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Research article

Evaluation and Regional Adjustment of the Ultra-High-Resolution GGMplus Geoid Model: A Case Study in Türkiye

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Abstract. The Global Gravity Model plus (GGMplus) ultra-high-resolution geoid model and its regionally adjusted version, ADJ_GGMplus, are evaluated over Türkiye by comparing them with national geoid models (TG-03 and TG-20) and GNSS/levelling observations. The GGMplus model, with a spatial resolution of approximately 200 meters, offers a significant potential for regional geoid modelling, particularly in topographically and geologically complex areas. However, systematic biases – especially in regions with steep gravity gradients – necessitate regional calibration. In this context, the primary objective of this research is to derive and evaluate the ADJ_GGMplus model by incorporating 187 GNSS/levelling control points to improve local geoid accuracy. National-scale comparisons and local-scale analyses across 17 regions with varying geographical characteristics were conducted to quantify model performance. The results indicate that unadjusted GGMplus tends to underestimate geoid heights, with deviations reaching several decimetres in rugged terrain, whereas ADJ_GGMplus significantly improves model performance by reducing absolute mean errors from over 0.9 m to 0.19–0.35 m in critical regions and substantially mitigating systematic biases across the study areas.. Statistical metrics such as RMS, skewness, kurtosis, and Kolmogorov-Smirnov test results support these findings. Overall, the adjusted model demonstrates enhanced reliability and suitability for geodetic, engineering, and sea-level-related applications in Türkiye.

Keywords: *GGMplus; TG-03 geoid model; TG-20 geoid model; Geoid modelling*

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INTRODUCTION

The geoid – defined as an equipotential surface of the Earth's gravity field that best fits the mean sea level (MSL)(Rapp 1974) and extends beneath the continents – is accepted in geodesy as the reference surface for vertical control networks; yet, because computations for horizontal control networks are performed on the ellipsoid, determining the geoid has become one of geodesy's fundamental objectives (Torge 1980). The geoid is a function of the Earth's mass distribution, and the observations employed in its determination mirror the spatial variability of mass density within the Earth. This surface can be determined globally or regionally by integrating data acquired through various measurement techniques. Depending on the spatial scale, the geoid consists of components with distinct wavelengths. The so-called ultra-short component, defined between 20 km and 2 km, theoretically requires a spherical-harmonic expansion on the order of degree 2,000 to degree 20,000 to fully capture localized topographic and mass density variations (Torge 1980), whereas currently available global gravity models generally operate at lower degrees and rely on high-resolution topographic data to resolve these ultra-short wavelengths. Long-wavelength contributions reflect the influence of deep-seated mass anomalies, whereas medium-

and short-wavelength components – constituting a significant share of gravity anomalies – are controlled by regional geodetic and topographic structures. The ultra-short component captures the effects of local topography and shallow disturbing masses (Aksoy *et al*. 1999). Contemporary practice generally derives long-wavelength effects from global geopotential coefficients, medium-wavelength effects from gravity data, and short- to ultra-short-wavelength effects via combined approaches (Soycan 2002; Soycan *et al*. 2023).

In recent years, studies involving the Global Gravity Model plus (GGMplus; Hirt *et al*. 2013) model have highlighted its potential and versatility in high-resolution geoid and gravity field applications across diverse geographical and methodological contexts.

For instance, Khazraei *et al*. (2017) investigated the integration of global and regional geoid models within a limited area in Iran (~ 100 km²), evaluating EGM2008, GGMplus, and IRGeoid10 against GNSS/levelling data using the Least Squares Variance Component Estimation (LS-VCE) method. Despite a small extent of the study area, their use of 2D first- and second-order polynomial models revealed that second-order modelling yielded a better performance, with EGM2008 producing the lowest standard deviation (~ 0.002 m). In a different context, Morozova *et al*. (2021) assessed a quasi-geoid model in Latvia, using astrogeodetic vertical deflection (VD) observations from a digital zenith camera (VESTA) together with GNSS/levelling data. Through the DFHRS method, they tested three modelling strategies and found that the optimal results (~ 0.006 m standard deviation) were achieved by integrating both terrestrial VD measurements and VD derivatives from GGMplus and EGM2008, with GGMplus showing stronger agreement in terms of VD consistency. Similarly, Indriana *et al*. (2020) validated terrestrial gravity measurements in Semarang, Indonesia, through statistical correlation and coherence analyses against GGMplus data. High correlation values (0.86–0.95 for 2D, ~ 0.93 for 1D) affirmed the reliability of GGMplus for validating field data, while low correlation values (~ 0.4–0.6) successfully indicated potential acquisition errors. Furthermore, Camacho and Alvarez (2021) conducted a comparative assessment of EIGEN-6C4 and GGMplus models over a volcanic region in central Mexico, employing 3D gravity inversions to investigate subsurface density distributions. Their results demonstrated that the GGMplus model, with its finer spatial resolution (~ 200 m), more effectively captured shallow and high-frequency geological structures than EIGEN-6C4 (~ 1 km) did, underscoring its advantage for a detailed geophysical modelling. Collectively, these studies underscore the effectiveness of GGMplus in small-scale and regional applications, particularly where high-resolution gravity data and precise modelling are essential. Recent comprehensive investigations over Türkiye have demonstrated that while high-degree global geopotential models (such as EGM2008, EIGEN-6C4, and XGM2019e) provide consistent global coverage, their direct application in topographically and tectonically complex regions leads to decimetre-level discrepancies unless regional refinement using GNSS/levelling control networks is applied (Soycan, Yilmaz 2026).

In this study, the performance of the GGMplus model and its regionally adjusted version, ADJ_GGMplus (refined using 187 GNSS/levelling control points), was evaluated and compared with the national geoid models of Türkiye, TG-03 and TG-20, at the national scale. Additionally, performance analyses of both models were conducted across 17 local regions.

The main objectives of this study are (i) to assess the performance of GGMplus over Türkiye, (ii) to quantify its regional discrepancies, and (iii) to evaluate the improvement obtained through the regional adjustment of GGMplus using GNSS/levelling control points.

The study consists of four main sections. The first section covers the regional use of global geoid models and related academic studies. The second section provides information on the definition of the geoid and geoid modelling methods. The third section presents the application of the GGMplus global geoid model in Türkiye along with its numerical results. The final section includes conclusions and recommendations.

STUDY AREA, DATASETS, AND METHODOLOGY

Geoid determination is a complex geodetic process aimed at characterizing the physical properties of the Earth's gravity field and enabling the precise computation of orthometric heights. Modern positioning relies on two distinct surfaces: the geoid, which is a physical equipotential surface corresponding to mean sea level, and the reference ellipsoid, which is a mathematical surface used for geometric coordinates. Global Navigation Satellite Systems (GNSS) provide horizontal position and vertical (ellipsoidal) height relative to the reference ellipsoid. To obtain physically meaningful orthometric heights, ellipsoidal heights are converted using geoid undulation (N). Among the primary approaches for geoid determination are gravimetric, geometric, and hybrid methods. Gravimetric models utilize terrestrial, marine, and satellite gravity observations combined with topographic terrain reductions (Moritz 1980; Ollikainen 1997; Kiamehr, Sjöberg 2005; Corchete 2010; Abbak *et al*. 2012). Geometric geoid heights are derived directly from GNSS ellipsoidal heights and precise levelling

orthometric heights (Deniz *et al*. 2001; Soycan, Soycan 2003). Hybrid geoid models combine gravimetric models with GNSS/levelling control networks via regional surface fittings, providing optimal accuracy for geodetic and engineering infrastructure (Aksoy *et al*. 1999; Corchete 2010; Hirt 2011; Kılıçoğlu *et al*. 2011).

In recent years, the integration of satellite gravimetry missions, such as GRACE (Tapley *et al*. 2019; Chen *et al*. 2022) and GOCE (Rummel *et al*. 2011), with high-resolution digital elevation models (e.g., SRTM, TanDEM-X) has enabled the development of more detailed and reliable geoid models at both global and regional scales. In this context, ultra high-resolution gravity models like GGMplus have introduced a new dimension to local-scale geoid determination, significantly enhancing the accuracy and applicability of geodetic and engineering applications.

Since the 1970s, various studies have been conducted in chronological order to develop local and regional geoid models in Türkiye. In an early attempt, Ayan (1978) used the astro-geodetic deflection of vertical observations at 98 stations. Subsequently, the South-western Anatolia Doppler Geoid was computed using satellite Doppler measurements (Ayhan *et al*. 1987). Türkiye's first gravimetric geoid model, TG-91, was developed by the General Command of Mapping by integrating the GPM2-T1 global geopotential model, gravity data, and Digital Elevation Models (DEM) (Ayhan 1993). This was followed by the Türkiye Doppler Geoid (TDG-92) in 1992 and the Türkiye Astro-geodetic Geoid (TAG-94) in 1994 (Ayhan, Alp 1994). In the late 1990s, GPS/levelling data were integrated with TG-91 to form TG-99 and TG-99A. Later, the TG-03 national geoid model was developed using the Remove-Restore technique based on the EGM96 global model, terrestrial/marine gravity, DEM data, and GPS/levelling observations, achieving an accuracy of 8.8 cm with a spatial resolution of 3 arc-minutes (~ 5 km) (Kılıçoğlu *et al*. 2005). The densification networks established by local authorities also utilize GNSS and levelling measurements to transform horizontal position and vertical (ellipsoidal) height into orthometric heights using geoid undulations.

The Türkiye Geoid-2020 (TG-20) represents the current official hybrid geoid model of Türkiye, developed by the General Directorate of Mapping (HGM 2021). Covering 35°–43°N and 25°–45°E, TG-20 has a spatial resolution of 7.2 arc-seconds (~ 200 m) and incorporates ~ 265,000 terrestrial gravity observations, the GOCO06S global model, XGM2019e, and the SRTM V4.1 DEM using the LSMSA method (Yıldız *et al*. 2021). Alignment with the national vertical datum was achieved using a 4-parameter transformation based on 182 GPS/levelling control benchmarks, attaining a standard deviation below 2 cm across validation profiles. While TG-20 serves as the official national standard, GGMplus offers an ultra-high-resolution (~ 200 m) global dataset with uniform spectral gravity representation, providing distinct advantages in high-frequency topographic modelling, geophysical density inversion, and unsurveyed cross-border applications where dense terrestrial gravity networks are unavailable.

GGMplus (Global Gravity Model plus) offers high-resolution (200 m) gravity maps and datasets for terrestrial and near-coastal regions worldwide within ±60° latitude. It is the first model to achieve local-level resolution with a near-global extent, bridging the gap between earlier models that either focused on global coverage with coarse resolution or detailed representation over limited areas. GGMplus represents Earth's gravity field using commonly applied functionals: (i) gravity accelerations, (ii) gravity disturbances, (iii) deflections of the vertical in North-South and East-West directions, and (iv) quasigeoid heights, covering 3,062,677,383 points at a spatial resolution of 7.2 arc-seconds (Hirt *et al*. 2013). The features of GGMplus are given in Table 1. This high resolution enables a detailed representation of small-scale gravity variations across both continental and island regions. The model is based on an advanced hybrid approach that integrates satellite-derived gravity data with topographic elevation models to enhance gravity field modelling.

To derive the regionally adjusted geoid model, ADJ_GGMplus, a four-parameter transformation model based on least-squares adjustment was implemented using 187 GNSS/levelling control points distributed across Türkiye. First, the GNSS/levelling-derived geoid heights (N_GNSS/levelling) at the control points were calculated as:

$$N_{\text{GNSS/levelling}} = h - H \tag{1}$$

where h is the GNSS-derived ellipsoidal height and H is the orthometric height obtained from precise levelling. The differences (ΔN) between the GNSS/levelling geoid heights and the original GGMplus geoid heights (N_GGMplus) were then formed:

$$\Delta N = N_{\text{GNSS/levelling}} - N_{\text{GGMplus}} \tag{2}$$

A four-parameter differential correction surface was fitted to these height differences using the following mathematical formulation:

$$\Delta N(\varphi, \lambda) = x_0 + x_1\cos(\varphi - \varphi_0)\cos(\lambda - \lambda_0) + x_2\cos(\varphi - \varphi_0)\sin(\lambda - \lambda_0) + x_3\sin(\varphi - \varphi_0) \tag{3}$$

where φ and λ are the geodetic latitude and longitude of the control points, respectively. To reduce numerical correlation among the parameters, the coordinates φ and λ were centralized relative to the study area's

mean latitude (φ_0) and longitude (λ_0) using ($\varphi - \varphi_0$) and ($\lambda - \lambda_0$). The transformation parameters estimated via least-squares adjustment define the spatial correction surface, where x_0 represents the systematic (uniform) bias (offset), while x_1, x_2, and x_3 represent the tilt and rotation effects of the geoid surface relative to the ellipsoid. Once the optimal parameters were determined, the smooth regional correction surface $\Delta N_{corr}(\varphi, \lambda)$ was evaluated across the entire GGMplus model grid – rather than being applied strictly at control points – and added to the original model to construct the final adjusted geoid surface:

$$N_{ADJ_GGMplus} = N_{GGMplus} + \Delta N_{corr}(\varphi, \lambda) \quad (4)$$

One of the distinguishing features of GGMplus is its ability to retain the spectral content of gravity data across a wide bandwidth, effectively combining long-wavelength satellite observations with short-wavelength topographic contributions. This approach enables the model to achieve not only global coverage but also the precision required for local and regional applications. The GGMplus model surpasses the resolution offered by conventional global gravity models, providing a modern solution to the need for high-resolution geoid determination. In this context, evaluating the model's applicability at the local scale is particularly critical in regions with significant topographic variability. In morphologically complex and gravitationally heterogeneous areas such as Türkiye, the performance of GGMplus represents a noteworthy subject of investigation for both academic research and applied geodesy.

Table 1 The features of GGMplus

Feature	Description
Resolution	~ 7.2 arc-seconds (approximately 200 m)
Coverage	Global (60° N, 60° S)
Data Layers	Geoid height, gravity anomaly, gravity potential
Data Sources	EGM2008, SRTM30_PLUS, GOCE, GRACE
Method	Spectral harmonic combination + topographic reduction (Remove–Restore approach)

RESULTS AND DISCUSSION

In the evaluation of model performances, the differences between reference geoid heights (N_{ref}) and model-derived geoid heights (N_{model}) were evaluated using the Root Mean Square Error (RMSE) and Standard Deviation (SD), where N_{ref} denotes the GNSS/levelling-derived geoid heights at the control points, and N_{model} represents the geoid heights interpolated from the respective models. The RMSE quantifies the overall magnitude of discrepancies including systematic biases, while the SD represents the dispersion of residuals around the mean error ($ME = \Delta N_{mean}$):

$$RMSE = \sqrt{\left[\frac{1}{n}\sum\left(N_{ref} - N_{model}\right)^2\right]},$$

$$SD = \sqrt{\left[\frac{1}{n-1}\sum\left(\left(N_{ref} - N_{model}\right) - ME\right)^2\right]} \quad (5)$$

To demonstrate the effectiveness of GGMplus compared to global models, a comparison with Earth Gravitational Model 2008 (EGM2008) at the scale of Türkiye has been conducted and is presented in Fig. 1.

The difference map of the obtained geoid heights is presented in Fig. 2, and the corresponding numerical data are provided in Table 2.

Figure 2 displays the EGM2008 – GGMplus difference map for 19,844,979 grid points across Türkiye, illustrating both the spatial distribution of inter-model discrepancies and their statistical characteristics. A continuous colour spectrum conveys the magnitude and sign of the differences: blue-to-purple hues denote negative values, green shades indicate near-zero agreement, and warm colours ranging from yellow to deep red mark positive values. Pronounced positive differences (reds) cluster in the north-eastern sector of Eastern Anatolia, indicating that EGM2008 yields higher geoid heights there than GGMplus. Conversely, Western Anatolia and the southern coastal belt exhibit predominantly negative differences (blue-purple), whereas Central Anatolia and the mid-Black Sea region appear largely in green, implying close concordance between the models.

Statistically, the mean and median differences are 0.130 m and 0.100 m, respectively, confirming a systematic tendency for EGM2008 to exceed GGMplus. The minimum and maximum differences are –0.413 m and 0.874 m, giving an overall range of 1.287 m. The root-mean-square error is 0.215 m, with a standard deviation of 0.172 m and a variance of 0.030 m², indicating that most deviations fall within ≈ 0.20 m of the mean. A positive skewness of 0.993 reveals that large positive outliers are more common than negative ones, and a kurtosis of 4.41 points to heavy tails relative to a normal distribution. Robust location estimates that down-weight extremes – the 10% trimmed mean (0.120 m), Winsorised mean (0.122 m), tri-mean (0.106 m), and interquartile mean (0.104 m) – show that the bulk of the differences concentrate around 0.10–0.12 m. The mean absolute deviation is 0.126 m, and the median absolute deviation is 0.090 m.

These results demonstrate that significant, spatially coherent differences exist between EGM2008 and GGMplus over Türkiye, especially in a topographically complex terrain, whereas flatter regions display a stronger agreement. This finding aligns with the national-scale assessments of Soycan and Yilmaz (2026), who reported that EGM2008-based models

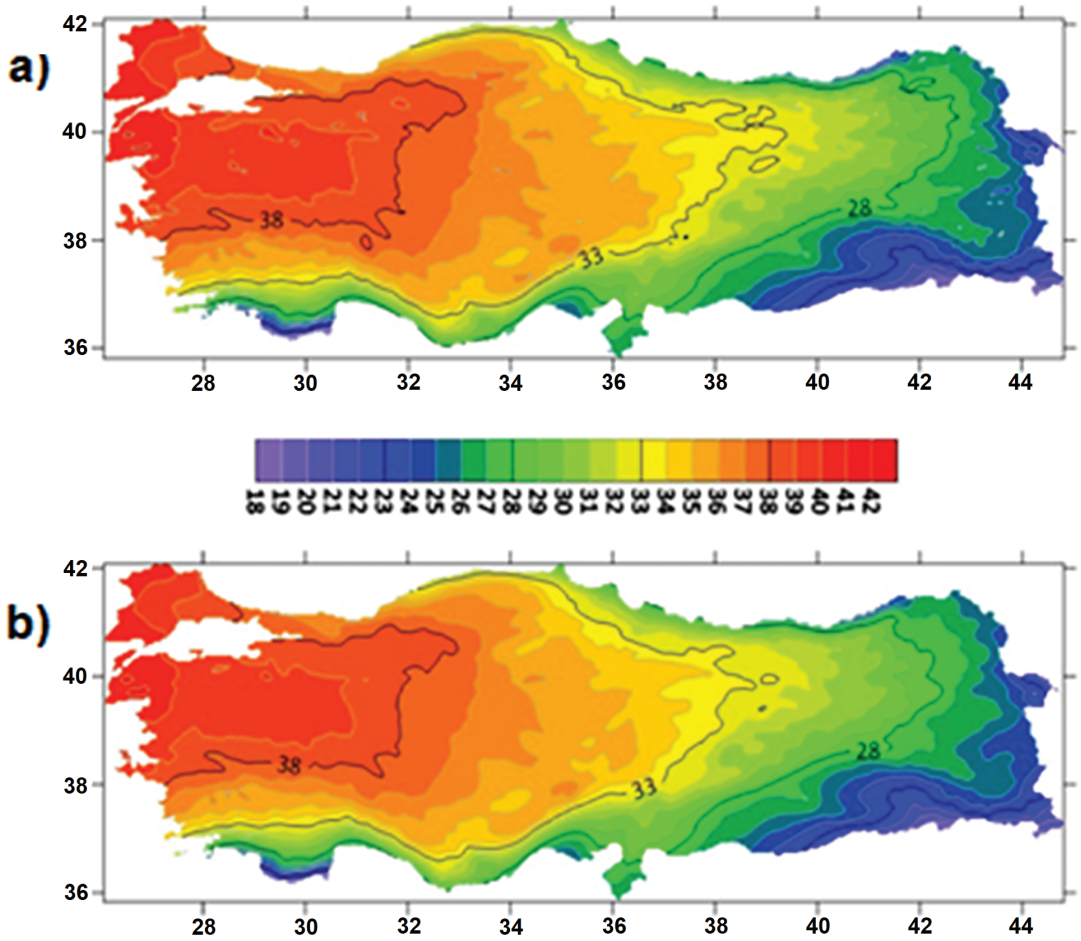


Fig. 1 Geoid height maps (m) derived from GGMplus (a) and EGM2008 (b) (Türkiye)

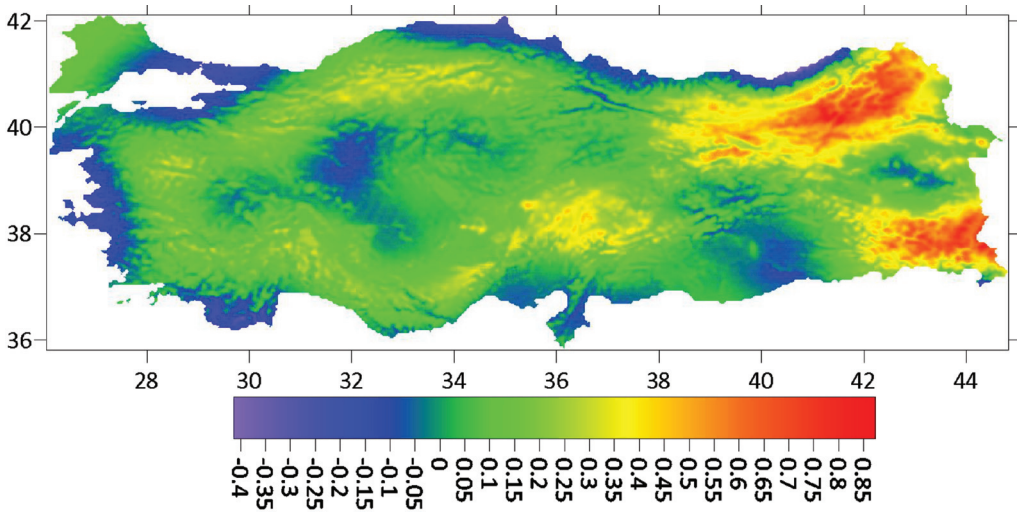


Fig. 2 Geoid height differences (m) derived from GGMplus and EGM2008 (Türkiye)

exhibit substantial variations across Anatolia due to data resolution limits and terrain effects and that TG-20 provides a significantly more stable reference surface compared to earlier national or unadjusted global models. Therefore, this study focuses on the comparison of GGMplus with national geoid models.

Application of GGMplus in Türkiye

The GGMplus model, with its high-resolution global geoid data, enables detailed local-scale analyses in countries with complex topographic and geological structures, such as Türkiye. The region encompasses

significant elevation and gravity variations between high mountainous areas (e.g., Eastern Anatolia), low-lying plains (e.g., Çukurova), and coastal zones (Aegean, Mediterranean, and Black Sea regions). This diversity often results in gravity anomalies that are inadequately captured by conventional global geoid models due to their limited resolution. The 200-meter resolution of GGMplus provides a substantial advantage in modelling these small-scale variations with improved accuracy. Figure 3 presents the study area along with its corresponding digital elevation model (DEM).

Initial studies conducted within the scope of GGMplus applications over Türkiye have shown that the model provides high accuracy particularly in the western and central Anatolian regions, where the topography is relatively smooth. However, in topographically complex and high-elevation areas such as Eastern Anatolia, some discrepancies have been observed when compared with local gravity data. These differences are generally attributed to the adequacy of topographic reductions, region-specific errors in the SRTM-based terrain data, and the spectral coverage of the satellite data used in the model. Consequently, the applicability of GGMplus in Türkiye varies regionally, and calibration with local gravity measurements may be required in certain areas.

Comparisons with TG-03, the most widely used model in geodetic applications across Türkiye, have shown that GGMplus yields results closely aligned with TG-03 in certain regions, while in others, differences can reach up to several decimetres. This variation necessitates evaluating GGMplus not as a reference model but rather as a supplementary or initial model. Particularly in rural areas where sufficient GPS/levelling data are lacking, the GGMplus model serves as a valuable preliminary data source in the early stages of geoid modelling and related geodetic applications.

The potential of GGMplus over Türkiye extends beyond academic research and can be utilized in a wide range of applications, including infrastructure projects, engineering practices, map production, and sea level modelling. For instance, in coastal regions, GGMplus can play an effective role in defining the geoid surface for sea level analysis and transformations between height reference systems. However, in such applications, it is crucial to assess the model's accuracy through validation against local gravity measurements and GPS/levelling data. Figure 4 illustrates the ADJ_GGMplus results employed in this study, along with the 187 GNSS/levelling points utilized during the adjustment procedure.

In conclusion, while the GGMplus model serves as a comprehensive, readily accessible, and high-resolution resource for Türkiye, its use in precision applications is recommended to be supported by local corrections and hybrid modelling approaches. In this context, evaluating GGMplus under the specific conditions of Türkiye holds strategic importance for understanding both the capabilities and limitations of the model.

Table 2 Descriptive statistics of the differences between GGMplus and EGM2008 (differences are given in meters)

1%-tile:	–0.205	Minimum:	–0.413
5%-tile:	–0.095	Maximum:	0.874
10%-tile:	–0.048	Mean:	0.130
25%-tile:	0.020	Median:	0.100
50%-tile:	0.100	Root Mean Square:	0.215
75%-tile:	0.206	Trim Mean (10%):	0.120
90%-tile:	0.361	Interquartile Mean:	0.104
95%-tile:	0.486	Midrange:	0.230
99%-tile:	0.666	Winsorized Mean:	0.122
Skewness:	0.993	TriMean:	0.106
Kurtosis:	4.414	Variance:	0.030
Sum:	2579305.460	Standard Deviation:	0.172
Sum Absolute:	3112394.075	Interquartile Range:	0.187
Sum Squares:	921021.666	Range:	1.287
Mean Square:	0.046	Median Abs. Deviation:	0.090
Standard Error:	0.000	Average Abs. Deviation:	0.126

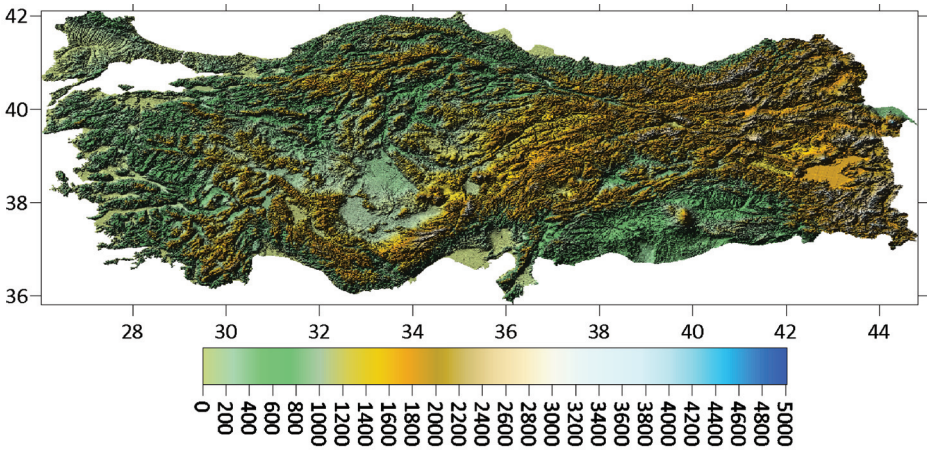


Fig. 3 The study area and digital elevation model

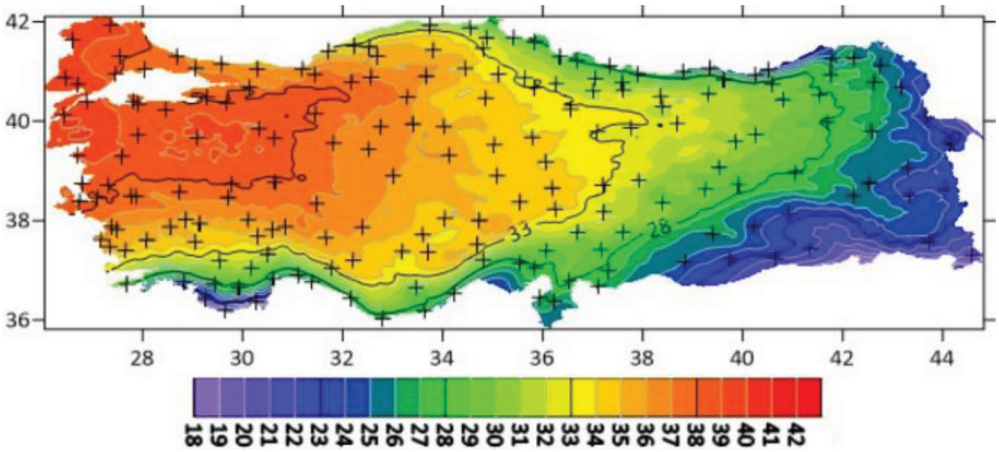


Fig. 4 The ADJ_GGMplus geoid height model (m) and 187 GNSS/levelling points used in GGMplus's adjustment

In this section, the GGMplus geoid model is compared with other geoid models generated using different data sources and methodologies, as well as with geoid heights derived from GNSS-levelling observations. For this purpose, all geoid models were converted into a regular grid data format, and geoid height differences at the grid corners were compared between GGMplus and ADJ_GGMplus models and the national geoid models TG-03 and TG-20. Figure 1 presents the GGMplus and EGM2008 geoid height maps over Türkiye.

The primary datasets used in this study are as follows:

- GGMplus geoid model (200 m resolution)
- TG-03 national geoid model
- TG-20 national geoid model
- GNSS and levelling data (local measurement data)

The test areas were selected from regions of Türkiye with diverse geographical characteristics. These regions are suitable for model validation due to their high topographic variability and dense data coverage. The collected data were preprocessed to minimize errors and systematic biases. This preprocessing involved data cleaning, error analysis, and coordinate transformations. Geoid heights from the GGMplus model were calculated using gravity anomalies and topographic corrections, while geoid heights from GNSS and levelling data were determined through geometric methods.

Figure 5 and Table 3 present a comparative evaluation of the analyses conducted on gravity potential data across Türkiye. These values are of critical importance for assessing the accuracy of the geoid models. Figure 5a (TG-20 *vs*. ADJ_GGMplus) and Fig 5c (TG-03 *vs*. ADJ_GGMplus) present visualizations of the geoid height differences for the adjusted models. In particular, the TG_20 *vs* ADJ_GGMplus data reveal prominent positive anomalies (red areas) in the eastern part of Türkiye, while lower values (cooler colours) are observed in the west. This pattern indicates that the high elevations and a mountainous terrain in the east significantly influence the gravity potential. Similarly, the TG03–ADJ_GGMplus map also exhibits high anomalies in the east, but additionally shows notable positive values around the Marmara region.

Figure 5b (TG-20 *vs*. GGMplus) and Fig. 5d (TG-03 *vs*. GGMplus) are based on the original datasets and were generated directly from the GGMplus model without any adjustments. In the TG-03 *vs*. GGMplus comparison, negative anomalies (represented by purple and dark blue tones) are predominant, particularly in the western regions. In contrast, the TG-20 *vs*. GGMplus comparison shows a smoother transition and more limited deviations overall. As TG-20 is a more recent model, it can be considered to provide a more realistic and balanced distribution due to the applied corrections.

In Table 3, the key statistical parameters of the four datasets are compared.

- TG-03 vs. GGMplus shows the widest range, with a minimum of −4.85 m and the most negative mean (−1.112 m). These indicate that this model pair contains more extreme values and exhibits a pronounced negative systematic offset.
- The TG-20 vs. ADJ_GGMplus comparison exhibits a slightly positive mean difference (+0.131 m) and the lowest variance and standard deviation among the four comparisons, reflecting a more balanced distribution.

The skewness and kurtosis metrics further highlight the distributional differences: comparisons involving TG-03 display negatively skewed and highly leptokurtic (peaked) behaviour, whereas the TG-20 comparisons are more symmetrical and closer to a normal distribution. Together, these results suggest that TG-20, particularly when combined with the adjusted GGMplus surface, provides a more stable and realistic representation of the geoid over Türkiye.

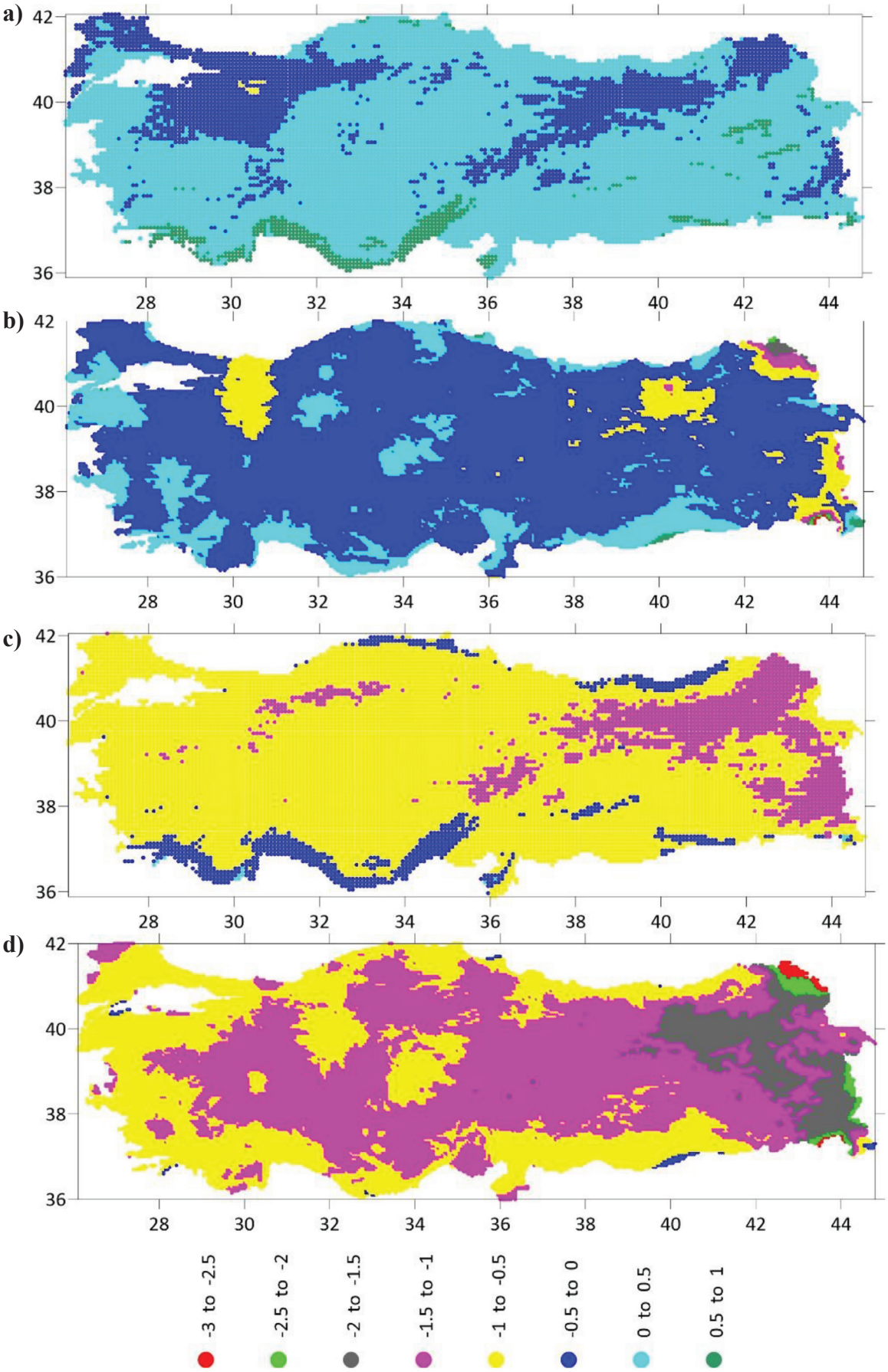


Fig. 5 Geoid height differences (m): a) TG-20 *vs*. ADJ_GGMplus, b) TG-20 *vs*. GGMplus, c) TG-03 *vs*. ADJ_GGMplus, d) TG-03 *vs*. GGMplus

Table 3 The statistical results between GGMplus and ADJ_GGMplus and the TG-03 and TG-20 models (differences are given in meters)

Metric	TG-03 *vs*. GGMplus	TG-20 *vs*. GGMplus	TG-03 *vs*. ADJ_GGMplus	TG-20 *vs*. ADJ_GGMplus
Number of values	32364	11691	32407	11691
Minimum	–4.853	–1.488	–3.767	–0.528
Maximum	–0.020	0.137	0.928	1.214
Range	4.832	1.625	4.695	1.742
Mean	–1.112	–0.804	–0.175	0.131
Median	–1.052	–0.822	–0.130	0.120
First quartile	–1.205	–0.926	–0.267	0.012
Third quartile	–0.938	–0.695	–0.039	0.245
Standard error	±0.002 m	±0.002 m	±0.001 m	±0.002 m
95% confidence interval	0.003	0.004	0.003	0.004
99% confidence interval	0.004	0.005	0.004	0.005
Variance	0.092	0.045	0.063	0.043
Average deviation	0.207	0.157	0.164	0.156
Standard deviation	0.303	0.211	0.251	0.208
Coefficient of variation	–0.273	–0.263	–1.428	1.583
Skew	–2.468	0.502	–3.232	0.253
Kurtosis	15.870	1.212	28.166	1.063
Kolmogorov-Smirnov stat	0.137	0.060	0.118	0.042
Critical K-S stat, alpha =.10	0.007	0.011	0.007	0.011
Critical K-S stat, alpha =.05	0.008	0.013	0.008	0.013
Critical K-S stat, alpha =.01	0.009	0.015	0.009	0.015

In conclusion, the TG-20 vs. ADJ_GGMplus dataset demonstrates a more stable, balanced, and realistic model both visually and statistically. This outcome may be attributed to the fact that TG-20 has been updated using more modern and accurate datasets. For reliable assessments in geological structure analysis, subsurface modelling, and engineering applications involving gravity data, it is essential to rely on high-accuracy models such as TG-20 vs. ADJ_GGMplus.

Another analysis was conducted based on the local-scale performance of the GGMplus and ADJ_GGMplus models. A total of 17 regions with varying characteristics were selected from different parts of Türkiye, and the models were evaluated within these areas. The corresponding statistical values are presented in Table 4 and Table 5. Several factors contribute to the formation of geoid differences, including topographic effects, gravity data quality, satellite orbit errors, and data density. Analyzing these factors is essential for understanding the model's performance. For the geoid differences, the following statistical metrics were calculated:

- Mean Error (ME)
- Standard Deviation (SD)
- Root Mean Square Error (RMS)

These metrics were used to assess the accuracy of the models and characterize the distribution of errors.

The performance of the GGMplus and ADJ_GGMplus models across 17 different regions in Türkiye was evaluated based on geoid height differences expressed in meters. The analysis revealed that the GGMplus model exhibited systematic negative biases in all 17 regions, indicating an underestimation of geoid heights at the local scale. Notably, in regions 4, 13, and 15, the mean deviations of the GGMplus model reached –1.022 m, –0.997 m, and –0.893 m, respectively. However, after applying local adjustments, these deviations were significantly reduced, with mean values improving to –0.273 m, –0.239 m, and –0.301 m in the same regions. These results demonstrate that local corrections effectively mitigate systematic errors in the model.

From a statistical perspective, the ADJ_GGMplus model reduces the mean deviation in all 17 regions, whereas its effect on the shape of the error distribution is not systematic. The standard deviation decreased in 9 of the 17 regions and increased in 7 (Table 5), while the standard error remained unchanged in 9 regions, decreased in 3 and increased in 5 (Table 4). Skewness and kurtosis analyses reveal that the GGMplus model exhibits markedly non-normal distributions, with negative skewness in 8 of the 17 regions and positive skewness in the remaining 9, and with heavy tails in regions 1, 4, 5 and 15 (kurtosis > 5). After adjustment, the absolute skewness decreased in 7 regions and increased in 10, so the adjustment mainly removes the systematic bias rather than reshaping the error distributions.

For example, in region 4, the GGMplus model showed extreme values with a skewness of –3.232 and a kurtosis of 14.108; after the adjustment these changed only marginally, to –3.026 and 13.309, so the pronounced asymmetry of this region persisted. Similarly, in region 10, where the GGMplus model exhibited large deviations, the mean error was reduced from –0.963 m to –0.186 m following correc-

Table 4 Statistical comparison of GGMplus and ADJ_GGMplus with local geoid heights

		Number of values	Min.	Max.	Mean	Median	1.quar.	3.quar.	Std. err. (m)
1	LOCAL-GGMPLUS	592	–0.888	0.019	–0.625	–0.643	–0.694	–0.575	±0.005
	LOCAL-ADJ_GGMPLUS	592	–0.177	0.759	0.093	0.082	0.049	0.112	±0.005
2	LOCAL-GGMPLUS	28	–1.093	–0.804	–0.979	–1.001	–1.049	–0.919	±0.015
	LOCAL-ADJ_GGMPLUS	28	–0.397	–0.103	–0.285	–0.308	–0.352	–0.218	±0.015
3	LOCAL-GGMPLUS	27	–0.872	–0.805	–0.835	–0.835	–0.851	–0.822	±0.003
	LOCAL-ADJ_GGMPLUS	27	–0.356	–0.304	–0.324	–0.321	–0.336	–0.315	±0.003
4	LOCAL-GGMPLUS	1281	–2.468	–0.630	–1.022	–0.965	–1.059	–0.908	±0.006
	LOCAL-ADJ_GGMPLUS	1281	–1.636	0.059	–0.273	–0.232	–0.325	–0.154	±0.006
5	LOCAL-GGMPLUS	912	–1.836	–0.124	–0.800	–0.822	–0.865	–0.741	±0.003
	LOCAL-ADJ_GGMPLUS	912	–1.068	0.653	–0.039	–0.065	–0.108	0.021	±0.003
6	LOCAL-GGMPLUS	156	–0.954	–0.621	–0.774	–0.769	–0.813	–0.728	±0.006
	LOCAL-ADJ_GGMPLUS	156	–0.059	0.158	0.062	0.067	0.031	0.092	±0.004
7	LOCAL-GGMPLUS	219	–0.891	–0.641	–0.768	–0.766	–0.791	–0.739	±0.003
	LOCAL-ADJ_GGMPLUS	219	–0.233	0.052	–0.084	–0.077	–0.115	–0.043	±0.004
8	LOCAL-GGMPLUS	1135	–1.523	–0.438	–0.714	–0.701	–0.788	–0.621	±0.003
	LOCAL-ADJ_GGMPLUS	1135	–0.709	0.293	0.013	0.018	–0.062	0.116	±0.004
9	LOCAL-GGMPLUS	1149	–1.094	–0.484	–0.834	–0.829	–0.895	–0.772	±0.003
	LOCAL-ADJ_GGMPLUS	1149	–0.413	0.240	–0.142	–0.140	–0.202	–0.091	±0.003
10	LOCAL-GGMPLUS	278	–1.179	–0.593	–0.963	–0.983	–1.025	–0.915	±0.005
	LOCAL-ADJ_GGMPLUS	278	–0.455	0.111	–0.186	–0.201	–0.237	–0.146	±0.004
11	LOCAL-GGMPLUS	41	–0.848	–0.726	–0.797	–0.796	–0.811	–0.779	±0.004
	LOCAL-ADJ_GGMPLUS	41	–0.418	–0.307	–0.362	–0.359	–0.377	–0.342	±0.005
12	LOCAL-GGMPLUS	32	–1.015	–0.839	–0.901	–0.887	–0.929	–0.867	±0.009
	LOCAL-ADJ_GGMPLUS	32	–0.447	–0.284	–0.349	–0.346	–0.381	–0.308	±0.009
13	LOCAL-GGMPLUS	1176	–1.452	–0.756	–0.997	–0.972	–1.060	–0.893	±0.004
	LOCAL-ADJ_GGMPLUS	1176	–0.696	–0.010	–0.239	–0.212	–0.297	–0.138	±0.004
14	LOCAL-GGMPLUS	122	–0.942	–0.784	–0.864	–0.871	–0.883	–0.849	±0.003
	LOCAL-ADJ_GGMPLUS	122	–0.351	–0.139	–0.264	–0.272	–0.301	–0.229	±0.004
15	LOCAL-GGMPLUS	462	–2.728	–0.385	–0.893	–0.788	–0.983	–0.646	±0.019
	LOCAL-ADJ_GGMPLUS	462	–2.113	0.219	–0.301	–0.207	–0.402	–0.053	±0.018
16	LOCAL-GGMPLUS	31	–0.812	–0.661	–0.736	–0.738	–0.747	–0.723	±0.005
	LOCAL-ADJ_GGMPLUS	31	–0.473	–0.306	–0.382	–0.378	–0.386	–0.371	±0.006
17	LOCAL-GGMPLUS	44	–0.932	–0.678	–0.844	–0.859	–0.876	–0.831	±0.009
	LOCAL-ADJ_GGMPLUS	44	–0.413	–0.165	–0.336	–0.354	–0.370	–0.322	±0.009

Table 5 Other statistical results of GGMplus and ADJ_GGMplus with local geoid heights

		Avr. dev.	Std. dev.	Skew	Kurtosis	Kolmogorov-Smirnov stat	Critical K-S stat, alpha =.10	Critical K-S stat, alpha =.05	Critical K-S stat, alpha =.01
1	LOCAL-GGMPLUS	0.079	0.118	2.271	8.727	0.139	0.050	0.056	0.067
	LOCAL-ADJ_GGMPLUS	0.060	0.110	2.961	13.629	0.212	0.050	0.056	0.067
2	LOCAL-GGMPLUS	0.066	0.076	0.444	–0.773	0.131	0.229	0.255	0.306
	LOCAL-ADJ_GGMPLUS	0.066	0.077	0.537	–0.597	0.141	0.238	0.264	0.317
3	LOCAL-GGMPLUS	0.013	0.017	–0.237	–0.304	0.114	0.233	0.259	0.311
	LOCAL-ADJ_GGMPLUS	0.011	0.014	–0.784	–0.139	0.204	0.233	0.259	0.311
4	LOCAL-GGMPLUS	0.135	0.217	–3.232	14.108	0.186	0.034	0.038	0.045
	LOCAL-ADJ_GGMPLUS	0.130	0.205	–3.026	13.309	0.153	0.034	0.038	0.045
5	LOCAL-GGMPLUS	0.075	0.102	0.236	15.804	0.112	0.040	0.045	0.054
	LOCAL-ADJ_GGMPLUS	0.077	0.104	0.322	14.711	0.115	0.040	0.045	0.054
6	LOCAL-GGMPLUS	0.061	0.077	–0.241	–0.535	0.073	0.097	0.108	0.130
	LOCAL-ADJ_GGMPLUS	0.036	0.046	–0.256	–0.075	0.050	0.097	0.108	0.130

		Avr. dev.	Std. dev.	Skew	Kurtosis	Kolmogorov-Smirnov stat	Critical K-S stat, alpha =.10	Critical K-S stat, alpha =.05	Critical K-S stat, alpha =.01
	LOCAL-GGMPLUS	0.032	0.042	–0.518	0.582	0.065	0.082	0.091	0.109
7	LOCAL-ADJ_GGMPLUS	0.046	0.057	–0.492	–0.181	0.065	0.082	0.091	0.109
	LOCAL-GGMPLUS	0.093	0.117	–0.882	1.924	0.056	0.036	0.040	0.048
8	LOCAL-ADJ_GGMPLUS	0.100	0.125	–0.631	0.621	0.054	0.036	0.040	0.048
	LOCAL-GGMPLUS	0.072	0.090	0.044	0.199	0.026	0.036	0.040	0.048
9	LOCAL-ADJ_GGMPLUS	0.069	0.089	0.270	0.707	0.036	0.036	0.040	0.048
	LOCAL-GGMPLUS	0.063	0.082	1.366	2.999	0.111	0.073	0.081	0.097
10	LOCAL-ADJ_GGMPLUS	0.055	0.071	0.800	2.280	0.101	0.073	0.081	0.097
	LOCAL-GGMPLUS	0.020	0.026	0.283	0.623	0.097	0.189	0.210	0.252
11	LOCAL-ADJ_GGMPLUS	0.022	0.029	–0.479	–0.302	0.123	0.189	0.210	0.252
	LOCAL-GGMPLUS	0.040	0.048	–0.725	–0.281	0.159	0.215	0.238	0.286
12	LOCAL-ADJ_GGMPLUS	0.039	0.046	–0.473	–0.729	0.107	0.229	0.255	0.306
	LOCAL-GGMPLUS	0.106	0.138	–1.045	0.754	0.095	0.036	0.039	0.047
13	LOCAL-ADJ_GGMPLUS	0.104	0.135	–1.083	0.815	0.103	0.036	0.039	0.047
	LOCAL-GGMPLUS	0.022	0.028	0.655	0.244	0.112	0.110	0.122	0.147
14	LOCAL-ADJ_GGMPLUS	0.038	0.045	0.578	–0.450	0.112	0.110	0.122	0.147
	LOCAL-GGMPLUS	0.269	0.398	–2.114	5.033	0.179	0.057	0.063	0.075
15	LOCAL-ADJ_GGMPLUS	0.271	0.396	–2.038	4.769	0.157	0.057	0.063	0.075
	LOCAL-GGMPLUS	0.020	0.028	0.190	2.248	0.117	0.218	0.242	0.290
16	LOCAL-ADJ_GGMPLUS	0.021	0.032	–0.397	2.162	0.213	0.218	0.242	0.290
	LOCAL-GGMPLUS	0.042	0.059	1.404	1.839	0.206	0.183	0.203	0.244
17	LOCAL-ADJ_GGMPLUS	0.043	0.059	1.568	1.986	0.226	0.183	0.203	0.244

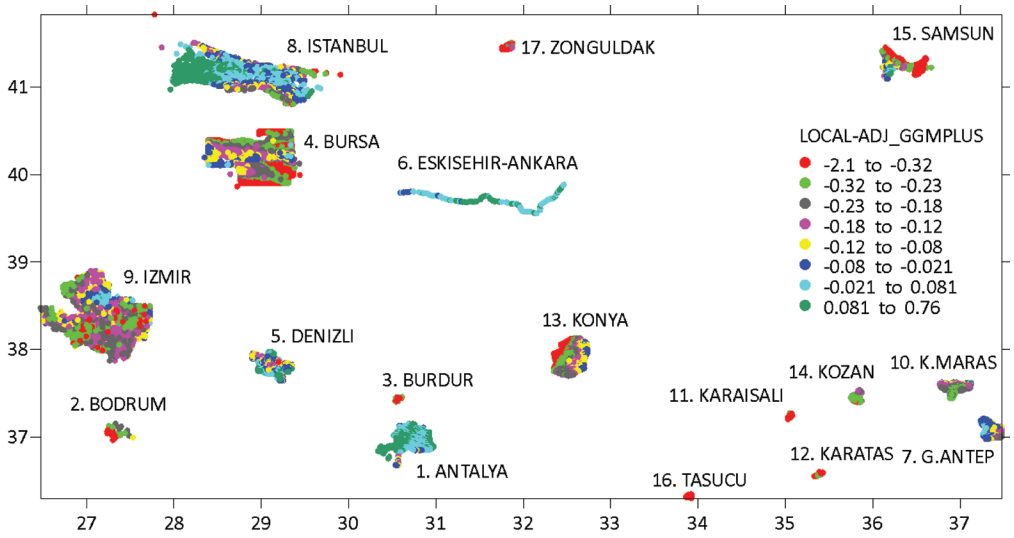


Fig. 6 The maps of geoid height differences (m) between local – ADJ_GGMplus

tion, with notable improvements observed across all statistical metrics.

The results of the Kolmogorov–Smirnov (K–S) test further support these improvements. In the adjusted model, the K–S statistic decreased in 6 of the 17 regions, remained unchanged in 2 and increased in the remaining 9 (Table 5), so the adjustment does not systematically bring the error distributions closer to normality. For instance, in region 12 the K–S statistic for the GGMplus model was 0.159, which decreased to 0.107 after adjustment, and in region 6 it dropped from 0.073 to 0.050; in region 1, by contrast, it increased from 0.139 to 0.212. The improvement achieved by the adjustment is therefore evident in the mean deviations rather than in the normality of the error distributions.

The results obtained from 17 local regions reveal that the GGMplus model exhibits a systematic negative deviation in every region, ranging from –0.625 m to –1.022 m, with the largest values in regions 4, 13 and 2 (Table 4). In contrast, the adjusted model significantly reduces these errors in the same areas. In central and western Türkiye, the geoid height differences converge closer to zero after adjustment, indicating a more stable model performance (Fig. 6). This highlights the limitations of global models in accurately representing local gravity fields and demonstrates that regional corrections can substantially enhance model accuracy.

In conclusion, the GGMplus model contains notable systematic deviations in local areas across Türkiye; however, these biases can be effectively corrected through local adjustments. The ADJ_GGMplus model provides a more reliable solution by both reducing mean differences and normalizing error distributions. These improvements clearly underscore the necessity of local geoid corrections for high-precision height determination, engineering projects, hydrographic applications, and cartographic studies.

CONCLUSION

The findings of this study underscore the potential and limitations of the GGMplus geoid model in the context of Türkiye's complex geophysical landscape. While GGMplus provides high-resolution gravity data suitable for local-scale analysis, it exhibits notable systematic deviations when evaluated against national models and ground-truth GNSS/levelling observations – particularly in regions with rugged topography such as Eastern Anatolia and the Black Sea coast. The adjusted model, ADJ_GGMplus, developed using 187 GNSS/levelling points, effectively mitigates these biases and yields significant improvements in both statistical consistency and spatial accuracy. Visual and numerical analyses confirm that ADJ_GGMplus aligns more closely with TG-20 and local geoid heights, offering a more realistic representation of the gravity field. These results highlight the necessity of regional corrections in geoid modelling and confirm that hybrid approaches, integrating global gravity models with local observations, are essential for achieving high-precision height determination. The enhanced accuracy and stability of the ADJ_GGMplus model make it particularly valuable for engineering, infrastructure development, sea-level monitoring, and scientific research across Türkiye.

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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.

REFERENCES

Abbak, R.A., Sjöberg, L.E., Ellmann, A., Ustun, A. 2012. A precise gravimetric geoid model in a mountainous area with scarce gravity data: A case study in central Turkey. *Studia Geophysica et Geodaetica 56(4)*, 909–927. https://doi.org/10.1007/s11200-011-9001-0

Aksoy, A., Ayan, T., Çelik, R. N., Demirel, H., Deniz, R., Gürkan, O. 1999. Güncel gelişmeler ışığında mekansal bilgi sistemleri için jeodezik altyapı ve problemleri [Geodetic infrastructure and its challenges for spatial information systems in light of recent developments]. *TMMOB HKMO İstanbul Şubesi Konferansı* [*Conference of the Istanbul Branch of the Chamber of Surveying and Cadastre Engineers*]. İTÜ Sosyal Tesisleri, Maçka, İstanbul. [In Turkish].

Ayan, T. 1978. Türkiye Jeoiti [The Geoid of Türkiye]. *Harita Dergisi* [*Journal of Mapping*] (*85*), 5–17. [In Turkish].

Ayhan, E. 1993. Jeoit determination in Turkey (TG-91). *Bulletin Géodésique 67*, 10–22.

Ayhan, M.E., Alp, O. 1994. Türkiye Astrojeodezik Jeoidi – 1994 (TAG-94) [Turkish Astrogeodetic Geoid – 1994 (TAG-94)] (Internal Report No. Jeof-94-2). Harita Genel Komutanlığı Jeodezi Dairesi Başkanlığı [Department of Geodesy, General Command of Mapping], Ankara. [In Turkish].

Ayhan, M.E., Bank, E., Lenk, O., Şeker, H.A. 1987. South-Western Anatolia (Aegean Region) Doppler Geoid. *Bollettino di Geodesia e Scienze Affini XLVI(4)*, 293–308.

Camacho, M., Alvarez, R. 2021. Geophysical modeling with satellite gravity data: Eigen-6C4 *vs*. GGM Plus. *Engineering 13(12)*, 690–706. https://doi.org/10.4236/eng.2021.1312050

Chen, J., Cazenave, A., Dahle, C., Llovel, W., Panet, I., Pfeffer, J., Moreira, L. 2022. Applications and challenges of GRACE and GRACE follow-on satellite gravimetry. *Surveys in Geophysics 43(1)*, 305–345. https://doi.org/10.1007/s10712-021-09685-x

Corchete, V. 2010. The high-resolution gravimetric geoid of Italy: ITG2009. *Journal of African Earth Sciences 58(4),* 580–584. https://doi.org/10.1016/j.jafrearsci.2010.05.010

Deniz, R., Akyilmaz, O., Erol, S., Ozoner, B., Denli, H. 2001. Precise geoid determination using GPS & levelling measurement. In: Altan, M.O., Gründig, L. (eds), *Proceedings of the Fourth International Symposium 'Turkish-German Joint Geodetic Days'*, Berlin Technical University, 591–596 pp.

HGM (Harita Genel Müdürlüğü). 2021. Türkiye Yükseklik Sisteminin Modernizasyonu ve Gravite Altyapısının İyileştirilmesi Projesi (2015K090710) Proje Tamamlama Raporu [Project Completion Report of the Modernization of the Turkish Height System and Improvement of the Gravity Infrastructure Project (2015K090710)]. Harita Genel Müdürlüğü [General Directorate of Mapping], Ankara. [In Turkish].

Hirt, C. 2011. Assessment of EGM2008 over Germany using accurate quasigeoid heights from vertical deflections, GCG05 and GPS/levelling. *Zeitschrift für Geodäsie, Geoinformation und Landmanagement 136*, 138–149.

Hirt, C., Claessens, S.J., Fecher, T., Kuhn, M., Pail, R., Rexer, M. 2013. New ultrahigh-resolution picture of Earth's gravity field. *Geophysical Research Letters 40(16)*, 4279–4283. https://doi.org/10.1002/grl.50838

Indriana, R.D., Nurwidyanto, M.I., Sabri, L.M. 2020. Data validation of gravity field and satellite data using correlation and coherence method. *Journal of Physics and Its Applications 3(1)*. https://doi.org/10.14710/jpa.v3i1.9291

Khazraei, S.M., Nafisi, V., Amiri-Simkooei, A.R., Asgari, J. 2017. Combination of GPS and leveling observations and geoid models using least-squares variance component estimation. *Journal of Surveying Engineering 143(2)*, 04016023. https://doi.org/10.1061/(ASCE)SU.1943-5428.0000205

Kiamehr, R., Sjöberg, L.E. 2005. Comparison of the qualities of recent global and local gravimetric geoid models in Iran. *Studia Geophysica et Geodaetica 49(3)*, 289–304. https://doi.org/10.1007/s11200-005-0011-7

Kılıçoğlu, A., Demir, C., Fırat, O. 2005. Yeni Türkiye Jeoidi (TG-03)'nin hesabında kullanılan ölçüler ve yöntemler [Measurements and methods used in the computation of the New Turkish Geoid (TG-03)]. In: *TUJK Jeoit ve Düşey Datum Çalıştayı Bildiri Kitabı [Proceedings of the Turkish National Geodetic Commission Workshop on Geoid and Vertical Datum]*, Karadeniz Teknik Üniversitesi [Karadeniz Technical University], Trabzon, 53–76pp. [In Turkish].

Kılıçoğlu, A., Direnç, A., Yıldız, H., Bölme, M., Aktuğ, B., Simav, M., et al. 2011. Regional gravimetric quasi-geoid model and transformation surface to national height system for Turkey (THG-09). *Studia Geophysica et Geodaetica 55(4)*, 557–578. https://doi.org/10.1007/s11200-010-9023-z

Moritz, H. 1980. *Advanced Physical Geodesy*. Wichmann Verlag.

Morozova, K., Jäger, R., Zarins, A., Balodis, J., Varna, I., Silabriedis, G. 2021. Evaluation of quasi-geoid model based on astrogeodetic measurements: Case of Latvia. *Journal of Applied Geodesy 15(4),* 319–327. https://doi.org/10.1515/jag-2021-0030

Ollikainen, M. 1997. *Determination of Orthometric Heights Using GPS Levelling*. Finnish Geodetic Institute, Helsinki.

Rapp, R.H. 1974. The geoid: Definition and determination. *Eos, Transactions American Geophysical Union 55(3)*, 118–126.

Rummel, R., Yi, W., Stummer, C. 2011. GOCE gravitational gradiometry. *Journal of Geodesy 85(11)*, 777–790.

Soycan, M. 2002. Jeoit Yüksekliklerinin GPS ve Hassas Trigonometrik Nivelman Ölçüleri ile Belirlenmesi [Determination of Geoid Heights Using GPS and Precise Trigonometric Leveling Measurements]. *Doktora Tezi [PhD Thesis],* Yıldız Teknik Üniversitesi [Yıldız Technical University], İstanbul. [In Turkish].

Soycan, M., Soycan, A. 2003. Surface modeling for GPS-levelling geoid determination. *Newton's Bulletin 1*, 41–52.

Soycan, A., Yilmaz, Y. 2026. Regional assessment of recent high-degree global geoid models for Türkiye. *Baltica 39(1)*, 25–36. https://doi.org/10.5200/baltica.2026.1.3

Soycan, A., Yılmaz, Y., Soycan, M. 2023. Evaluation of several geoid models for GNSS height transformation in Türkiye. *Sigma Journal of Engineering and Natural Sciences 41(1)*, 130–144. https://doi.org/10.14744/sigma.2023.00013

Tapley, B.D., Watkins, M.M., Flechtner, F., Reigber, C., Bettadpur, S., et al. 2019. Contributions of GRACE to understanding climate change. *Nature Climate Change 9*, 358–369.

Torge, W. 1980. *Geodesy*. Walter de Gruyter, 134–137 pp.

Yıldız, H., Simav, M., Sezen, E., Akpınar, İ., Akdoğan, Y. A., Cingöz, A., Akabali, O.A. 2021. Determination and validation of the Turkish Geoid Model-2020 (TG-20). *Bulletin of Geophysics and Oceanography 62(3)*, 495–512.