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The Evaluation of Gravity Anomalies Based on Global Models by Land Gravity Data

M. Yilmaz, I. Yilmaz, M. Uysal

***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, observables, 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 modeling, (Free-air and Bouguer) gravity anomalies are calculated via recent global models (EGM2008, EIGEN6C4, and GECO) 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 (13.63 mGal) and RMSE (15.71 mGal) were obtained by EGM2008 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 modeling the gravity field of the Earth over the study area.

***Keywords*—**Free-air gravity anomaly, Bouguer gravity anomaly, global model, land gravity.

I. INTRODUCTION

THE measurement and mapping the Earth's surface is in charge of geodesy with respect to the classical definition of Helmert [1]. 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 and its variability [2]. The third pillar of this geodetic vision is allocated to determining-monitoring the gravity field of the Earth and its variations over spatio-temporal scales. The knowledge of the geometry 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 and plumb-lines are required for applications including the topographical surface such as gravity-driven water flow [3]. The understanding of the Earth's gravity field is essential not only for geodesy, but today it is also crucial 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 [4].

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 mean sea level (MSL) at the calm ocean, 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 heights of the points on 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 MSL, determining orthometric heights is labour-intensive and time-consuming. The extensive utilization of Global Navigation Satellite Systems for rapid determining accurate "ellipsoidal" heights (related to a geodetic reference ellipsoid) have triggered the necessity for accurate (and rapid) determination 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 height transformation between the ellipsoidal heights and

M. Yilmaz is with the Department of Geomatics, Faculty of Engineering, Afyon Kocatepe University, ANS Campus, TR-03200, Afyonkarahisar, Turkey (phone: +90 272 2281423; fax: +90 272 2281422; e-mail: mustafayilmaz@aku.edu.tr).

I. Yilmaz and M. Uysal are with Department of Geomatics, Faculty of Engineering, Afyon Kocatepe University, ANS Campus, TR-03200, Afyonkarahisar, Turkey (e-mail: iyilmaz@aku.edu.tr, muysal@aku.edu.tr).

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orthometric heights. The geoid determination has a robust connection with the measurement or the calculation of the gravity acceleration near the Earth's surface [5], [6]. 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 [7].

A global model (GM) of the Earth's gravity field is a mathematical approximation of the real gravity potential and allows computation of the physical quantities connected to the gravity field, i.e., gravitational potential, gravity disturbance, gravity anomaly, height anomaly, geoid undulation at each position in 3D space [8]. 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) [9], Gravity Recovery And Climate Experiment (GRACE) [10], and Gravity field and steady-state Ocean Circulation Explorer (GOCE) [11] missions have revolutionized our understanding of the global Earth's gravity field and its temporal changes by numerous GMs [12]. Gravity data can be acquired from satellite, airborne and terrestrial measurements at different spatial resolutions. The air- and space-based data have some disadvantages related mainly to the frailty of the gravitational field with altitude. Terrestrial gravity data provide full-field gravity field information oftentimes with a heterogeneous data density. Therefore, air- and space-based gravity data are combined with ground-based gravity data to derive combined GMs [13], [14].

The main purpose of this paper is the evaluation of the accuracy of combined high-degree GMs: Earth Gravitational Model 2008 (EGM2008) [15], European Improved Gravity model of the Earth by New techniques (EIGEN-6C4) [16], and GOCE-EGM2008 COmbined model (GECO) [17] for approximating the gravity field of the Earth. 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 in terms of the SD and RMSE over the study area.

II. THEORETICAL CHARACTERIZATION

A. 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 physical surface of the Earth and the corresponding value calculated by a gravity field model of the Earth for the same point with respect to the altitude, latitude, and topographical irregularities is called gravity anomaly [18]. In geodesy, the scalar difference 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) [19]:

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

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 [20]. This reduction procedure comprises a number of corrections that must be applied to the measured gravity value: the latitude correction, the Free-air correction, and the (simple) Bouguer correction [21].

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 [22] is a standard in geodesy for calculating the normal gravity on the surface of a geocentric reference ellipsoid that is used to represent the shape of the Earth [23]:

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

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 to compare the whole profile. This is called the Free-air correction (F), and when it is combined with the latitude correction leaves the Free-air anomaly. The gravity measurement point is almost never located exactly on the surface of the reference ellipsoid. This is accounted by the utilization of the vertical gradient of normal gravity as an approximation [7]:

$$F = -\frac{\partial \gamma}{\partial R} H \approx 0.3086H \tag{3}$$

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 expression for the Free-air correction can be derived by a second-order approximation that accounts the oblate shape of the Earth [23]. Consequently, the Free-air gravity anomaly (Δg_{FA}) becomes:

$$\Delta g_{FA} = g_P + F - \gamma \tag{4}$$

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 different density than the one above or below it. This is called the Bouguer correction (*B*) [24].

$$B = 2\pi G\rho H \tag{5}$$

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:

$$B = 0.1119H \tag{6}$$

Thus, the simple Bouguer anomaly can be defined as:

$$\Delta g_B = g_P + F - \gamma - B \tag{7}$$

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 ($H \approx 3000\ m$) [22].

B. Global Models

The determination of the Earth's global gravity field is one of the main tasks of geodesy. Since the 1960s, the Earth's real gravitational potential has been approximated from the combination of satellite tracking data, land and ship-tracking gravity data, marine gravity anomalies derived by using spherical harmonics [25]. The mathematical representation of the gravitational potential of the Earth in the space by spherical harmonic coefficients is called GM. GMs provide knowledge about 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 measurements alone, whereas for the combined models additionally terrestrial gravity measurements (over the continents) and altimetry measurements (over the oceans) are used [8].

The gravity anomaly (Δg) can be represented by spherical harmonic expansion with the following equation [26]:

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

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, $\overline{P}_{\ell m}$; Lengendre functions (fully normalised), $\overline{C}_{\ell m}, \overline{S}_{\ell m}$; Stokes' coefficients (fully normalised).

The launches of CHAMP, GRACE, and GOCE have led to 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 [27]. EGM2008, EIGEN-6C4, and GECO (high-degree combined models) that were mentioned in the Introduction section, are studied.

Earth Gravitational Model 2008: EGM2008 is a spherical harmonic model of the Earth's gravitational potential, complete to degree and order 2159, with additional spherical harmonic coefficients extending up to degree 2190 and order 2159. It is released by the National Geospatial-Intelligence Agency (NGA). EGM2008 is based on a least squares combination of the ITG-GRACE03S gravitational model along with its associated error covariance matrix, with 5′ × 5′ free-air gravity anomaly grid formed from terrestrial, altimetry-derived and airborne gravity data. The spectral content of EGM2008 was supplemented by a new elevation database based on the Shuttle Radar Topographic Mission solution along with other databases (GTOPO30, ICESat, etc.). EGM2008 represents a significant milestone in the Earth's gravity field modelling, by demonstrating for the first time ever, that given accurate and detailed gravimetric data, a single GM may provide the requirements of a very wide range of applications [28].

European Improved Gravity Model of the Earth by New Techniques 2014: EIGEN-6C4 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 (DTU12 altimeter data for the oceans, EGM2008 geoid height grid for the continents). The incorporation of these different data sets has been done by normal equations, which are generated as a function of their resolution and accuracy [16].

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 EGM2008. 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

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solution. From degree 360 to degree 2190, the GECO coefficients are the same of EGM2008 [17].

III. STUDY AREA, TERRESTRIAL DATA, 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 km^2 (~370 km x ~480 km) with a rough and mountainous ($H>1000\ m$) topography (Fig. 1).

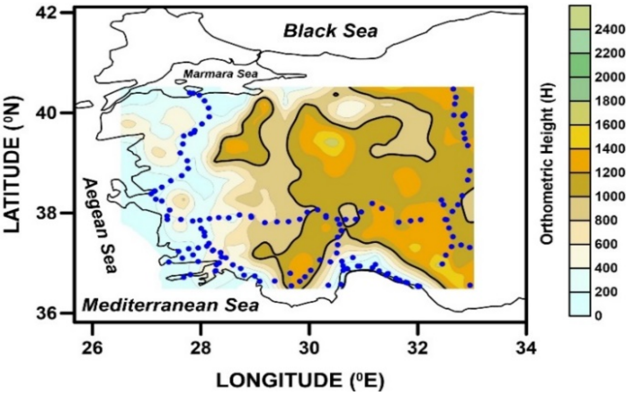

Fig. 1 The location - topography of the study area (heights in m) and the land gravity points

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 points 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 the International Standardization Net 1971 [29] 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 (terrestrial) gravity anomaly (Δg_T) and the gravity anomaly calculated by GMs (Δg_{GM}) using the following equation:

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

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 [30], [31]. 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.

IV. COMPARATIVE STUDY

The measured gravity anomalies based on terrestrial observations at discrete points provide an estimated accuracy of the GMs in the process of GM comparative evaluation. The usual and accepted practice is to select 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 EGM2008, EIGEN-6C4, and GECO are computed from the grids by the calculation service of International Centre for Global Earth Models (ICGEM) web page [32]:

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 [33] 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 [26]. The spherical approximation of the Free-air and (simple) Bouguer gravity anomalies are calculated by (8). The statistical values of these gravity anomalies based on GMs are given in Table I.

TABLE I
STATISTICS OF GRAVITY ANOMALIES BASED ON GMS OVER THE STUDY AREA (UNITS IN MGAL)

GM	FREE-AIR GRAVITY ANOMALY			
	Min.	Max.	Mean	SD
EGM2008	-138.27	280.62	53.41	39.09
EIGEN6C4	-138.79	277.76	53.40	39.07
GECO	-141.39	275.54	53.39	39.07
GM	BOUGUER GRAVITY ANOMALY			
	Min.	Max.	Mean	SD
EGM2008	-105.62	127.52	-31.19	46.46
EIGEN6C4	-105.33	128.16	-31.19	46.17
GECO	-105.26	126.99	-31.21	46.18

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 (9) for each GM by the Surfer® 13 software (Figs. 2-4). The statistical parameters of the Free-air and (simple) Bouguer gravity anomaly residuals associated with GMs are presented in Table II.

V. 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 II reveals that EGM2008, EIGEN6C4, and GECO solutions are very close to each other. The differences between the SD and

RMSE values are quite small.

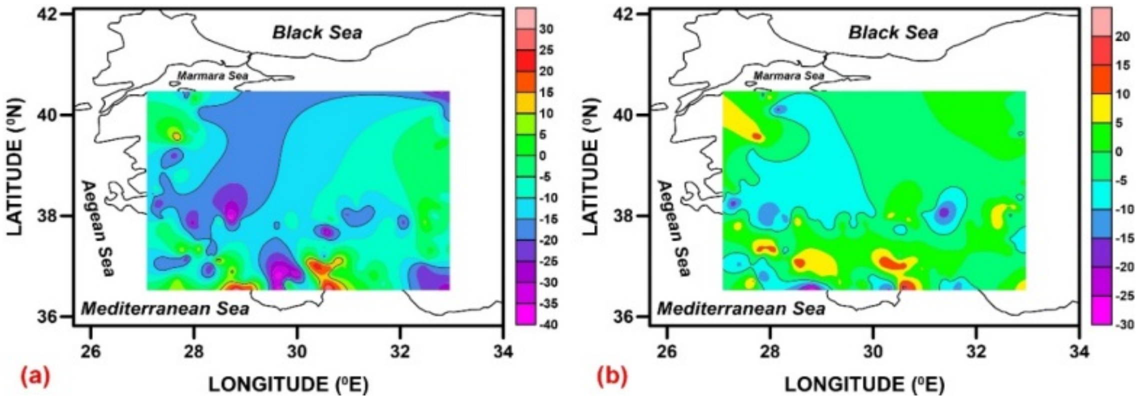

Fig. 2 EGM2008 gravity anomaly residual map (residuals in mgal) (a) Free-air (b) Bouguer

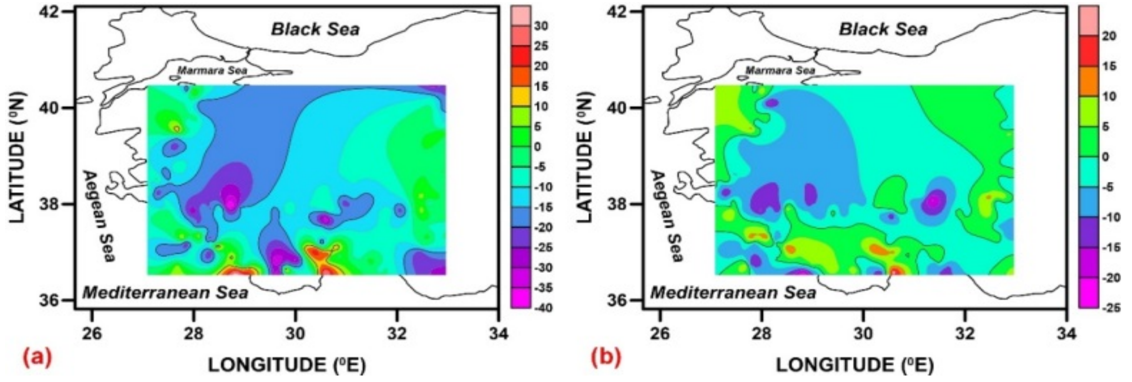

Fig. 3 EIGEN6C4 gravity anomaly residual map (residuals in mgal) (a) Free-air (b) Bouguer

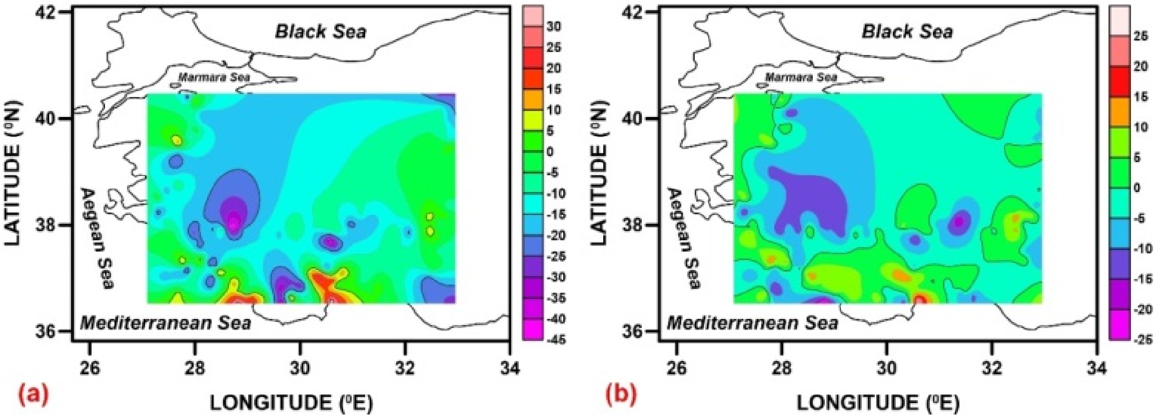

Fig. 4 GECO gravity anomaly residual map (residuals in mgal) (a) Free-air (b) Bouguer

TABLE II
STATISTICAL INFORMATION OF GRAVITY ANOMALY RESIDUALS BASED ON GMS OVER THE STUDY AREA (UNITS IN MGAL)

GM	Residual	Min.	Max.	Mean	Range	SD	RMSE
EGM2008	Free-air	-43.29	32.59	-7.90	75.88	13.63	15.71
	Bouguer	-29.72	24.01	-1.19	53.73	8.13	8.19
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

The visual interpretation of the gravity anomaly residual indicates that EGM2008, EIGEN6C4, and GECO have a similar Free-air and (simple) Bouguer gravity anomaly approximation over the study area.

SD is within a range of; 13.63 mGal to 13.88 mGal for Free-air gravity anomaly residual, 8.05 mGal to 8.16 mGal for (simple) Bouguer gravity anomaly residual. RMSE is within a range of; 15.71 mGal to 16.06 mGal for Free-air gravity anomaly residual, 8.12 mGal to 8.26 mGal for (simple) Bouguer gravity anomaly residual.

When the results presented in Table II are examined, the least SD (13.63 mGal) and RMSE (15.71 mGal) were obtained by EGM2008 for the Free-air gravity anomaly residuals. SDs and RMSEs of the GMs have a decreasing sequence as EGM2008 < 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 < EGM2008 < GECO.

From the minimum, maximum, and mean values in Table II, it is apparent that EGM2008, EIGEN6C4, and GECO overestimate the Free-air gravity anomalies. The approximations of the (simple) Bouguer gravity anomalies based on EGM2008, EIGEN6C4, and GECO are all largely negative (Figs. 2 (b)-4 (b)). This is a well-known characteristic of Bouguer gravity anomalies of land. The SDs of (simple) Bouguer gravity anomaly residuals in Table II are smaller than the SDs of Free-air gravity anomaly residuals due to the fact that (simple) Bouguer gravity anomalies are supposed to be smoother than Free-air gravity anomalies.

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

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

- The approximation of the Free-air gravity anomalies shows that EGM2008, EIGEN6C4, and GECO are almost identical with a slight advantage of EGM2008 over the study area.
- The (simple) Bouguer gravity anomaly modelling of EGM2008, EIGEN6C4, and GECO are similar with a slight advantage of EIGEN6C4. The data contributions of the satellite gravity mission GOCE to EIGEN6C4 have made 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 at regional-national scales in Turkey.
- By using a densified terrestrial 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, a major mission of geodesy is to calculate the functionals of the gravity field as accurately as possible from a GM and present these functionals to other geosciences. Therefore, further and future analysis of recent combined high-degree GMs (e.g. GOCE-based GMs) may give new for studying the Earth's gravity field.

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REFERENCES

[1] Helmert, F. R. Die Mathematischen und Physikalischen Theorieen der H¨oheren Geodäsie (Mathematical and Physical Theories of Higher Geodesy) (in German). Druck und Verlag von B.G. Teubner, Leipzig, Germany, (1880) 626 p.

[2] Plag, H-P., Altamimi, Z., Bettadpur, S., Beutler, G., Beyerle, G., Cazenave, A., Crossley, D., Donnellan, A., Forsberg, R., Gross, R., Hinderer, J., Komjathy, A., Ma, C., Mannucci, A. J., Noll, C., Nothnagel, A., Pavlis,, E. C., Pearlman, M., Poli, P., Schreiber, U., Senior, K., Woodworth, P. L., Zerbini, S., Zuffada, C. The goals, achievements, and tools of modern geodesy. In: Plag H-P, Pearlman M (Eds) Global Geodetic Observing System – Meeting the Requirements of a Global Society on a Changing Planet in 2020. Springer-Verlag, Berlin, Heidelberg, Germany, 2009, pp. 15-87.

[3] Dehant, V. International and national geodesy and its three pillars: (1) geometry and kinematics, (2) earth orientation and rotation, and (3) gravity field and its variability. In: Arijs E, Ducarme B (Eds) Earth Sciences Day of the CNBGG `Geodesy and Geophysics for the Third Millennium´. Belgian Academy of Sciences, 2005, pp. 27-35.

[4] Hildenbrand, T. G., Briesacher, A., Flanagan, G., Hinze, W. J., Hittelman, A. M., Keller, G. R., Kucks, R. P., Plouff, D., Roest, W., Seeley, J., Smith, D. A., Webring, M. Rationale and Operational Plan to Upgrade the U.S Gravity Database. USGS Open-File Report 02-463, 2002.

[5] Smith, D. The GRAV-D Project: Gravity for the Redefinition of the American Vertical Datum. A NOAA contribution to the Global Geodetic Observing System (GGOS) component of the Global Earth Observation System of Systems (GEOSS) Project Plan, 2007, http://www.ngs.noaa.gov/GRAV-D/pubs/GRAV- D_v2007_12_19.pdf (accessed 12 June 2018).

[6] Roman, D.R., Wang, Y.M., Saleh, J., Li, X. Geodesy, Geoids, & Vertical Datums: A Perspective from the U.S. National Geodetic Survey, Facing the Challenges - Building the Capacity. FIG Congress, 11-16 April 2010, Sydney, Australia, 2010.

[7] Li, X., Götze, H. J. Ellipsoid, geoid, gravity, geodesy, and geophysics, Geophysics (2001) 66 (6) 1660-1668.

[8] Barthelmes, F. Global models. In: Grafarend E (Ed) Encyclopedia of Geodesy. Springer International Publishing, Switzerland, 2014, pp.1-9, doi:10.1007/978-3-319-02370-0 43-1.

[9] Reigber, C., Lühr, H., Schwintzer, P. CHAMP mission status, Adv Space Res (2002) 30 (2) 129-134.

[10] Tapley, BD., Bettadpur, S., Watkins, M., Reigber, C. The gravity recovery and climate experiment: mission overview and early results, Geophys Res Lett (2004) 31 L09607.

[11] Floberghagen, R., Fehringer, M., Lamarre, D., Muzi, D., Frommknecht, B., Steiger, C. H., Pineiro, J., da Costa, A. Mission design, operation and exploitation of the gravity field and steady-state ocean circulation explorer mission, J Geod (2011) 85 (11) 749-758.

[12] Godah, W., Szelachowska, M., Krynski, J. On the analysis of temporal geoid height variations obtained from GRACE-based GGMs over the area of Poland, Acta Geophys (2017) 65 713-725.

[13] Novák, P. Direct modeling of the gravitational field using harmonic series, Acta Geodyn Geomater (2010) 7 (1) 35-47.

[14] Bolkas, D., Fotopoulos, G., Braun, A. On the impact of airborne gravity data to fused gravity field models, J Geod (2016) 90 (6) 561-571.

[15] Pavlis, N. K., Holmes, S. A., Kenyon, S. C., Factor, J. K. An earth gravitational model to degree 2160: EGM2008. General Assembly of the

Open Science Index, Geological and Environmental Engineering Vol:12, No:11, 2018 publications.waset.org/10009763.pdf

European Geosciences Union, 13-18 April, Vienna, Austria, 2008.

[16] Förste, C., Bruinsma, S. L., Abrikosov, O., Lemoine, J-M., Marty, J. C., Flechtner, F., Balmino, G., Barthelmes, F., Biancale, R. EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse. GFZ Data Services, 2014, doi: 10.5880/ICGEM.2015.1.

[17] Gilardoni, M., Reguzzoni, M., Sampietro, D. GECO: a global gravity model by locally combining GOCE data and EGM2008, Stud Geophys Geod (2016) 60 (2), 228-247.

[18] Hill, P., Bankey, V., Langenheim, V. Introduction to Potential Fields: Gravity. USGS fact sheet, 1997, http://pubs.usgs.gov/fs/fs-0239-95/fs-0239-95.pdf (accessed 12 June 2018).

[19] Hackney, R. I., Featherstone, W. E. Geodetic versus geophysical perspectives of the 'gravity anomaly', Geophys J Int (2003) 154 (1) 35-43.

[20] Mishra, D. C. Gravity anomalies. In: Lastovicka J (Ed) Geophysics and Geochemistry - Volume 3. EOLSS publishers/UNESCO, 2009, pp. 111-136.

[21] Featherstone, W. E., Dentith, M. C. A geodetic approach to gravity data reduction for geophysics, Comput Geosci (1997) 23 (10) 1063-1070.

[22] Hofmann-Wellenhof, B., Moritz, H. Physical Geodesy, 2nd edition. Springer-Verlag, Vienna, Austria, 2006.

[23] Hackney, R. I. Gravity, data to anomalies. In: Gupta HK (Ed) Encyclopedia of Solid Earth Geophysics. Springer, Dordrecht, the Netherlands, 2011, pp. 524-533.

[24] Sjöberg, L. E., Bagherbandi, M. Gravity Inversion and Integration - Theory and Applications in Geodesy and Geophysics. Springer, 2017, doi: 10.1007/978-3-319-50298-4.

[25] Rummel, R., Balmino, G., Johannessen, J., Visser, P., Woodworth, P. Dedicated gravity field missions-principles and aims, J Geodyn (2002) 33 3-20.

[26] Barthelmes, F. Definition of Functionals of the Geopotential and Their Calculation from Spherical Harmonic Models: Theory and Formulas Used by the Calculation Service of the International Centre for Global Earth Models (ICGEM). Scientific Technical Report STR09/02, Revised Edition, January 2013, GeoForschungZentrum Potsdam, 2013, doi: 10.2312/GFZ.b103-0902-26, http://icgem.gfz-potsdam.de/str-0902-revised.pdf (accessed 12 June 2018).

[27] Yilmaz, M., Turgut, B., Gullu, M., Yilmaz, I. The evaluation of high-degree geopotential models for regional geoid determination in Turkey, AKU J Sci Eng (2017) 17 (1) 147-153.

[28] Pavlis, N. K., Holmes, S. A., Kenyon, S. C., Factor, J. K. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), J Geophys Res (2012) 117 B04406, doi: 10.1029/2011JB008916.

[29] Morelli, C., Gantar, C., Honkasalo, T., McConnell, R. K., Tanner, J. G., Szabo, B., Uotila, U., Whalen, C. T. The International Gravity Standardization Net 1971 (IGSN71). International Association of Geodesy, Special Publication No. 4, 1974.

[30] Yilmaz, M., Gullu, M. A comparative study for the estimation of geodetic point velocity by artificial neural networks, J Earth Syst Sci (2014) 123 (4) 791-808.

[31] Karpik, A. P., Kanushin, V. F., Ganagina, I. G., Goldobin, D. N., Kosarev, N. S., Kosareva, A. M. Evaluation of recent Earth's global gravity field models with terrestrial gravity data Contrib Geophys Geod (2016) 46 (1) 1-11.

[32] Barthelmes, F., Köhler, W. International Centre for Global Earth Models (ICGEM), The Geodesists Handbook 2016, J Geod (2016) 90 (10) 907-1205, doi: 10.1007/s00190-016-0948-z.

[33] Pavlis, N. K., Factor, J. K., Holmes, S. A. Terrain-related gravimetric quantities computed for the next EGM, Proceedings of the 1st International Symposium of the International Gravity Field Service, J Mapp (Special Issue) (2007) 18 318-323.