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The Comparison of Gravity Anomalies based on Recent High-Degree Global Models

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Abstract

The Earth system generates different phenomena that are observable at the surface of the Earth such as: Mass deformations and displacements leading to plate tectonics, earthquakes, and volcanism. The dynamic processes associated with the interior, surface, and atmosphere of the Earth affect the three pillars of geodesy: Shape of the Earth, its gravity field, and its rotation. Geodesy establishes a characteristic structure in order to define, monitor, and predict of the whole Earth system. The traditional and new instruments, observable, and techniques in geodesy are related to the gravity field. Therefore, the geodesy monitors the gravity field and its temporal variability in order to transform the geodetic observations made on the physical surface of the Earth into the geometrical surface in which positions are mathematically defined. In this paper, the main components of the gravity field modelling, (Free-air and Bouguer) gravity anomalies are calculated via recent high-degree global models (EIGEN6C4, GECO, and WGM2012) over a selected study area. The model-based gravity anomalies are compared with the corresponding terrestrial gravity data in terms of standard deviation (SD) and root mean square error (RMSE) for determining the best fit global model in the study area at a regional scale in Turkey. The least SD (13.45 mGal) and RMSE (15.42 mGal) were obtained by WGM2012 for the Free-air gravity anomaly residuals. For the Bouguer gravity anomaly residuals, EIGEN6C4 provides the least SD (8.05 mGal) and RMSE (8.12 mGal). The results indicated that EIGEN6C4 can be a useful tool for modelling the gravity field of the Earth over the study area.

Güncel Yüksek Dereceli Küresel Model Temelli Gravite Anomalilerinin Karşılaştırılması

Anahtar klimeler
Serbest-hava gravite anomalisi;
Bouguer gravite anomalisi;
Küresel model;
Karasal gravite.

Özet

Yeryüzü sistemi, yer yüzeyinde gözlemlenebilen farklı doğal olgular oluşturur: Kütle deformasyonları ve levha tektoniklerine, depremlere ve volkanizmaya yol açan yer değiştirmeler gibi. Dünya'nın iç yapısı, fiziksel yüzeyi ve atmosferi ile ilişkili dinamik süreçler, jeodezinin üç ana yapısını etkiler: Dünyanın şekli, yer çekimi alanı ve dönüşü. Jeodezi, tüm yeryüzü sisteminin tanımlanması, izlenmesi ve kestirimi için karakteristik bir yapı oluşturur. Jeodezide geleneksel ve yeni araçlar, gözlenen büyüklükler ve teknikler yer çekimi alanı ile ilgilidir. Bu nedenle jeodezi, yeryüzünün fiziksel yüzeyi üzerinde yapılan jeodezik gözlemleri, konumların matematiksel olarak tanımlandığı geometrik bir yüzeye dönüştürmek için yerçekimi alanını ve onun zamansal değişimini izler. Bu çalışmada, yerçekimi alan modellemesinin ana bileşenleri, (Serbest-hava ve Bouguer) gravite anomalileri, seçilen bir çalışma alanı üzerinde güncel yüksek dereceli küresel modellerle (EIGEN6C4, GECO ve WGM2012) hesaplanmıştır. Model temelli gravite anomalileri, Türkiye'de bulunan bölgesel ölçekteki çalışma alanı için en uygun küresel modeli belirlemek amacıyla, standart sapma (SS) ve karesel ortalama hata (KOH) bakımından, karasal gravite verisi ile karşılaştırılmıştır. Serbest-hava gravite anomali farkları için en küçük SS (13.45 mGal) ve KOH (15.42 mGal) WGM2012 tarafından elde edilmiştir. Bouguer gravite anomali farkları için, EIGEN6C4 en küçük SS (8.05 mGal) ve KOH (8.12 mGal) değerini sağlamıştır. Sonuçlar, EIGEN6C4'ün, çalışma alanı üzerinde yeryüzünün yer çekimi alanını modellemek için yararlı bir araç olabileceğini göstermiştir.

1. Introduction

The measurement and mapping the surface of the Earth is in charge of geodesy with respect to the remarkable definition of Helmert (1880). Although this effective notion is still valid, the scope of geodesy has been expanded, particularly through the developments in space-geodetic technologies. Today, geodesy is a branch of science devoted to determining and representing the size, shape, rotation, and gravitational field of the Earth and their variations in a three-dimensional (3D) space over time. The modern concept of geodesy is characterized by three pillars: (i) geometry and kinematics, (ii) orientation and rotation of the Earth, and (iii) gravity field (Plag et al., 2009). The last pillar of the related geodetic vision is allocated to determining-monitoring the gravity field of the Earth and its variations over spatio-temporal scales. The information of the Earth's gravity field in essence fulfils the transformation task of geodetic measurements made in gravity-dependent physical surface into the mathematical (geometrical) surface for defining positions. Also, the equipotential surfaces are required for applications including the topographical surface such as gravity-driven water flow (Dehant, 2005). The understanding of the Earth's gravity field is essential for a broad range of geophysical and geological utilizations from regional to global scales. At regional scales, gravity information can efficiently be used in a diverse field of geologic challenges about upper crust, such as: describing characteristics related to natural hazards and searching the natural resources. At global scales, gravity information is utilized in determining the Earth's shape, calculating the orbits of artificial satellites, monitoring the changes in the mass of the Earth, serving geophysical interpretation, mapping lithospheric form, and tracking geodynamic structure of the Earth system (Hildenbrand et al., 2002).

Traditionally, geodetic measurements are based on three different surfaces: (1) the physical surface of the Earth, (2) the ellipsoid, a mathematical reference surface, (3) the equipotential surface best fitting with the undisturbed (mean) sea surface, called the geoid. The understanding of the Earth's gravity field is vital for clearly defining of these three surfaces.

The vertical positioning that requires the "height" and the corresponding datum surface is an essential component of the most of the geodetic applications. The basis for the determination of height is accurate gravity data. Conventionally, the actual point heights related to the Earth's physical surface are determined by incorporating geometric levelling and gravity measurements. The heights are calculated as curved distances along the local plumb-line (the gravity vector) from the geoid at each point. These "orthometric" heights are more useful in mapping, surveying, navigation, and other geophysical applications, because they better relate to water-flow in the geophysical sense. While a geoid better relates heights to the mean sea level, determining orthometric heights is labour-intensive and time-consuming. The extensive utilization of satellite based systems for rapid calculation of accurate "ellipsoidal" heights (related to a geodetic reference ellipsoid) have triggered the necessity for accurate (and rapid) characterization of orthometric heights associated with the geoid. The ellipsoidal heights are inconvenient for topographic/floodplain mapping due to the topographical irregularities. The geoid is a viable option for a height transformation process from ellipsoidal to orthometric. The determination of the geoid has a robust connection with the measurement or the calculation of the gravity acceleration near the Earth's surface (Smith, 2007; Roman et al., 2010). In using the Earth's gravity field to determine the geoid, the acceleration of gravity is obtained by point gravity measurements located at the Earth's physical surface. In the geoid determination, these gravity values must be reduced onto the geoid by converting them into gravity anomalies (Li and Götze, 2001).

A global model (GM) of the Earth's gravity field is a mathematical approximation of the real gravity potential and allows computation of the gravitational quantities such as: gravitational potential, gravity disturbance, gravity anomaly, height anomaly, geoid undulation at each position in 3D space (Barthelmes, 2014). The operational and scientific progressions in space-based techniques provide significant developments in the global gravity field model determinations. The launches of the CHAllenging Minisatellite Payload (CHAMP) (Reigber et al., 2002), Gravity Recovery And Climate Experiment (GRACE) (Tapley et al., 2004), and Gravity field and steady-state Ocean Circulation Explorer (GOCE) (Floberghagen et al., 2011) missions have pioneered our understanding of the global Earth's gravity field and its variations over time by numerous GMs (Godah et al., 2017). Gravity data can be obtained from satellite, airborne and ground based measurements at various geographical resolutions. The air- and space-based data have some disadvantages related mainly to the frailty of the gravitational field associated with the altitude. Terrestrial gravity data provide full-field gravity field knowledge oftentimes with a heterogeneous data density. Therefore, air- and space-based gravity data are combined with ground-based gravity data to derive combined GMs (Novák, 2010; Bolkas et al., 2016).

The primary purpose of this paper is the evaluation of the accuracy of recent combined high-degree GMs: European Improved Gravity model of the Earth by New techniques (EIGEN6C4) (Förste et al., 2014), and GOCE-EGM2008 COmbined model (GECO) (Gilardoni et al., 2016), and the World Gravity Map 2012 (WGM2012) (Bonvalot et al., 2012) for approximating the Earth's gravity field. The land gravity data in the study area were used to quantify the GMs' performance in assessing the combined model that best coincides the study area in Turkey for gravity field modelling at a regional scale, and the comparison results are presented with regard to the standard deviation (SD) and root mean square error (RMSE) over the study area.

2. Theoretical Background

2.1. Gravity Anomaly

The measured gravity at a point on the Earth's physical surface is affected by sources that form the Earth's gravity field. Gravity caused by known sources such as the rotation of the Earth, the distance from the geocentre, topographic relief, tidal variation, and gravity meter fluctuations can be removed from the measured gravity by using realistic Earth models. The difference between the measured gravity on the Earth's physical surface and the correspondent value calculated by a gravity field model for the identical point with respect to the altitude, latitude, and topographical irregularities is called gravity anomaly (Hill et al., 1997). In geodesy, the scalar distinction between gravity measured at a point that has been reduced to the geoid (g_P) and a theoretical value of the normal gravity at that point predicted from a reference ellipsoid (γ) (for the same geodetic latitude) is defined as the gravity anomaly (Δg) (Hackney and Featherstone, 2003):

$$\Delta g = g_P - \gamma \tag{1}$$

Gravity anomalies are defined as Free-air and Bouguer gravity anomalies by applying a sequence of gravity corrections to the measured gravity. In the geodetic literature, the computation of gravity anomalies is characterized as a reduction process where measured gravity is reduced to the geoid (Mishra, 2009). This reduction procedure comprises a number of rectifications that must be applied to the measured gravity value: the latitude correction, the Free-air correction, and the (simple) Bouguer correction (Featherstone and Dentith, 1997).

Latitude correction: The theoretical gravity that is a function of latitude should be removed for leaving only local effects. This process is called latitude correction that accounts the reference ellipsoid's gravity effect. The Somigliana-Pizetti closed-form expression (Hofmann-Wellenhof and Moritz, 2006) is a standard in geodesy for calculating the normal gravity on the surface of a geocentric reference ellipsoid that is used for the representation of the Earth's shape (Hackney, 2011):

$$\gamma = \gamma_a \frac{1 + k\sin^2\phi}{\sqrt{1 - e^2\sin^2\phi}} \tag{2}$$

where γ_a is normal gravity at the equator of the reference ellipsoid, k is the normal gravity constant, ϕ is the geocentric latitude of the gravity measurement point, and e^2 is the square of the first numerical eccentricity of the reference ellipsoid.

Free-air correction: The elevation of the point where each gravity measurement was made must be reduced to a reference datum for comparing the whole profile. This is called the Free-air correction (*F*), and its combination with the latitude correction leaves the Free-air anomaly. The gravity measurement point is almost never located on the reference ellipsoid's surface. This is accounted by the utilization of the vertical gradient of normal gravity as an approximation (Li and Götze, 2001):

$$F = -\frac{\partial \gamma}{\partial R} H \approx 0.3086H \quad (3)$$

where *R* is the radius of the spherical Earth model (in kilometers) and *H* is the elevation of the measurement point in free air (above or below the geoid) (in meters). Conventionally, the linear approximation (*0.3086H*) is sufficient for many practical purposes. However, a more precise representation of the Free-air correction can be derived by a second-order approximation that accounts the oblate shape of the Earth (Hackney, 2011). Consequently, the Free-air gravity anomaly (Δg_{FA}) becomes:

$$\Delta g_{FA} = g_P + F - \gamma \quad (4)$$

Bouguer correction: The attraction of any mass between the physical surface of the Earth and the vertical datum surface should be corrected. Hence, the topographic masses between the points where gravity were measured (Earth's physical surface) and the geoid are modelled as being made up of an infinite number of plates of thickness *H*. These plates have no lateral variation in density, but each slab may have a distinct density than the one above or below it. This is called the Bouguer correction (*B*) (Sjöberg and Bagherbandi, 2017).

$$B = 2\pi G \rho H \quad (5)$$

where *G* is the gravitational constant and ρ is the topographic density. If the standard topographic mass density is considered as $\rho = 2.67\ g/cm^3$, the Bouguer correction becomes:

$$B = 0.1119H \quad (6)$$

Thus, the simple Bouguer anomaly can be defined as:

$$\Delta g_B = g_P + F - \gamma - B \quad (7)$$

This simple process is refined by taking into account the actual topography's deviation from the Bouguer plate. This process is called as terrain correction. The Bouguer correction and the corresponding Bouguer anomalies are called complete (refined) or simple with regard to the application of terrain correction. In practice, the Bouguer reduction should be actualized in two stages as the effect of the Bouguer plate and the terrain. The amount of the terrain correction is ~50 mgal for the mountains ($H \approx 3000\ m$) (Hofmann-Wellenhof and Moritz, 2006).

2.2. Global Models

The determination of the Earth's gravity field is one of the major missions of geodesy. Since the 1960s, the Earth's real gravitational potential has been approximated through the combination of satellite tracking data, land and ship-tracking gravity data, marine gravity anomalies derived by using spherical harmonics (Rummel et al., 2002). The mathematical representation of the gravitational potential of the Earth in the space by spherical harmonic coefficients is called GM. GMs provide knowledge regarding with the Earth, its shape, its interior and fluid envelope. All related gravity field functionals can be calculated by GMs. There are essentially two classes of GMs: satellite-only and combined models. The satellite-only models are calculated by satellite observations alone. Whereas, for the combined models additionally terrestrial gravity data and altimetry measurements are used (Barthelmes, 2014).

The gravity anomaly (Δg) can be represented by spherical harmonic expansion with the following equation (Barthelmes, 2013):

$$\Delta g(\mathrm{r},\lambda,\varphi) = \frac{G \cdot M}{r^2} \sum_{\ell=0}^{\ell_{\max}} \left(\frac{R}{r}\right)^{\ell} (\ell - 1) \sum_{m=0}^{\ell} \bar{P}_{\ell m}(\sin\varphi) \left[\bar{C}_{\ell m} \cos m\lambda + \bar{S}_{\ell m} \sin m\lambda\right] \quad (8)$$

The notations are:

(r, λ, φ); radius, longitude, and latitude of the computation point,

G; gravitational constant,

M; mass of the Earth,

R; reference radius of the Earth,

ℓ, m; degree, order of spherical harmonics,

$\bar{P}_{\ell m}$; Lengendre functions (fully normalised),

$\bar{C}_{\ell m}$, $\bar{S}_{\ell m}$; Stokes' coefficients (fully normalised).

The launches of CHAMP, GRACE, and GOCE have led significant achievements in the determination of the Earth’s gravity field. Thus, the technological and scientific developments in artificial satellite techniques and calculation algorithms resulted in releasing high-degree combined GMs (Yilmaz et al., 2017. In this paper, EIGEN6C4, GECO, and WGM2012 (recent high-degree combined models) are studied.

European Improved Gravity Model of the Earth by New Techniques 2014: EIGEN6C4 is a static global combined gravity field model up to degree and order 2190. It has been generated by the collaboration between GeoForschungsZentrum (Geo-Research Centre) (GFZ) Potsdam and Groupe de Recherche de Géodésie Spatiale (Space Geodesy Research Group) (GRGS) Toulouse. EIGEN-6C4 is developed by the combination of LAGEOS, GRACE RL03 GRGS, GOCE-SGG (November 2009 till October 2013) data plus 2′ × 2′ free-air gravity anomaly grid. The incorporation of these different data sets has been done by normal equations, which are generated as a function of their resolution and accuracy (Förste et al., 2014).

Global Gravity Model by Locally Combining GOCE Data and EGM2008: GECO is a global gravity model up to degree and order 2190, computed by incorporating the GOCE-only TIM R5 solution into Earth Gravitational Model 2008 (EGM2008) (Pavlis et al., 2008). The EGM2008 geoid is computed on a global spherical grid of resolution 30' x 30' by making a synthesis from EGM2008 coefficients up to degree 359. The GOCE geoid undulations on the same grid are computed by making a synthesis from the TIM R5 coefficients up to degree 250. Two geoid grids are combined with a least-squares adjustment process. Finally, the GECO spherical harmonic coefficients are computed as a weighted average of the coefficient errors of EGM2008 and TIM R5 combined solution. From degree 360 to degree 2190 the GECO coefficients are the same of EGM2008 (Gilardoni et al., 2016).

World Gravity Map 2012: WGM2012 is the first map of a high resolution grid of the Earth's gravity anomalies, computed on a global scale. The realization of WGM2012 has been carried out by the Bureau Gravimétrique International (BGI) with the support of UNESCO and other scientific agencies. WGM2012 gravity anomalies are derived from EGM2008, DTU10 and ETOPO1 (1' x 1') at the global scale. The gravity anomalies have been calculated by spherical harmonic expansion of the Earth’s topography-bathymetry up to degree 10800 (Bonvalot et al., 2012).

3. Study Area, Land Data, and Evaluation Methodology

The study area covering the western Anatolian parts of Turkey is limited by the geographical boundaries: 36°.5 N ≤ φ ≤ 40°.5 N; 26°.5 E ≤ λ ≤ 33°.0 E, and it approximately defines a total area of 180000 km2 (~370 km x ~480 km) with a rough and mountainous ($H>1000$ *m*) topography (Fig. 1).

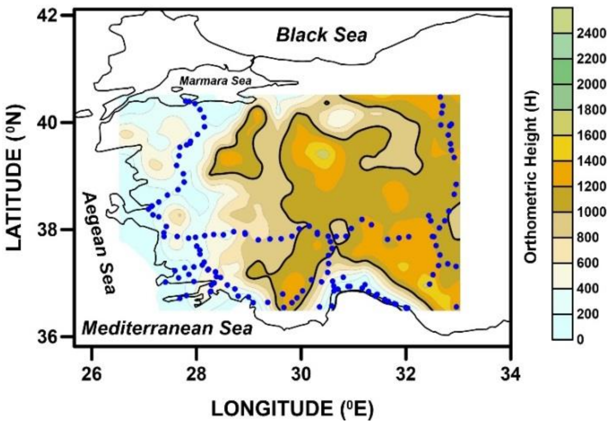

Figure 1. The location - topography of the study area (heights in *m*) and the land gravity points.

The evaluation procedure of gravity anomalies refers to a terrestrial gravity data set over the study area that is comprised of 145 land gravity points (blue spots in Fig. 1) compiled by BGI. The land gravity data are in the Geodetic Reference System-1980. Although mainly measured before 1971, the measured land gravity values have been connected to IGSN71 (Morelli et al., 1974) system. The accuracy of land gravity values is about 0.25 ~ 0.75 mGal.

The comparative evaluation of the GM based (Free-air and Bouguer) gravity anomalies was carried out by the residuals ($\delta\Delta g$) between the measured (land) gravity anomaly (Δg_L) and the gravity anomaly calculated by GMs (Δg_{GM}) using the following equation:

$$\delta\Delta g = \Delta g_L - \Delta g_{GM} \tag{9}$$

The quantitative statistical evaluation of gravity anomaly residuals ($\delta\Delta g$) was executed with the minimum, maximum, mean, SD, and RMSE values as the common criteria for the accuracy (Yilmaz and Gullu, 2014; Karpik et al., 2016). SD and RMSE are defined by:

$$\mathrm{SD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\delta\Delta g_i - M\Delta g\right)^2} \tag{10}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\delta\Delta g_i\right)^2} \tag{11}$$

where $M\Delta g$ represents the mean value of the gravity anomaly residuals, n is the number of terrestrial gravity points, and i refers to the residual sequence.

4. Comparative Study

The measured gravity anomalies based on terrestrial observations at discrete points provide information abot the accuracy of the GMs in the comparative process. The common and accepted practice is selection of the GM that has a best fit to the terrestrial data. The evaluation of GMs focuses on the gravity anomaly residuals. In the GM approach of the evaluation procedure; the gravity anomalies based on EIGEN6C4 and GECO, are computed from the grids by International Centre for Global Earth Models (ICGEM) *calculation service* (Barthelmes and Köhler, 2016). The gravity anomalies based on WGM2012 are computed from the grids by BGI *land gravity database* (Bonvalot, 2016).

The Free-air gravity anomaly is defined as the magnitude of the gradient of the downward continued potential on the geoid minus the magnitude of the gradient of the normal potential on the ellipsoid. The (simple) Bouguer gravity anomaly is defined by the Free-air gravity anomaly minus the attraction of the Bouguer plate. It is computed by the Free-air gravity anomaly minus $2\pi G\rho H$. The spherical harmonic model DTM2006 (Pavlis et al., 2007) is used for the calculation of the topographic heights (H). A constant topographic mass density of $2.67\ g/cm^3$ has been used for $H\geq 0$ m (Barthelmes, 2013). The spherical approximation of the Free-air and (simple) Bouguer gravity anomalies are calculated by equation (8). The statistical values of these gravity anomalies based on GMs are given in Table 1.

Table 1. Statistics of gravity anomalies based on GMs over the study area (units in mGal)

GM	FREE-AIR GRAVITY ANOMALY			
	Min.	Max.	Mean	SD
EIGEN6C4	-138.79	277.76	53.40	39.07
GECO	-141.39	275.54	53.39	39.07
WGM2012	-137.51	294.25	53.51	39.10
GM	**BOUGUER GRAVITY ANOMALY**			
	Min.	Max.	Mean	SD
EIGEN6C4	-105.33	128.16	-31.19	46.17
GECO	-105.26	126.99	-31.21	46.18
WGM2012	-33.26	238.30	73.84	48.24

In order to specify the occurrence and magnitude of gravity anomaly residuals, the graphical depictions were used for the qualitative evaluation of GMs by producing the Free-air and (simple) Bouguer gravity anomaly residual maps with regard to equation (9) for each GM by the Surfer® 13 software (Fig.s 2-4). The statistical parameters of the Free-air and (simple) Bouguer gravity anomaly residuals associated with GMs are presented in Table 2.

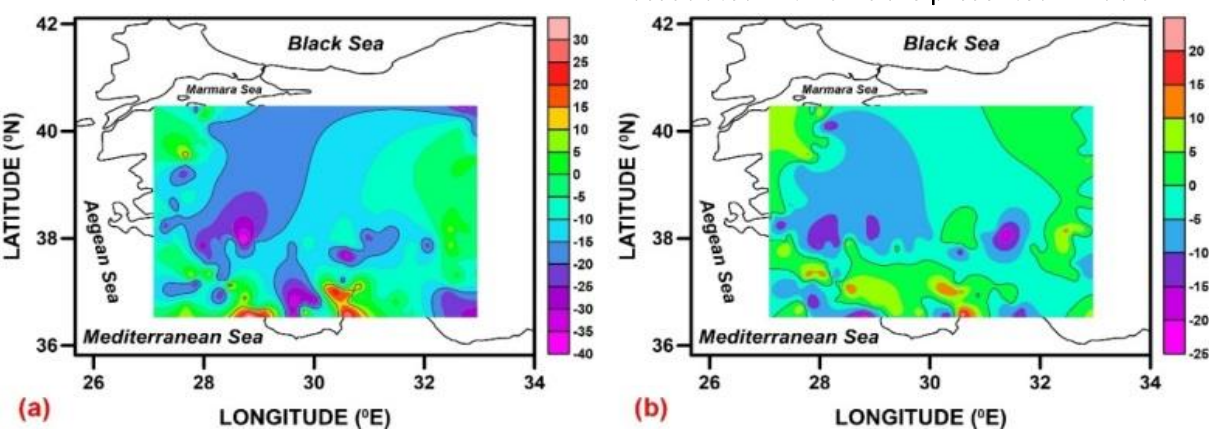

Figure 2. EIGEN6C4 gravity anomaly residual map (residuals in mgal) (a) Free-air (b) Bouguer.

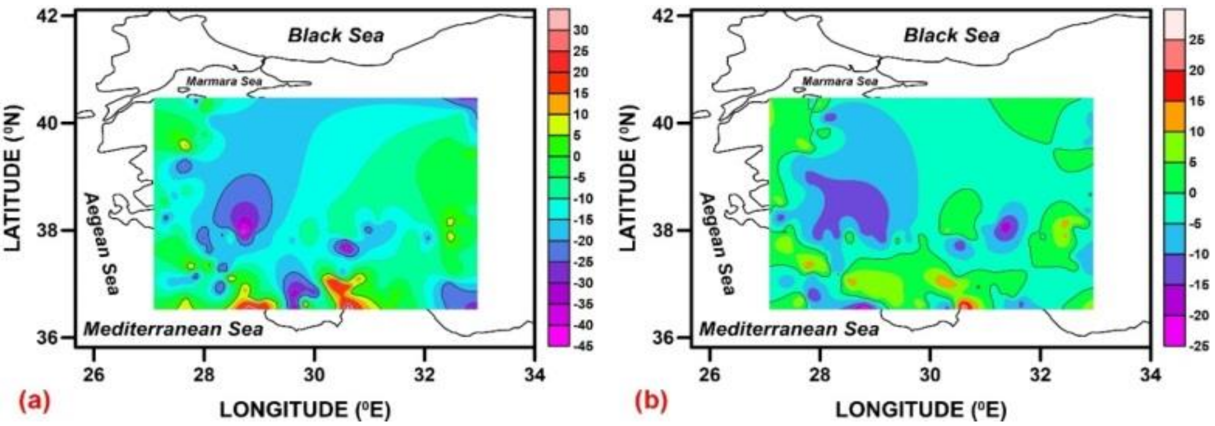

Figure 3. GECO gravity anomaly residual map (residuals in mgal) (a) Free-air (b) Bouguer.

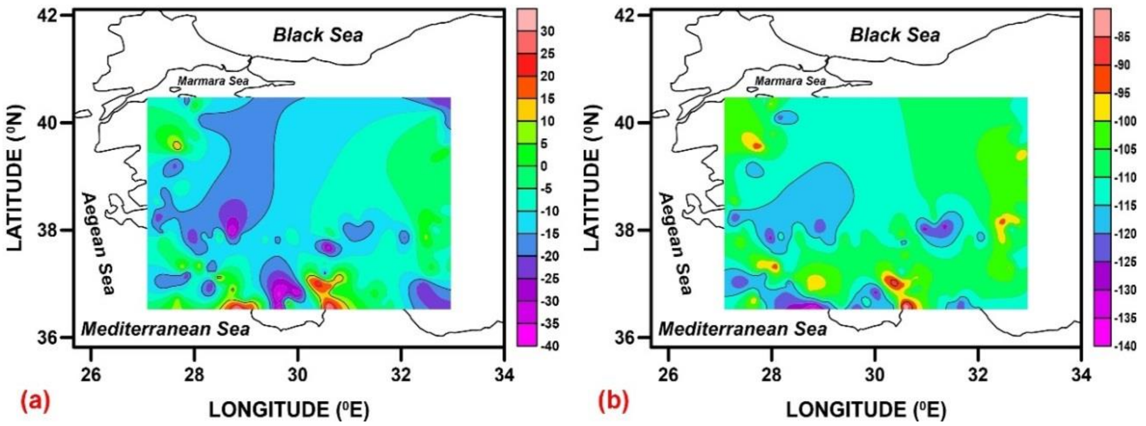

Figure 4. WGM2012 gravity anomaly residual map (residuals in mgal) (a) Free-air (b) Bouguer.

Table 2. Statistical information of gravity anomaly residuals based on GMs (units in mGal)

GM	Residual	Min.	Max.	Mean	Range	SD	RMSE
EIGEN6C4	Free-air	-42.86	35.04	-7.96	77.90	13.72	15.82
	Bouguer	-24.03	24.56	-1.25	48.59	8.05	8.12
GECO	Free-air	-46.01	35.29	-8.15	81.30	13.88	16.06
	Bouguer	-26.07	26.70	-1.44	52.77	8.16	8.26
WGM2012	Free-air	-40.92	34.16	-7.63	75.08	13.45	15.42
	Bouguer	-137.19	-79.10	-109.75	58.09	9.75	110.17

5. Results and Conclusions

The analysis of the explanatory statistics (minimum, maximum, mean, SD, and RMSE) of the

Free-air and (simple) Bouguer gravity anomaly residuals given in Table 2 reveals that EIGEN6C4, GECO, and WGM2012 solutions are very close to each other, except for the (simple) Bouguer gravity anomaly modelling of WGM2012. The differences between the SD and RMSE (based on these GMs) values are quite small.

The visual interpretation of the gravity anomaly residuals indicates that EIGEN6C4, GECO, and WGM2012 have a similar Free-air gravity anomaly approximation over the study area. Solely, WGM2012 shows major discrepancy than the other GMs regarding to the land Bouguer gravity anomaly data. This behaviour of WGM2012 in modelling the (simple) Bouguer gravity anomalies deserves further investigation. The topographic model used for WGM2012 calculations (ETOPO1) may be remarked as a preliminary conclusion

SD is within a range of; 13.45 mGal to 13.88 mGal for Free-air gravity anomaly residual, 8.05 mGal to 9.75 mGal for (simple) Bouguer gravity anomaly residual. RMSE is within a range of; 15.42 mGal to 16.06 mGal for Free-air gravity anomaly residual, 8.12 mGal to 110.17 mGal for (simple) Bouguer gravity anomaly residual.

When the results presented in Table 2 are examined, the least SD (13.45 mGal) and RMSE (15.42 mGal) were obtained by WGM2012 for the Free-air gravity anomaly residuals. SDs and RMSEs of the GMs have a decreasing sequence as: WGM2012 < EIGEN6C4 < GECO for the Free-air gravity anomaly modelling. For the (simple) Bouguer gravity anomaly residuals, EIGEN6C4 provides the least SD (8.05 mGal) and RMSE (8.12 mGal) with a decreasing sequence as: EIGEN6C4 < GECO < WGM2012.

From the minimum, maximum, and mean values in Table 2, it is apparent that EIGEN6C4, GECO, and WGM2012 overestimate the Free-air gravity anomalies. The approximations of the (simple) Bouguer gravity anomalies based on EIGEN6C4 and GECO are all largely negative (Fig. 2b-3b). The modelling of (simple) Bouguer gravity anomalies based on WGM2012 is completely negative (Fig. 4b). This is a representative feature of the land Bouguer gravity anomalies. The SDs of (simple) Bouguer gravity anomaly residuals in Table 2, are smaller than the SDs of Free-air gravity anomaly residuals due to the fact that the (simple) Bouguer gravity anomalies are expected to be smoother than the Free-air gravity anomalies.

From the visual analysis of the gravity anomaly residual maps (Fig.s 2-4), the Free-air gravity anomaly residuals exhibit identical geographical characteristics, but the magnitudes are different. The spatial structure of the (simple) Bouguer gravity anomaly residuals is similar, but the magnitudes are quite different, especially, WGM2012.

The comparative results in terms of SD and RMSE of the evaluation of GM based gravity anomalies led the following conclusions in a regional scale:

- The approximation of the Free-air gravity anomalies shows that EIGEN6C4, GECO, and WGM2012 are almost identical with a slight advantage of WGM2012 over the study area.
- The (simple) Bouguer gravity anomaly modelling of EIGEN6C4 and GECO are similar with a slight advantage of EIGEN6C4. WGM2012 provides the lowest accuracy in modelling the (simple) Bouguer gravity anomalies over the study area. The data contributions of GOCE to EIGEN6C4 and GECO have made significant improvement, particularly in modelling the Bouguer gravity anomalies.

Moreover the qualitative and quantitative analysis results of this study suggest that:

- Due to its better statistics (in terms of SD and RMSE), the use of EIGEN6C4 can be recommended as a feasible GM for gravity anomaly modelling tool in geodetic applications in regional-national scales in Turkey.
- By using a densified land gravity measurement network with an improved spatial distribution, the Free-air and (simple) Bouguer gravity anomaly can be modelled by GMs with more accuracy.

Furthermore, detailed analysis of recent combined high-degree GMs (by filtering the residual quantities resulting from the high frequencies of GMs) may lead more consistent options for studying the Earth's gravity field.

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