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Baltica

BALTICA Volume 39 Number 1 June 2026: 25–36
https://doi.org/10.5200/baltica.2026.1.3

Research article

Regional assessment of recent high-degree global geoid models for Türkiye

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Soycan, A., Yilmaz, Y. 2026. Regional assessment of recent high-degree global geoid models for Türkiye. *Baltica 39 (1)* 25–36. Vilnius. ISSN 0067-3064.

Manuscript submitted 9 July 2025 / Accepted 9 February 2026 / Available online 5 March 2026

Abstract. The validation of recent global geoid models is essential for improving the accuracy and reliability of geodetic applications in Türkiye. This study aims to assess the performance of global geoid models, such as the Earth Gravitational Model 2008 (EGM2008) and other satellite-based models by comparing them with regional and national geoid models constructed using high-precision local GNSS and levelling data. The geoid undulations from global models are compared with those obtained from the Turkish national geoid model, developed from gravity measurements and geodetic surveys conducted by national agencies. The analysis involves statistical evaluation using Root Mean Square Error (RMSE) and standard deviations to quantify discrepancies. The results show significant variations in geoid heights, especially in tectonically active regions, highlighting the limitations of global models in accurately representing local geoid features. Based on the validation results, suggestions for improving the global models by incorporating local geophysical data are discussed. The findings emphasize the importance of region-specific geoid models for precise height transformations and geodetic applications in Türkiye.

Keywords: *Global Geoid Models (GGMs); GNSS/levelling data; geoid height validation; gravity field modelling; spherical harmonic expansion; local geoid refinement*

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INTRODUCTION

According to Pavlis (2013), Global Geopotential Models (GGMs) provide a mathematical representation of the Earth's external gravitational potential. These models include numerical values for specific parameters, error statistics corresponding to these values, and a set of mathematical formulas, constants, and computational methods used to derive gravity-related quantities (synthesis) and to estimate associated uncertainties through error propagation using a covariance matrix.

Geoid models play a crucial role in modern geodesy, providing a representation of the Earth's shape and serving as a reference surface for height determination. The geoid, defined as a hypothetical sea level surface under the influence of Earth's gravity field, is essential for converting between ellipsoidal heights (obtained from GNSS) and orthometric heights (obtained from levelling). However, the accuracy of geoid models can vary significantly depending on the resolution and data sources used (Mishra, Ghosh 2017). Recent advancements in global geoid modelling, such as the Earth Gravitational Model (EGM2020) (Barnes *et al.* 2020), have provided high-resolution global models derived from satellite gravity missions and other geophysical data. While these global models offer broad coverage, they often fail to account for the local geophysical and topographic variations that can be significant in tectonically active regions (Kim *et al.* 2018), such as Türkiye. Türkiye's complex geological structure, including its active seismic zones and varied terrain, necessitates a more refined geoid model to ensure accurate geodetic measurements (Nergizci *et al.* 2024).

The objective of this study is to validate the performance of recent global geoid models by comparing them with regional and national geoid models that have been developed specifically for Türkiye. These local models, constructed using high-precision GNSS and levelling data, are more sensitive to the region's unique gravitational characteristics. By conducting a comprehensive comparison between the global and local models, this research aims to assess the discrepancies in geoid undulations and highlight potential areas where global models can be improved. This validation process is vital for improving the reliability of geodetic applications in Türkiye, including height systems, infrastructure development, and precise positioning. The results will provide valuable insights into the limitations of current global geoid models and contribute to the enhancement of geoid modelling methodologies in geophysically diverse regions.

RELATED WORKS

The evaluation and application of Global Geopotential Models (GGMs) in regional geoid modelling have garnered considerable attention in recent years, particularly with the release of high-resolution models such as EGM2008 (Pavlis *et al.* 2008), European Improved Gravity model of the Earth by New techniques – Combined Model Version (EIGEN-6C4) and Experimental X-field Gravity Model 2019e (XGM2019e_2159). Numerous studies have assessed the performance of these models across diverse geodetic conditions, utilizing GNSS/levelling, terrestrial gravity data, and spectral analysis.

One of the most prominent global models, EGM2008 (Pavlis *et al.* 2012), represents a significant advancement in gravity field modelling. Developed through the combination of GRACE-derived satellite data and a globally merged 5-arc-minute grid of free-air gravity anomalies, EGM2008 achieves a resolution complete to degree and order 2159 and demonstrates an accuracy improvement by a factor of three to six over its predecessor, EGM96. The model's validation using independent GPS/levelling data revealed geoid discrepancies as low as 5–10 cm in regions with high-quality gravity data, underscoring its capability to rival regional models in some areas.

Building on this, Nyoka *et al.* (2022) conducted a comprehensive evaluation of 31 global geopotential models over Kenya, using GNSS-levelling data and gravity anomalies. Their results showed that EGM2008 performed slightly better in terms of geoid undulations, with a standard deviation of about 40.89 cm. Other high-resolution models, including EIGEN-6C4 and XGM-based solutions, exhibited comparable performance. In the analysis of residual gravity anomalies, EIGEN-6C4 provided the best fit. Considering both geoid undulations and gravity anomalies together, the study identified Satellite Gravity Gradiometry – Ultra-high-degree Gravitational Model 1 (SGG-UGM-1) and Satellite Gravity Gradiometry – Ultra-high-degree Gravitational Model 2 (SGG-UGM-2) as the most suitable models for future geoid modelling in Kenya.

A notable regional contribution is the UQG2012 quasigeoid model developed for Ukraine and Moldova by Marchenko *et al.* (2015). The model integrates dense terrestrial gravity data, multi-mission satellite altimetry over the Black Sea, and about 4,070 GPS/levelling points using a least-squares collocation approach with regularization. Long-wavelength signals were removed with EGM2008 up to degree and order 720, while terrain effects were modelled using the high-resolution SRTM3 digital terrain model. Validation against independent first- and second-order GPS/levelling data yielded root-mean-square differences of approximately 1.5 cm, demonstrating a clear improvement over earlier regional and continental quasigeoid solutions and confirming its centimetre-level regional performance.

In another study conducted in Kenya, Odera (2020) evaluated recent high-degree combined global gravity field models, including EGM2008, EIGEN-6C4, GECO, and SGG-UGM-1, over Kenya, using both GNSS/levelling-derived geoid undulations and free-air gravity anomalies. The results showed that all models perform at a comparable level over the region. In terms of geoid undulations, the assessment based on 18 GNSS/levelling points in the Nairobi area indicated that EIGEN-6C4 provides slightly a better agreement than EGM2008, GECO, and SGG-UGM-1. A countrywide evaluation using 8,690 free-air gravity anomalies further demonstrated that EIGEN-6C4 and SGG-UGM-1 achieve the best correspondence, reflecting the contribution of GOCE data in the long-to-medium wavelength components. Based on the combined analysis, the study concluded that EIGEN-6C4 represents the most suitable reference model for precise geoid modelling in Kenya, particularly when integrated with local terrestrial gravity data within a remove–compute–restore framework.

Similarly, in Ecuador, Carrión *et al.* (2023) compared several GGMs using both GNSS/levelling-derived geoid heights and geopotential values. They found that the XGM2019 e_2159 and EIGEN-6C4 models outperformed others in terms of both geometric and geophysical consistency. Importantly, the study revealed a strong influence of elevation and terrain complexity on model performance, suggesting that high-resolution GGMs still benefit from complementary local data.

In a North African context, a recent study in Egypt (Dawod, Al-Krargy 2023) highlighted the effectiveness of newer high-degree GGMs like EGM2008 and SGG-UGM-2. By comparing model-derived geoid heights to 13 GPS/levelling benchmarks and evaluating residuals, the authors determined that EGM2008 provided the lowest standard deviation, while SGG-UGM-2 demonstrated robustness in gravity anomaly comparisons. The study reinforced the necessity of incorporating high-quality terrestrial data to mitigate residual biases.

In Iran, GGM evaluations have extended beyond simple accuracy checks to the fusion of regional and global models. A hybrid geoid modelling approach using remove-compute-restore (RCR) techniques and combining EIGEN-6C4 with regional gravimetric models demonstrated superior results compared to standalone global or regional models. This approach achieved an RMS error of 0.14 m, validating the benefit of synergistic model integration over complex terrains like the Iranian plateau (Hosseini-Asl *et al.* 2021).

Lastly, a study conducted in the Netherlands addressed the optimal height transformation in the Amsterdam system. Using both regional gravimetric models and GGMs, the authors determined that the combined approach (incorporating EGM2008 and EIGEN-6C4) significantly improved the accuracy of orthometric heights. Their work highlighted the advantage of combining global and local models to refine geoid-based height systems even in low-relief areas (Fedorchuk *et al.* 2025).

GLOBAL GEOID MODELS

Global Geoid Models (GGMs) are constructed using spherical harmonic expansions. The lower and intermediate components of these expansions are primarily obtained through data derived from satellite orbit analyses, satellite-to-satellite tracking missions, and gravity gradiometry. To reach higher degrees and orders in the expansion, satellite-based data are integrated with terrestrial and oceanic gravity measurements, Digital Elevation Models (DEMs), and outputs from satellite altimetry (Torge, Müller 2012). Various techniques – such as mass points, finite elements, and splines – have been used to model the Earth's gravity field (Sünkel 1981, 1984; Meissl 1981), but spherical harmonics remain the standard for global representation. For this study, five global models (EGM2008, SGG-UGM-2, gravity field and EGM combined model (GECO), EIGEN-6C4, XGM2019e) and their adjusted versions with national GNSS/Levelling points were used**.** Table 1 lists the GGMs and their limitations. These models are broad, offering global coverage, but they may lack the accuracy needed for specific regions like Türkiye due to local geophysical anomalies.

The geopotential function W in spherical coordinates can be expressed as:

$$W(r,\theta,\lambda) = \frac{GM}{r}\left[1 + \sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^{n} \sum_{m=0}^{n} P_{nm}(\cos\theta) \left(C_{nm}\cos(m\lambda) + S_{nm}\sin(m\lambda)\right)\right] \quad (1)$$

where:

- C_{nm}, S_{nm} are the spherical harmonic coefficients,
- P_{nm} is unnormalized associated Legendre polynomials,
- R is the Earth's mean radius, r is the radial distance,
- θ and λ are the geocentric latitude and longitude,
- n and m are the degree and order of the spherical harmonics,
- a is the reference Earth radius,
- r is the geocentric radius,
- GM is Earth's gravitational parameter,

Table 1 GGMs and their limitations

GGM	n_{max}	Data Source	Limitations
EGM2008 (Pavlis *et al.* 2012)	2190 (~10 km)	Satellite, altimetry, terrestrial data	Satellite-only component relies on early GRACE-era solution (e.g., ITG-GRACE03S; 57 months, ~Sep 2002 – Apr 2007); no incorporation of later GRACE releases or GRACE-FO-era information.
SGG-UGM-2 (Liang *et al.* 2020)	2190 (~10 km)	GOCE, GRACE, altimetry + EGM2008-derived continental gravity data	High-degree land signal is inherited from EGM2008-derived continental gravity; therefore, not fully independent over continents.
XGM2019e (Zingerle *et al.* 2020)	2190 (~10 km)	GOCE, GRACE, EGM2008, terrestrial data	Possible medium-frequency errors.
EIGEN-6C4 (Förste *et al.* 2014)	2190 (~10 km)	GRACE, GOCE, altimetry + surface gravity anomaly grids (with EGM2008 over continents)	Over continents at shorter wavelengths, high-degree content is largely inherited from EGM2008/DTU grids; improvements mainly reflect GOCE/GRACE at low – medium degrees.
GECO (Gilardoni *et al.* 2016)	2190 (~10 km)	GOCE, EGM2008	Although complete to d/o 2190 (nominal ~10 km), GECO inherits EGM2008 coefficients from degree 360 to 2190; thus improvements are confined mainly to low–medium degrees (GOCE-updated band).

- *Cos(mλ), Sin(mλ)* are longitudinal variation terms,
- *(a/r)*^{n} is radial attenuation factor.

National geoid models for Türkiye

Over the past 35 years, Türkiye has developed several regional and national geoid models using various methods including gravimetric, astrogeodetic, and GNSS/levelling techniques (Soycan 2013; Yılmaz *et al.* 2006; Tuşat 2011; Doganalp and Selvi 2015; Kirici and Sisman 2015; Doganalp 2016; Karaaslan *et al.* 2016; Albayrak *et al.* 2020).

Initial studies began in the 1970s, using vertical deflection components at 98 astronomical stations. These early efforts were limited due to sparse and uneven data. In the 1980s, Doppler-based geoid models were introduced in southwest Anatolia using satellite technology (Ayan 1976, 1978; Gurkan 1979). The first national gravimetric geoid model, Türkiye Geoid-1991 (TG-91), was produced in 1991 using gravity data, terrain elevation, and the GPM2-T1(n_{max} = 200) global geopotential model. It employed the remove-restore method and least squares collocation (Ayhan 1993). In 1992, Turkiye Doppler Geoid-1992 (TDG-92) Doppler geoid, and in 1994, Türkiye Astro-Geodetic Geoid-1994 (TAG-94) astro-geodetic geoid were developed (Ayhan, Alp 1994). The establishment of the construction of Turkiye National Fundamental GPS Network (TUTGA99) in 1999 allowed for consistent GNSS-derived ellipsoidal heights. Combined with precise levelling "Turkiye's National Vertical Control Network (TUDKA)", it enabled the production of Turkiye Geoid-1999 (TG-99) and its update TG-99A, which incorporated GNSS/levelling data into the TG-91 model. TG-99A had an internal accuracy of ±5 cm and an external accuracy of ±10 cm, using 3 × 3 arc-minute grids (Ayhan *et al.* 2002). Later, an improved model TG-03 (Kılıçoğlu *et al.* 2005) was developed using enhanced global geopotential models (e.g., EGM96), denser gravity data, GNSS/levelling observations, and digital terrain models via the remove-restore method. TG-03 achieved a reported absolute accuracy of 8.8 cm.

Finally, Türkiye Geoid-2020 (TG-20) was announced. TG-20 was developed under the coordination of the General Directorate of Mapping as a result of the "Modernization of the Turkish Height System and Improvement of the Gravity Infrastructure Project" (HGM 2021) conducted between 2015 and 2020. TG-20 is the current official geoid model for Türkiye and its surrounding region, covering the area between 35°N–43°N latitude and 25°E–45°E longitude. TG-20 is a hybrid geoid model, computed using approximately 265,000 land gravity data points, the GOCO06S global geopotential model, and the SRTM V4.1 digital elevation model with a resolution of 7.2 arc-seconds. Gaps in gravity data over surrounding seas were filled using the XGM2019e global geopotential model up to degree and order 5399. The model was computed using the Least Squares Modification of Stokes' Formula with Additive Corrections (LSMSA), implemented via the LSMS-GEOLAB software (Yildiz *et al.* 2021). The transformation of the TG-20 gravimetric geoid to the national height system was performed using a four-parameter transformation, based on 182 historical GPS/leveling benchmarks uniformly distributed across the country. Absolute validation was conducted using 278 simultaneously collected GPS/levelling points located along seven test profiles, particularly in regions with high geoid slope variability. The standard deviation of differences in most test profiles was found to be below 2 cm, indicating a high level of accuracy for the model (Yildiz *et al.* 2021).

Other global and regional geoid models for Türkiye

In addition to Türkiye's national geoid models (e.g., TG-91, TG-99A, TG-03, THG-09, TG-20) and global geopotential models (e.g., EGM96, EGM2008, EGM2020), several alternative models provide regional representations of the geoid with varying resolution and accuracy.

One key group includes the European Gravimetric Geoid (EGG) series – such as EGG97 (Denker, Torge 1998), EGG2008 (Denker 2009), and EGG2015 (Denker 2015) – developed by the IAG and EuroGeographics. These models combine European gravity, GNSS/levelling, and altimetry data, offering higher resolution geoid representations applicable to eastern Europe, including Türkiye.

A notable high-resolution quasi-geoid model is Global Gravity Model Plus (GGMplus) (Hirt *et al.* 2013) developed in 2014 by Curtin University. It offers ~200 m resolution over land areas by integrating EGM2008, SRTM elevation data, and topographic modelling via the residual terrain model (RTM) approach. GGMplus is especially valuable in mountainous or inaccessible regions and serves as a useful tool in geophysics, hydrology, and Earth system science, although it does not replace national models like TG-20.

Another alternative is Geoid Model for the Mediterranean Region (GEOmed) (Brovelli, Sansó 1993), a regional hybrid quasi-geoid model developed under ESA and IAG initiatives for the Mediterranean region. GEOmed incorporates satellite, terrestrial gravity, GNSS/levelling, and high-resolution DEMs. It supports cross-border geodetic unification and vertical datum integration, offering valuable supplemental geoid information for Türkiye's coastal regions and aiding validation or refinement of national models.

STUDY AREA

Türkiye (Turkey) lies at the crossroads of Europe and Asia from 25◦ E to 45◦E and from 35◦N to 43◦N. Türkiye has a highly diverse and rugged topography, shaped by active tectonics, mountain-building processes, and erosion. Türkiye's surface area is 783,562 km^2. In the study area shown in Fig. 1. GNSS/levelling points are distributed for validation purposes at a density of one point per 4,200 km^2.

Methodology

Before describing the methodological steps, it is important to clarify the scope of the comparisons performed in this study. The high-degree terrestrial gravity information of the most recent combined global geopotential models over Türkiye is largely inherited from the EGM2008 gravity database. Consequently, the main differences between these models primarily originate from their low- and medium-degree components, which are determined by different satellite mission datasets and combination strategies. Given that the national TG-20 geoid model is based on dense terrestrial gravity observations and achieves an accuracy of approximately 2 cm, substantial improvements from global models are not expected.

Accordingly, no regional gravimetric geoid was computed using terrestrial gravity data in this study. Instead, geoid heights were directly derived from the published spherical harmonic coefficients of the selected Global Geopotential Models (GGMs) using standard synthesis formulas. For each GGM, geoid undulations were computed at the locations of GNSS/levelling benchmarks and on regular grids over Türkiye, and subsequently compared with the corresponding heights from national (TG-03, TG-20) and regional (EGG2015, GGMplus) geoid models.

To reduce systematic offsets and datum inconsistencies between the models and the GNSS/levelling data, low-order surface fitting and similarity transformations were applied. No remove-compute-restore (RCR) procedure or local gravity data integration was performed in this study.

Geoid height (N) at a given point on Earth's surface is the difference between the gravitational potential at that point and the reference ellipsoid's potential. The reference ellipsoid is an idealized, mathematically defined shape that approximates the Earth's shape, assuming a smooth, non-rotating Earth. The relationship between the geopotential and geoid height can be expressed as (Heiskanen, Moritz 1967; Bernhard, Moritz 2005; Sansò, Sideris 2013):

$$N=(U-W)/\gamma, \tag{2}$$

where:

- N is the geoid height,
- W denotes the gravity potential of the geoid, U is the normal gravity potential of the reference ellipsoid,
- γ is the normal gravitational acceleration at the location (approximately 9.81 m/s²).

The process of transforming from the geopotential model to geoid heights involves evaluating the differences in gravitational potential between the geoid and the reference ellipsoid at a specific point. This transformation requires high-precision gravity data

Fig. 1 Location map of Türkiye and its surrounding region, showing the hypsometric scale (in meters) on the right and the spatial distribution of the available geodetic dataset

and detailed topographic information to correct for regional variations.

The computation of geoid heights from global models follows a structured workflow:

- **Data Collection**: Satellite gravity data from missions like GRACE and GOCE are used in global models such as SGG-UGM-2 and XGM2019e_2159 to provide gravity field information. Additionally, terrestrial, and regional data (e.g., GNSS and levelling) are incorporated to enhance the resolution and accuracy.
- **Integration with GNSS/Levelling Data:** To refine geoid height estimates, GNSS and levelling date are incorporated. The relationship between orthometric height (H), ellipsoidal height (h), and geoid height (N) is given by:

$$H= h-N \quad (6)$$

Using least-squares adjustments or geoid modelling software, these datasets are combined to improve the geoid solution's local accuracy, especially in tectonically complex regions like Türkiye.

RESULTS AND DISCUSSION

In this study, to mitigate long- and medium-wavelength geoid errors and datum inconsistencies between geoid models and GPS/levelling data, we first fitted the global surfaces to a dense Turkish GNSS/levelling network using an optimal least-squares adjustment based on low-order polynomial, similarity, or collocation transformations. We then performed a staged evaluation: (i) intercompared five global geoids, (ii) benchmarked the regional solutions EGG2015 and GGMplus against five global geoid models and their adjusted versions, and (iii) Türkiye's national geoids TG-03 and TG-20 against five global geoid models and their adjusted versions.

Before presenting the intercomparison statistics, it should be noted that the results in Table 2 are based on the original, unadjusted global geoid models. No fitting to GNSS/levelling data was applied at this stage, as the aim is to assess the intrinsic consistency between the models.

The provided comparative statistics summarize the differences and characteristics between various gravity model comparisons (Table 2). In models such as GECO-XGM, GECO-SGG2, EIGEN-XGM, EIGEN-SGG2, and EIGEN-GECO, there are generally small average differences (e.g., average values range between –0.0025 m and 0.0004 m), indicating consistency across the models. However, differences in standard deviation (SD) and standard deviation values are observed. For example, GECO-XGM and GECO-SGG2 exhibit SD values of ±0.0968 m and ±0.0870 m, respectively, whereas the EIGEN-SGG2 and EIGEN-GECO pairs show lower values (±0.0529 m and ±0.0626 m). This primarily indicates a higher level of similarity between the EIGEN-SGG2 and EIGEN-GECO models, which can be attributed to their use of common terrestrial gravity data inherited from the EGM2008 model, rather than implying lower variance or superior performance. On the other hand, differences in EGM-XGM, EGM-SGG2, EGM-GECO, EGM-EIGEN, and SGG2-XGM show higher variance and RMSE values. For instance, EGM-XGM has an RMSE value of ±0.1531 m and a maximum deviation of 1.1555 m, which is significantly higher. As expected, after fitting the models to the GNSS/levelling data, the mean and median differences are close to zero, reflecting the removal of systematic offsets. This indicates that the EGM model tends to

Table 2 Comparison of the global geoid models with each other (original, unadjusted models; no GNSS/levelling fitting applied). The differences are in meters (m)

	GECO-XGM (m)	GECO-SGG2 (m)	EIGEN-XGM (m)	EIGEN-SGG2 (m)	EIGEN-GECO (m)
Minimum:	–0.4871	–0.3846	–0.4047	–0.3684	–0.2918
Maximum:	0.8590	0.9568	0.7469	0.7376	0.2867
Mean:	–0.0012	–0.0025	–0.0008	–0.0022	0.0004
Median:	–0.0002	–0.0001	–0.0013	–0.0006	–0.0006
Std Deviation:	±0.0968	±0.0870	±0.0709	±0.0529	±0.0626
Med. Abs. Dev.:	0.0463	0.0440	0.0309	0.0202	0.0345
Avr. Abs. Deviation:	0.0657	0.0612	0.0454	0.0320	0.0463
	EGM-XGM (m)	EGM-SGG2 (m)	EGM-GECO (m)	EGM-EIGEN (m)	SGG2-XGM (m)
Minimum:	–0.5433	–0.4277	–0.6410	–0.4704	–0.3302
Maximum:	1.1555	1.1114	0.7703	0.5954	0.7966
Mean:	0.0020	0.0006	0.0031	0.0028	0.0014
Median:	–0.0029	–0.0017	0.0059	–0.0001	–0.0001
Std Deviation:	±0.1531	±0.1366	±0.1473	±0.1320	±0.0673
Med. Abs. Dev.:	0.0703	0.0737	0.0742	0.0696	0.0329
Avr. Abs. Deviation:	0.1027	0.0979	0.1063	0.0960	0.0460

exhibit more deviations, particularly highlighting the significant differences between EGM-GECO and EGM-XGM. Therefore, the standard deviation and spatial distribution of residuals provide a more meaningful measure of the relative model performance. In summary, the relatively closer agreement among the EIGEN- and GECO-based models can be attributed to their more complete use of GRACE data, while the larger discrepancies observed in EGM2008-based comparisons are consistent with the limited temporal coverage of GRACE data in EGM2008. This indicates that careful model selection is required depending on the application and the underlying data content of the models. The closer agreement observed for EIGEN- and GECO-based models mainly reflects their more complete use of GRACE information rather than inherently higher accuracy. The small standard error values suggest a high level of internal consistency in the model-to-model comparisons. Figure 2 illustrates the results of the inter-comparison among the global gravity field models.

A comparative analysis was conducted between the EGG2015 model and five global geopotential models: EGM2008, EIGEN_6C4, GECO, SGG-UGM-2, and XGM2019e_2159 (Table 3). In their original (unadjusted) form, all models produced negative mean differences with respect to EGG2015, indicating that they generally estimated lower geoid heights. The observed negative mean differences mainly reflect systematic offsets between the reference potential (W_0) adopted by the global geopotential models and the zero level of the EGG2015 model, which is partly aligned with the European vertical datum (NAP). These offsets represent differences in reference surfaces rather

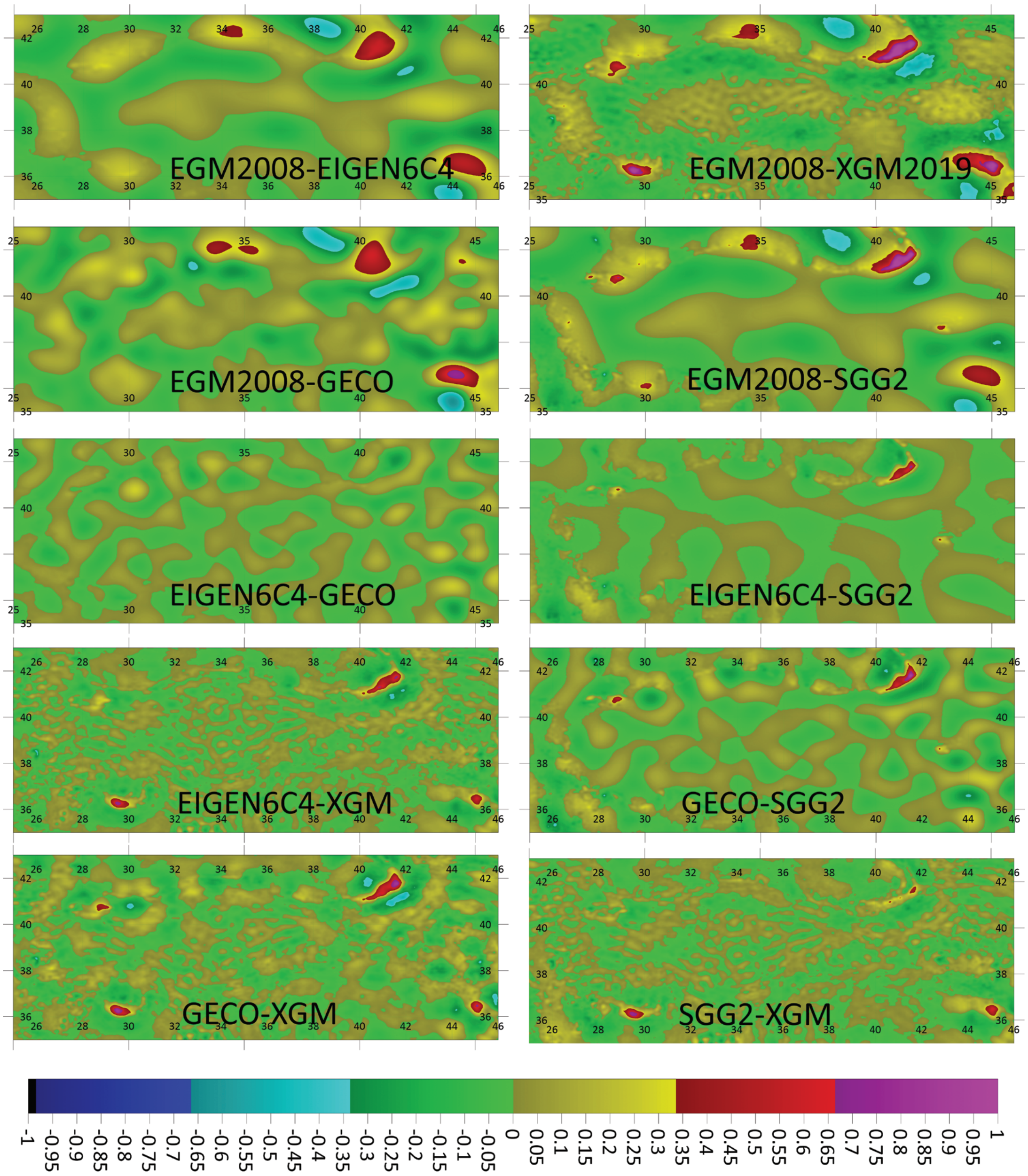

Fig. 2 Differences between the geoid heights of the global models. The differences are in meters (m)

than deficiencies in the models themselves. Among them, the GECO model exhibited the smallest mean bias (−0.5629 m), suggesting it aligns most closely with EGG2015 in terms of central tendency. The EIGEN_6C4 model demonstrated the lowest Root Mean Square (RMS) error and standard deviation, indicating the highest precision and least variability. On the other hand, XGM2019e_2159 displayed the widest range of error values, having both the most extreme minimum and maximum differences.

After fitting the global models to the GNSS/levelling data using a least-squares–estimated low-order similarity transformation, the mean differences shifted to positive values, implying that the adjusted models tend to estimate higher geoid heights than EGG2015. It should be emphasized that this systematic positive shift of the mean differences does not necessarily indicate a physically higher geoid level relative to EGG2015. Since no terrestrial or regional gravity data were used in this study and the adjustments were performed solely based on GNSS/levelling observations, the observed offset (~ 0.31–0.32 m) mainly reflects the realization of the origin of Türkiye's vertical height datum and the empirical bias absorbed by the low-order surface fitting. Therefore, the improved performance of the adjusted models should be interpreted in a relative and statistical sense within the adopted reference framework rather than as a direct physical datum difference. The adjusted XGM2019e_2159 model exhibits the lowest RMS value (±0.3671 m), which is largely driven by its small mean offset (0.3131 m) relative to EGG2015. However, the mean difference mainly reflects differences in the reference surface, whereas the standard deviation provides a more robust measure of the model fit. Based on the standard deviation, the EIGEN- and SGG-based models show the best agreement with EGG2015. These results show that the adjustment process improved the consistency of all models with EGG2015 by reducing systematic offsets, particularly for XGM2019e_2159, while the best model agreement in terms of standard deviation is achieved by the EIGEN- and SGG-based models.

On the other hand, in the comparison of GGMplus with other gravity field models (EGM2008, EIGEN_6C4, GECO, SGG-UGM-2, and XGM2019e_2159), it is observed that the minimum and maximum differences for EGM2008 and EIGEN_6C4 are identical, ranging from –0.5693 m to 0.8964 m, while XGM2019e_2159 exhibits the highest maximum value at 1.0229 m. The mean differences across all models are very close, with values between 0.1319 and 0.1355. In terms of error measures, SGG-UGM-2 shows the lowest root mean square (RMS) error (±0.1849 m) and standard deviation (±0.1285 m), indicating slightly better consistency compared to others (Table 4). The median absolute deviation and average absolute deviation values also point to a marginally better performance for SGG-UGM-2 and GECO models. Standard error values are uniformly low (around ±0.0005 to ±0.0007), suggesting high reliability in the dataset. After applying adjustments (ADJ_), the models show substantially higher minimum and maximum values, ranging between 0.2189 and 2.1396. The mean values after ad-

Table 3 The comparison of the global geoid models and the adjusted version with EGG2015. The differences are in meters (m)

EGG2015					
	EGM2008	EIGEN_6C4	GECO	SGG-UGM-2	XGM2019e_2159
Minimum:	–1.7148	–1.7594	–1.8111	–1.7384	–1.7025
Maximum:	0.2118	0.1006	0.2348	0.3199	0.3625
Mean:	–0.5661	–0.5648	–0.5629	–0.5670	–0.5641
Median:	–0.5805	–0.5805	–0.5761	–0.5808	–0.5857
Root Mean Square:	±0.5898	±0.5866	±0.5883	±0.5902	±0.5885
Std Deviation:	±0.1655	±0.1584	±0.1709	±0.1641	±0.1679
Med. Abs. Dev.:	0.0909	0.0910	0.0958	0.0935	0.0902
Avr. Abs. Deviation:	0.1230	0.1189	0.1274	0.1224	0.1227
Standard Error:	±0.0006	±0.0006	±0.0007	±0.0006	±0.0006
	ADJ_ EGM2008	ADJ_ EIGEN_6C4	ADJ_ GECO	ADJ_ SGG-UGM-2	ADJ_ XGM2019e_2159
Minimum:	–0.5498	–0.7523	–0.7090	–0.6906	–0.8285
Maximum:	1.1306	1.1528	1.1488	1.1333	1.2321
Mean:	0.3240	0.3321	0.3492	0.3261	0.3131
Median:	0.3095	0.3125	0.3342	0.3076	0.2935
Root Mean Square:	±0.3732	±0.3795	±0.4035	±0.3742	±0.3671
Std Deviation:	±0.1853	±0.1836	±0.2023	±0.1835	±0.1916
Med. Abs. Dev.:	0.1088	0.0969	0.1102	0.0987	0.0994
Avr. Abs. Deviation:	0.1404	0.1354	0.1493	0.1368	0.1405
Standard Error:	±0.0007	±0.0007	±0.0008	±0.0007	±0.0007

justment are approximately around 1.000 m for all models, indicating a systematic shift. RMS values remain close to ±1.000 m, with XGM2019e_2159 showing the lowest RMS error (±1.0201 m) among the adjusted models. Standard deviations after adjustment are slightly higher compared to the unadjusted case, but still reflect reasonable consistency, with EIGEN_6C4 showing the smallest variation (0.1629 m). Overall, the adjustment process homogenizes the results across different models, but slight performance differences are still notable, particularly favouring SGG-UGM-2 and XGM2019e_2159.

Another comparison was made with the global models and their adjusted versions using TG-03 and TG-20. The results are shown in Table 5. The provided statistical data compares the differences between various gravity models (TG-20 and TG-03) in terms of their spatial coordinates and geoid heights. For the TG-20 model, the data includes values for latitude (LAT), longitude (LON), and height (N), as well as for the different models: EGM2008, EIGEN_6C4, GECO, SGG-UGM-2, XGM2019e_2159, and their adjusted versions (ADJ). The TG-20 model generally shows a range of values for geoid height differences from –1.3043 m to 0.3304 m, with the adjusted versions of the models (such as ADJ_EGM2008, ADJ_EIGEN_6C4) showing improvements, with a maximum of 1.2978 m for ADJ_EGM2008. The mean values for the geoid height differences in the TG-20 model are close to –0.7, with low standard deviations, indicating relatively consistent results across the models.

In contrast, the TG-03 model, which has a larger number of values (32412), shows a broader range of geoid height differences with a minimum of –4.6611 m and a maximum of 0.9572 m for EGM2008 and similar ranges for other models like EIGEN_6C4 and GECO. The geoid height differences for TG-03 are more dispersed, with slightly higher standard deviations (ranging from 0.2287 m to 0.2609 m for the adjusted versions), suggesting more variability in the results. The mean value for geoid height differences in TG-03 is around –1.0 m, with the adjusted versions showing less deviation.

In summary, the TG-20 model offers relatively more stable and consistent geoid height difference values with lower variance, particularly when compared to the TG-03 model, which exhibits larger variations and a broader range of results. This suggests that TG-20 may be more suitable for applications requiring higher precision and consistency, while TG-03, with its broader range and variability, could be applicable for situations where a wider scope of data is needed. The adjusted models in both TG-20 and TG-03 provide slight improvements in terms of geoid height difference values, indicating that these adjustments help in refining the results.

Although the applied surface fitting significantly reduced systematic offsets between the global models and the GNSS/levelling data, it mainly corrects long-wavelength and datum-related biases. Local and medium-wavelength discrepancies, which originate from model errors, terrain effects, and inherited terrestrial gravity uncertainties, remain largely unaffected. Fur-

Table 4 The comparison of the global geoid models and the adjusted version with EGG2015. The differences are in meters (m)

GGMplus					
	EGM2008	EIGEN_6C4	GECO	SGG-UGM-2	XGM2019e_2159
Minimum:	–0.5693	–0.5693	–0.2385	–0.2880	–0.3429
Maximum:	0.8964	0.8964	0.8024	0.8997	1.0229
Mean:	0.1319	0.1319	0.1355	0.1330	0.1352
Median:	0.1091	0.1091	0.1069	0.1019	0.1023
Root Mean Square:	±0.2268	±0.2268	±0.1906	±0.1849	±0.1941
Std Deviation:	±0.1844	±0.1844	±0.1340	±0.1285	±0.1393
Med. Abs. Dev.:	0.0982	0.0982	0.0728	0.0691	0.0710
Avr. Abs. Deviation:	0.1370	0.1370	0.0998	0.0961	0.1020
Standard Error:	±0.0007	±0.0007	±0.0005	±0.0005	±0.0006
	ADJ_ EGM2008	ADJ_ EIGEN_6C4	ADJ_ GECO	ADJ_ SGG-UGM-2	ADJ_ XGM2019e_2159
Minimum:	0.3512	0.4092	0.3629	0.4086	0.2189
Maximum:	2.1335	2.1105	2.1009	2.1020	2.1396
Mean:	1.0116	1.0228	1.0420	1.0171	1.0040
Median:	0.9866	0.9889	1.0184	0.9857	0.9793
Root Mean Square:	±1.0321	±1.0357	±1.0576	±1.0305	±1.0201
Std Deviation:	±0.2046	±0.1629	±0.1812	±0.1653	±0.1803
Med. Abs. Dev.:	0.1089	0.0809	0.0962	0.0829	0.0888
Avr. Abs. Deviation:	0.1510	0.1176	0.1331	0.1194	0.1282
Standard Error:	±0.0008	±0.0007	±0.0007	±0.0007	±0.0007

Table 5 The comparison of the global geoid models and the adjusted version with TG-03 and TG-20. The differences are in meters (m)

TG-03							
Number of values: 32412	Min.	Max.	Mean	Med.	Standard error	Average deviation	Standard deviation
EGM2008	–4.6611	0.0433	–0.9865	–0.9655	±0.0013	0.1454	0.2287
EIGEN_6C4	–4.6014	0.1099	–0.9985	–0.9761	±0.0012	0.1363	0.2236
GECO	–4.7410	0.0492	–0.9983	–0.9797	±0.0013	0.1467	0.2373
SGG-UGM-2	–4.5801	0.1364	–1.0008	–0.9765	±0.0012	0.1337	0.2192
XGM2019e_2159	–4.6944	0.0547	–1.0005	–0.9794	±0.0012	0.1363	0.2240
ADJ_EGM2008	–3.7871	0.9572	–0.1351	–0.1197	±0.0013	0.1467	0.2304
ADJ_EIGEN_6C4	–3.8210	0.9466	–0.1310	–0.1181	±0.0013	0.1449	0.2341
ADJ_GECO	–3.8656	0.9979	–0.1167	–0.1025	±0.0014	0.1692	0.2609
ADJ_SGG-UGM-2	–3.8003	0.9730	–0.1377	–0.1210	±0.0013	0.1409	0.2275
ADJ_XGM2019e_2159	–3.9044	0.9975	–0.1480	–0.1343	±0.0013	0.1481	0.2387
TG-20							
Number of values: 11691	Min.	Max.	Mean	Med.	Standard error	Average deviation	Standard deviation
EGM2008	–1.3043	0.3304	–0.6788	–0.7135	±0.0015	0.1267	0.1666
EIGEN_6C4	–1.2390	0.4068	–0.6908	–0.7231	±0.0015	0.1235	0.1662
GECO	–1.2802	0.1934	–0.6905	–0.7199	±0.0017	0.1357	0.1806
SGG-UGM-2	–1.1289	0.4323	–0.6931	–0.7271	±0.0015	0.1213	0.1623
XGM2019e_2159	–1.1801	0.5040	–0.6927	–0.7228	±0.0016	0.1257	0.1735
ADJ_EGM2008	–0.3950	1.2978	0.1721	0.1321	±0.0017	0.1367	0.1834
ADJ_EIGEN_6C4	–0.3564	1.2674	0.1763	0.1401	±0.0017	0.1335	0.1829
ADJ_GECO	–0.4302	1.2206	0.1907	0.1600	±0.0019	0.1463	0.2007
ADJ_SGG-UGM-2	–0.3149	1.2491	0.1697	0.1354	±0.0017	0.1324	0.1803
ADJ_XGM2019e_2159	–0.3912	1.6230	0.1594	0.1289	±0.0018	0.1366	0.1928

thermore, the GNSS/levelling network and the national TG models are not fully identical in terms of reference frame and error characteristics. Consequently, the standard deviation with respect to TG-03 and TG-20 does not necessarily decrease after adjustment.

CONCLUSION

This study assessed the performance of high-degree Global Geoid Models (GGMs) over Türkiye by comparing them with national geoid models TG-03 and TG-20 using detailed GNSS/levelling datasets. The results showed that while global models such as EIGEN_6C4 and SGG-UGM-2 improved after local adjustment, they still could not match the precision and consistency of the TG-20 model, which demonstrated superior geoid height accuracy across the region. The analysis highlighted notable discrepancies in areas with complex topography and tectonic activity, underscoring the limitations of GGMs when applied without regional refinement.

The study emphasizes that while GGMs offer valuable global coverage, they are insufficient on their own for high-precision applications in geophysically complex regions like Türkiye. Instead, integrating local gravity measurements and GNSS/levelling data through hybrid modelling approaches significantly enhances accuracy. Looking ahead, future geoid models should also incorporate dynamic geophysical factors such as crustal density variations and seismic activity to better represent Türkiye's subsurface characteristics. These findings advocate for the development of tailored regional models in other tectonically active regions as well.

ACKNOWLEDGMENTS

The authors sincerely thank the two anonymous reviewers for their valuable comments and suggestions, which greatly improved the quality of this manuscript.

Conflict of interests

The authors declare that they have no conflict of interest. Artificial intelligence tools were used only for language editing and revision of the manuscript. The authors are fully responsible for the content of this article.

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