

In particular, the GRACE data are utilized for monitoring the redistribution of water in the Earth's system in relation to ice-sheet mass balance, continental water-storage change, sea-level rise and ocean circulation due to the aforementioned reason. There have been many studies about tracking the seasonal and annual movements of water in the different parts of the Earth by using GRACE data (Awange et al. 2007 and 2009; Ramillien et al. 2008; Schmidt et al. 2008; Yildiz et al., 2011). Most of them are concerning that the GRACE data is compared with hydrological models for some river basins (Tapley et al. 2004b; Wahr et al. 2004; Ilk et al. 2005; Schmidt et al. 2006; Fukuda 2010). It is very useful to model the hydrological cycle, and also to manage the water resources.

Moreover, the GRACE mission contributes to determine whether the ice-sheets and glaciers are melting or growing (Fleming et al. 2004; Timmen et al. 2004; Ramillien et al. 2006; Velicogna and Wahr 2011). Combining the GRACE measurements with altimeter data, it can be used to distinguish between the sea level changes due to thermal expansion and those due to usual water movements.

Additionally, the GRACE mission leads to examine the deep ocean currents which are a natural climate regulator (Macrander 2010; Janjic et al. 2011).

The GRACE data also provide to track density variations of the solid Earth. So, the factors such as the earthquakes, volcanic activities, motions of tectonic plates, mantle convection causing thermal, mechanical and compositional variations in the Earth's crust as well as the post-glacial rebound which is ongoing since the end of last ice age, are investigated via GRACE. (Sun and Okubo 2005; Panet et al. 2010).

The Earth's rotational changes depend on mass redistribution in the atmosphere, hydrosphere and oceans. Jin et al. (2010) have estimated polar motion of the Earth using the GRACE data.

In all studies, it is essential that the validation GRACE data has been approved by using comparisons between the GRACE-derived and model-derived estimations of mass variability.

The signal separation is a considerable problem in GRACE data analysis. Because the GRACE detects mass variations integrated over vertical columns which are caused by different phenomena. Among the statistical approaches, PCA (Principal Component Analysis) or its versions and ICA (Independent Component Analysis) methods have been frequently proposed to decompose the GRACE data into space and time components. These methods are compared by Forotan and Kusche (2011).

Actually, the gravity estimations of GRACE contain information about mass variability due to the un-modeled signal introduced by the geophysical phenomena and the residual signal from a well-defined a-priori static model. Because it is a common practice to subtract the contribution of an a-priori static gravity field model from the observations. The residual observations (signals) then reflect the deviations of the true gravity field from the a-priori reference model (Liu 2008). The effects such as the oceanic and solid Earth tides, pole-tides, atmospheric variations etc. can be modeled from the phenomena for them with satisfactory precision and resolution before constructing the GRACE gravity field model (at the pre-processing stage). It is aimed to minimize an effect which called temporal aliasing. For instance, ECMWF (European Centre for Medium-Range Weather Forecasts) meteorological field models are used to remove atmospheric effects from the raw data (Wahr et al. 1998; Tapley et al. 2004a; Wahr et al. 2006).

2.2. GRACE Data Errors

The GRACE data include large errors along the satellites' orbits. The system-noise errors in the inter-satellite range-rate, accelerometer error, error in the ultrastable oscillator and error in the orbits are called GRACE measurement errors (Wahr et al. 1998). Since GRACE satellites have nearly polar orbits, their along-track directions are mostly parallel to north-south direction. Thus, accuracy of east–west variations of GRACE-derived gravitational field are sensed much worse than north–south ones. This condition arise the north-south striping effects which is stronger in higher degree. Actually, the presence of these striping mean the correlations in the gravity field coefficients. So, the noise causes to degrade in GRACE solutions for especially the short wavelength components. Recently, the analysis of noise in GRACE data has been discussed by Ditmar et al. (2011). The smoothing of GRACE data is necessary to suppress this error. The most preferred method is smoothing with Gaussian filter which is proposed by Wahr et al. (1998). Swenson and Wahr (2006) have designed a filter to remove correlated errors in the spherical harmonic coefficients (A modified version of this filter is given by Chen et al. (2008)).

Moreover, Swenson et al. (2003) have developed a filter called the optimal regional filter to minimize both GRACE measurement errors and leakage errors. The leakage errors which are the undesired signals from the outside of the study area, cause temporal aliasing.

Because of all the errors referred, the accurate estimations from GRACE data are obtained only for regions having scales of a few hundred km and greater. The spatial resolution of GRACE enables that an estimate of a surface mass variation is not a point measurement, but rather a spatial average (spatial resolution=20000/ $n_{\max}$ [km]; $n_{\max}$: the maximum degree of the gravity models).

2.3 Mass Change

On a reference sphere, the static part of the Earth's gravitational potential V is expressed as a series of spherical harmonics (Hofmann-Wellenhof and Moritz 2005)

$$V(r,\theta,\lambda) = \frac{GM}{R}\sum_{n=0}^{\infty}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right)\overline{P}_{nm}(\cos\theta) \tag{1}$$

where r, θ, λ are the spherical geocentric coordinates of the computation point: radial distance, co-latitude and longitude, respectively; GM is the geocentric gravitational constant; R is the semi-major axis of a reference ellipsoid; C_{nm} and S_{nm} are spherical harmonic coefficients with n, m being degree and order, respectively; $\overline{P}_{nm}(\cos\theta)$ are the fully normalized associated Legendre functions. In reality, because of the conditions such as the precision of the available data, the measurement altitude the gravity field can not be estimated with unlimited spatial resolution. Therefore, a certain truncation degree ($n_{\max}$) needs to be set in the equation (1).

The residual gravitational potential ΔV associated with the residual signal is given by

$$\Delta V(r,\theta,\lambda)=\frac{GM}{R}\sum_{n=0}^{n_{\max}}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}(\Delta C_{nm}\cos m\lambda+\Delta S_{nm}\sin m\lambda)\overline{P}_{nm}(\cos\theta) \tag{2}$$

In the equation (2), ΔC_{nm} and ΔS_{nm} represent the time variations of spherical harmonic coefficients.

The mass variations in the Earth are responsible for spatiotemporal changes in observations of the geoid. And it can be quantified in terms of geoid height N, which is the distance between the geoid and the reference ellipsoid. According to the Bruns formula, the geoid height can be derived from the disturbing potential, which is the difference between the real gravitational potential and the normal gravitational potential U:

$$N(\theta,\lambda)=\frac{V(r,\theta,\lambda)-U(r,\theta)}{\gamma(\theta,\lambda)} \tag{3}$$

where γ is the normal gravity on the ellipsoid. Since the normal gravitational potential U is connected with the reference ellipsoid, it does not change. For this reason, the differences in the geoid heights are completely determined by the residuals or changes of the gravitational potential. Hence, it is convenient that time variations in the shape of geoid are expanded by spherical harmonics (for details, see Wahr et al. (1998) and Liu (2008)):

$$\Delta N(\theta,\lambda)=R\sum_{n=0}^{n_{\max}}\sum_{m=0}^{n}(\Delta C_{nm}\cos m\lambda+\Delta S_{nm}\sin m\lambda)\overline{P}_{nm}(\cos\theta) \tag{4}$$

Then the variations of surface mass can be calculated by the following equation:

$$\Delta\sigma(\theta,\lambda)=\frac{R\rho_{earth}}{3}\sum_{n=0}^{n_{\max}}\sum_{m=0}^{n}\frac{2n+1}{1+k_n}(\Delta C_{nm}\cos m\lambda+\Delta S_{nm}\sin m\lambda)\overline{P}_{nm}(\cos\theta) \tag{5}$$

where ρ_{earth} is the average density of the Earth, and k_n are the load Love numbers representing the effects of the Earth's response to surface loads. The ratio $\Delta\sigma/\rho_{earth}$ represents the variation in equivalent water thickness which is often used for interpretation of the seasonal variations of global land water from the GRACE solutions.

We have indicated that GRACE level 2 datasets contain some errors. So, the use of the equation (5) triggers to misinterpret surface mass variability. The low pass filtering is one of the methods used to reduce the errors. This method, which is a kind of spatial average, means that smaller weights are given to the higher degree coefficients. Accordingly, the equation (5) can be modified as:

$$\Delta\sigma(\theta,\lambda)=\frac{R\rho_{ave}}{3}\sum_{n=0}^{n_{\max}}W_n\sum_{m=0}^{n}\frac{2n+1}{1+k_n}\left(\Delta C_{nm}\cos m\lambda+\Delta S_{nm}\sin m\lambda\right)\overline{P}_{nm}(\cos\theta) \tag{6}$$

where W_n is the weight value for degree n. For Gaussian filter which is the most known averaging function,

$$W(\gamma)=\frac{b}{2\pi}\frac{\exp[-b(1-\cos\gamma)]}{1-\exp(-2b)},\ b=\frac{\ln 2}{1-\cos(r/R)} \tag{7}$$

these values can be calculated by the following recursive equations (Wahr et al. 1998):

$$W_0=\frac{1}{2\pi},\ W_1=\frac{1}{2\pi}\left[\frac{1+e^{-2b}}{1-e^{-2b}}-\frac{1}{b}\right],\ W_{n+1}=-\frac{2n+1}{b}W_n+W_{n-1} \tag{8}$$

The parameter r in the equation (7) is the averaging radius (i.e. the strength of the filter). We have mentioned the other filter methods applied in the section 2.2.

3. NUMERICAL INVESTIGATION

3.1 CNES/GRGS 10-day Gravity Field Solutions

The traditional numerical approach is to dynamic least-squares adjustment and subsequent parameter recovery through the estimation of corrections to background gravity model to produce GRACE solutions. The release 2 of CNES/GRGS 10-day gravity field solutions used in this paper is based on the same numerical approach (Bruinsma et al 2010). These solutions produced from the level 1-B data by GRGS with a different processing strategy, are expressed in normalized spherical harmonic coefficients to degree and order 50 at 10 day intervals. Since their spectrum is truncated at the 50th degree, their spatial resolution is around 400 km. Using these solutions, it is possible to estimate changes in the gravity field from 10 day period to the next. The CNES GRACE solutions can be downloaded from the International Gravimetric Bureau (BGI) web pages freely.

The 10-day solutions are stabilized towards the EIGEN-GRGS.RL02.MEAN-FIELD static gravity field at each given epoch, with a constraint law that depends on the degree and order of each coefficient. The static field model based on 4.5 years of GRACE data (March 2003 to September 2007; reference epoch is 2005.00) is complete to degree and order 160. The 10-day solutions only estimate deviations caused by un-modeled effects from the static gravity field. This is because the solid Earth tides + pole tide (IERS2003) (McCarthy and Petit 2003),

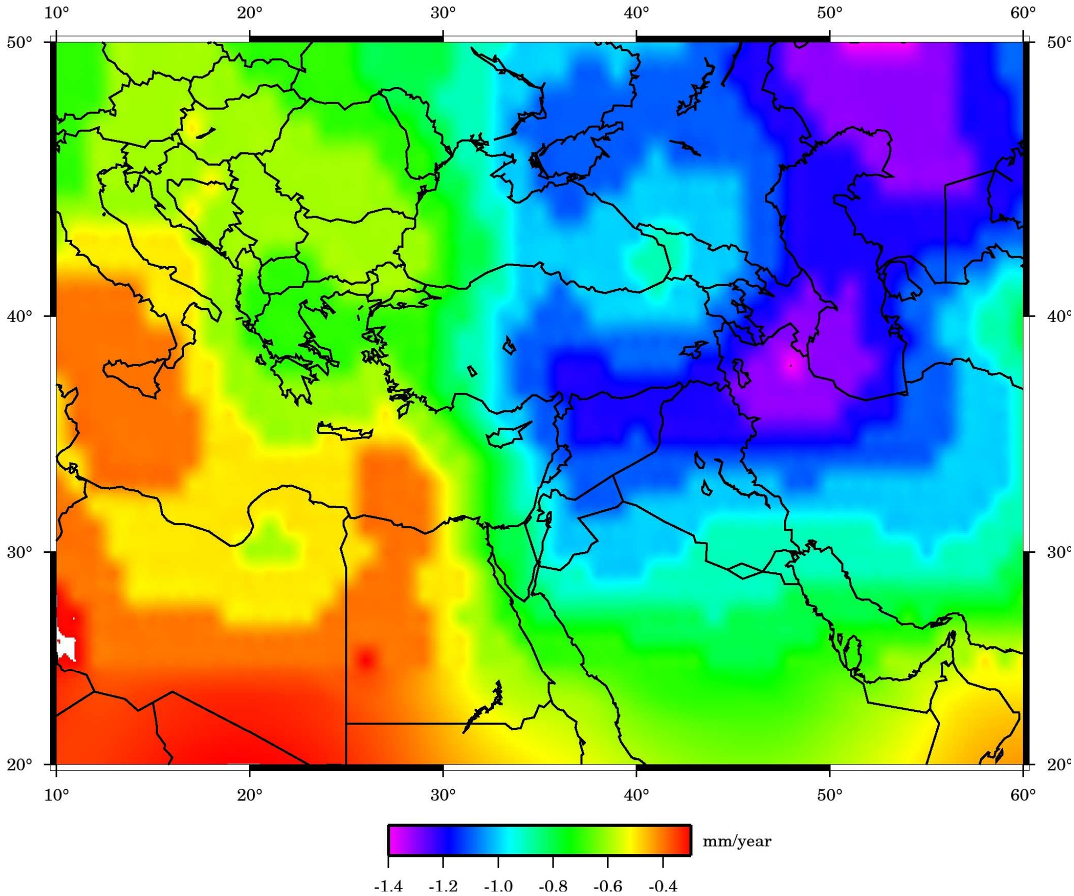

Figure 2. Velocities of secular variations of the height anomalies.

ocean tides + pole tide (FES2004 + Desai model) (LeProvost et al. 1994; Desai 2002), atmospheric mass (ECMWF 3-D pressure grids per 6 h) and barotropic ocean signals (MOG2D) (Carrere and Lyard 2003) and 3-D body perturbations were subtracted in the course of data processing. The current solutions for C_{20} have been replaced with a solution derived from LAGEOS. Also, estimates of degree one gravity field coefficients have been added to the solutions. For details, see Bruinsma et al. (2010).

Furthermore, the CNES GRACE solutions are much less affected from the striping effect since they have already been stabilized during their generation process. Consequently, the filtering is not necessary for the analysis of these solutions. For details, see Lemoine et al. (2007).

3.2 Application

The purpose of the application is to examine the gravity changes in a study region including Turkey and its near neighborhood. This region limited 25°–50° northern latitudes and 10°–60° eastern longitudes, covers most parts of Europe, Western Asia and Northern Africa.

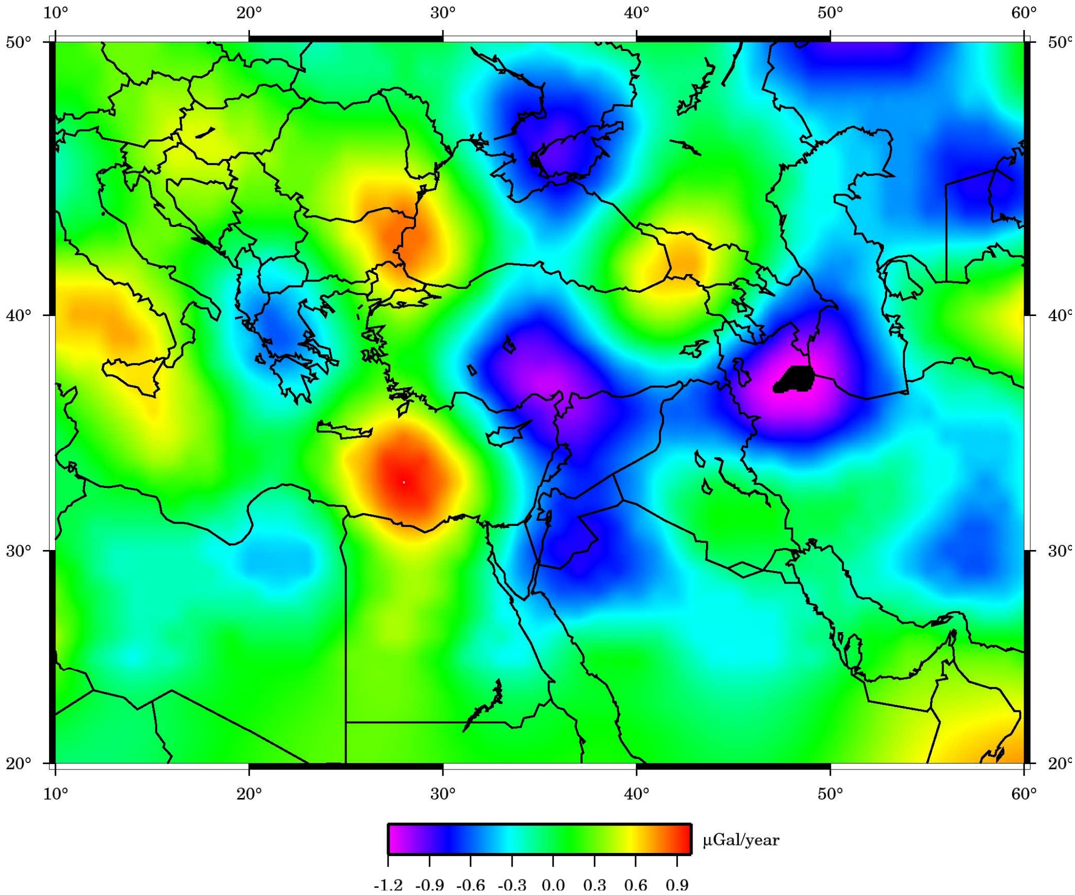

Figure 3. Velocities of secular variations of the gravity anomalies.

We have used about 8 years of GRACE data, spanning the interval from July 2002 to December 2010 except for some 10 days, resulting in 307 of 10-day solutions (The 14 fields are missing due to K-Band radar, GPS or accelerometer data gaps). The time series of height anomalies during about 8-year period are derived from the CNES GRACE solutions at the given latitudes and longitudes. The height anomalies are computed using a program called *harm2und*. With the help of spherical harmonic coefficients, this program (developed by second author) calculates various gravimetric quantities such as height anomalies, gravity anomalies and disturbances, components of vertical deflections etc. Then, the trends of these values are determined using the method of least squares. The results (velocities of variations), have been mapped (Figure 2). The same calculation steps are applied for the gravity anomalies (Figure 3).

The height and gravity anomalies show downward trend for the study region. The maximum of the velocities of secular variations are occurred on the southern west coasts of Caspian Sea. It is around -1.4 mm/year and -1.2 μGal/year for the height and gravity anomalies, respectively. Similar variations of the height and gravity anomalies are observed in the central part of Turkey, as well. On the other hand, especially, the velocity of variations in Mediterranean Sea is the least in the study region.

4. CONCLUSIONS

GRACE usually delivers monthly averages of the spherical harmonic coefficients describing the Earth's gravity field at scales of a few hundred kilometers and larger. This satellite mission enables to understand mass transport in the Earth system which includes processes in the oceans, atmosphere, hydrosphere, cryosphere and geosphere. However, the tracking mass variations at continental scales are impossible from ground measurements.

In this study, we investigated the variations of the height and gravity anomalies. The variations of these values are associated with each other. An increase in the geoid height indicates an increase in mass; a decrease in the geoid height indicates less mass. The largest of these variations are determined in the regions which have rich oil and ore reservoirs such as Caspian Sea. This is because the changes in large reservoirs caused the changes in the Earth's gravity field. Furthermore, the short-term and the long-term climate variations affect the gravity field. The tectonic movements, earthquakes and post-glacial rebound are important to understand changes in the local crustal structure for the 8-year period. However, the largest of those would be seasonal and inter-annual hydrological changes.

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