

Research Paper

Quality assessment of global gravity field models in the Antarctic region based on airborne gravity data

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ABSTRACT

As the largest ice sheet storage area in the world, Antarctica's gravity field characteristics are key data for studying ice sheet mass balance, sea level changes, and polar resource exploration. However, current gravity field modeling in polar regions faces two major challenges: First, the satellite orbital inclination limit (e.g., the GOCE mission has observation gaps within the latitude circle of 83.3°), which causes ill-posed problems in satellite gravity inversion. Although some studies have improved this using methods like Tikhonov regularization and spherical cap regularization, the applicability of different regularization methods in polar regions lacks systematic evaluation. Second, multi-source gravity data have frequency band limitations, and the study of frequency band characteristics in combined gravity models is relatively scarce. To address these issues, this paper utilizes international Antarctic airborne gravity datasets, including AntGG and PolarGap. It systematically evaluates the accuracy of six satellite gravity field models (such as DIR_R6 and GOCO06s) and five combined gravity models (such as EGM2008 and XGM2019e) in Antarctica, from both spatial and spectral perspectives. The study reveals the error distribution characteristics of different models in Antarctica and further quantifies the contribution characteristics of each model in different frequency bands. The results show that global gravity field models exhibit lower quality within the polar gap at the 83.3°S latitude circle, and introducing additional measurement data combined with regularization methods can significantly improve their accuracy. Additionally, among the combined gravity field models, the XGM2019e_2159 model performs best in Antarctica, and the inclusion of satellite altimetry data significantly improves its quality in oceanic regions. The findings of this study will provide experimental references for data selection and gravity field model optimization in Antarctic gravity field research.

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1. Introduction

The Earth's gravity field reflects the distribution of matter within and on the surface of the Earth, as well as its changes over time. It is one of the fundamental physical fields of the Earth. Detailed studies of the Earth's gravity field have always been one of the major scientific goals in modern geodesy, marine surveying, polar surveying, and solid Earth geophysics [1,2]. Antarctica

possesses the largest “continental ice sheet” on Earth and is rich in mineral resources, with a significant global impact. It holds irreplaceable scientific value for research [3–8]. The gravity field of Antarctica reflects the mass distribution, motion, and changes in the region. It is of great practical and scientific significance for establishing global and regional geodetic benchmarks, as well as for studying sea level rise, geological evolution, and resource exploration [9–12].

Currently, a significant amount of research has been conducted on the development of gravity field models. However, due to the lack of direct gravity measurement data, gravity field studies in Antarctica primarily rely on satellite gravity observations and global gravity field models. Gravity satellite missions, such as CHAMP, GRACE, GOCE, and GRACE-FO, have efficiently provided

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global medium-to-long wavelength gravity field information by acquiring observational data at satellite altitudes [13–16]. Based on satellite gravity observations, a series of satellite gravity field models have been released, including GRACE-based models such as ITSG-Grace2018s, Tongji-Grace02k, ITU_GRACE16, GGM05S, and GOCE-based models such as GOSG02S, GOCO06s, and the GO_CONS_GCF_2 series [17–26]. Compared to GRACE-based gravity field models, GOCE provides more precise long-wavelength gravity field information, with particular advantages in the mid-latitude and low-latitude regions. However, in polar regions, due to satellite orbital limitations (GOCE's orbital inclination is 96.7°), GOCE data exhibits gaps in the two polar areas (regions above latitudes 83.3° North and South). This results in an ill-conditioned normal equation during the gravity field inversion process, which impacts the accurate solution of low-order coefficients in global gravity field models. To overcome this issue, scholars both domestically and internationally have developed various solutions for GOCE gravity field inversion. For example, GOSG02S adopts the classical Tikhonov regularization method, GO_CONS_GCF_2_DIR_R6 (DIR_R6) uses spherical cap regularization combined with Kaula's regularization, GO_CONS_GCF_2_SPW_R5 (SPW_R5) employs a local covariance configuration method, GO_CONS_GCF_2_TIM_R6 (TIM_R6) uses a zero gravity anomaly observation equation for constraint in the polar region, GO_CONS_GCF_2_TIM_R6e (TIM_R6e) incorporates airborne gravity data as a constraint method in the polar region, and GOCO06s optimizes the solution equation by combining variance component estimation and regularization estimation methods, and it integrates gravity satellite observation data for the solution. However, there is limited research comparing and validating the applicability of these methods in gravity field modeling for the Antarctic region.

In addition, satellite gravity observation data exhibit high precision only within a limited frequency band [27,28]. Therefore, global models solely relying on satellite gravity data can only accurately approximate the medium-to long-wavelength information at approximately 80 km half-wavelength. To achieve a higher-precision gravity field model, it is necessary to combine multi-source observational data. Combined gravity field models, such as EGM2008, EIGEN-6C4, GECO, SGG-UGM-1, and XGM2019e, overcome the limitations of satellite gravity measurements in terms of accuracy and coverage by combining multiple data sources. These models can provide more detailed gravity field information for global or regional areas [29]. However, with the exception of XGM2019e, which incorporates airborne gravity data for the Antarctic region, other combined gravity field models mainly rely on satellite gravity observations for the entire Antarctic region [30–34]. Therefore, current global gravity field models have either employed different regularization methods or applied different types of data in response to the unique conditions in the polar gap. However, few studies have evaluated the quality of these models in the Antarctic region. As a result, there is an urgent need to conduct accuracy assessments of existing gravity field models in the Antarctic region.

In existing research, the accuracy evaluation of global gravity field models primarily involves methods such as variance of spherical harmonics, error variance of spherical harmonics, and comparisons with high-precision ground-based gravity field observation data [35]. Due to the extreme environmental conditions, ground-based gravity measurements in the Antarctic region are challenging to conduct, while airborne gravity measurements provide rich data for accuracy assessments of gravity field models in Antarctica. Currently, to address the lack of gravity data in Antarctica and improve the accuracy of the gravity field in the region, the International Scientific Committee on Antarctic Research-Geoscience Standing Committee (SCAR-GSCG) has

established the GIANT geodesy project, and the International Association of Geodesy (IAG) has launched the AntGP initiative. These initiatives aim to measure, collect, and analyze Antarctic gravity data, with airborne gravity anomaly data currently available for 73 % of the Antarctic region [36,37]. Furthermore, the ESA-funded PolarGap project has further utilized airborne gravity data to fill the observational gaps left by GOCE in Antarctica [38]. These airborne gravity data can not only be used for independent accuracy assessments of gravity field models in the Antarctic region but also provide empirical data support for optimizing gravity field model construction methods.

In this context, this paper systematically evaluates the accuracy of existing global gravity field models in the Antarctic region using airborne gravity measurement data. The error characteristics of the gravity field models are analyzed from both the spatial and spectral domains. Furthermore, the root mean square error (RMSE) is used to quantify the precision differences among the models. The objective is to provide a reference for the application of global gravity field models in Antarctica and to offer scientific support for gravity field modeling in the Antarctic region.

2. Research data

2.1. Gravity field models

Based on the different data sources used during model computation, the global gravity field models evaluated in this study can be classified into two types: one type includes satellite gravity field models based on satellite gravity measurements, such as GRACE and GOCE; the other type consists of combined gravity field models that combine multi-source data, including satellite gravity data, satellite altimetry data, ground, shipborne, and airborne gravity measurements. Since the GOCE satellite gravity field model provides significantly higher precision than the GRACE satellite gravity field model [39], this study mainly evaluates the accuracy of GOCE-based satellite gravity field models and combined gravity field models in the Antarctic region.

The satellite gravity field models evaluated in this paper include TIM_R6, SPW_R5, DIR_R6, GOCO06s, GOSG02S, and TIM_R6e. These models represent the latest gravity field models that address the issue of data gaps in polar regions using different approaches. DIR_R6 combines GOCE data with GRACE and SLR data and applies spherical cap regularization along with Kaula regularization to reduce the impact of data gaps [21]. SPW_R5 uses a local covariance configuration method, compressing the GOCE data collected along the orbit into a global grid [22]. TIM_R6 relies entirely on GOCE data, restoring the Earth's gravity field strictly based on GOCE data, with a zero gravity anomaly observation equation used as a constraint in the polar regions [23]. TIM_R6e is an extended version of TIM_R6, incorporating airborne gravity data to generate a $30' \times 30'$ gravity disturbance grid in the polar regions as new constraint conditions [24]. GOCO06s integrates multiple satellite data sources and uses Variance Component Estimation (VCE) to combine the individual contributions of GOCE, GRACE, kinematic LEO orbits, SLR, and regularized constraints through normal equations, improving data gaps in polar regions [25]. GOSG02S employs classical Tikhonov regularization techniques to stabilize the solution of the normal equation and address the ill-conditioning in the polar region [26]. By comparing these models with airborne gravity data, the applicability of different regularization methods for overcoming the data gaps in the polar region can be theoretically assessed.

The current combined gravity field models include EGM2008, EIGEN-6C4, GECO, SGG-UGM-2, and XGM2019e, with their

respective data contribution degree distributions shown in Fig. 1. EGM2008 integrates GRACE satellite gravity data, global ground measurements, and satellite altimetry data, with a maximum degree of 2190. In Antarctica, it primarily relies on GRACE satellite data [30]. EIGEN-6C4 and SGG-UGM-2 both use ground gravity anomaly grids derived from EGM2008, incorporating GOCE data at lower degrees [31,40]. GECO introduces the GOCE-TIM-R5 model at lower degrees, using coefficients from EGM2008 for degrees higher than 360 [33]. XGM2019e is a new model independent of EGM2008, which calculates spherical harmonic coefficients up to degree 719 using GOCO06s and a 15' ground gravity data set, and extends to degree 5480 based on gravity field data from EARTH2014. Notably, XGM2019e uses a 15' ground gravity data set that integrates airborne gravity data from Antarctica published by Scheinert et al. [34].

2.2. Airborne gravity data

This study uses airborne gravity data as validation data to evaluate the accuracy of various models. The airborne gravity data includes AntGG data, PolarGap data, IGGRV1B data, and several

datasets released by the British Antarctic Survey [36–38,41–51], with data acquisition links shown in Table 1. The gravity data provided by these datasets are free air anomalies (FAA), which are, in fact, the gravity disturbances in physical geodesy [52].

The data was filtered based on latitude criteria (south of 60°S), resulting in over 11.07 million data points, with their spatial distribution shown in Fig. 2. As seen in Fig. 2, there are certain data gaps in the oceanic regions between 120°E to 180°E and 90°W to 180°W. Apart from these gaps, the data used in this study largely covers the Antarctic region. The airborne gravity data is relatively smooth in oceanic areas, while in the land areas, some high anomalous values (absolute values of FAA exceeding 100 mGal) are present, predominantly located near the coastline of Antarctica.

3. Methods

3.1. Gravity disturbance calculation

Gravity disturbance refers to the deviation between the gravitational value at a specific point on Earth's surface and the reference gravity field (usually the gravity field derived from the geoid

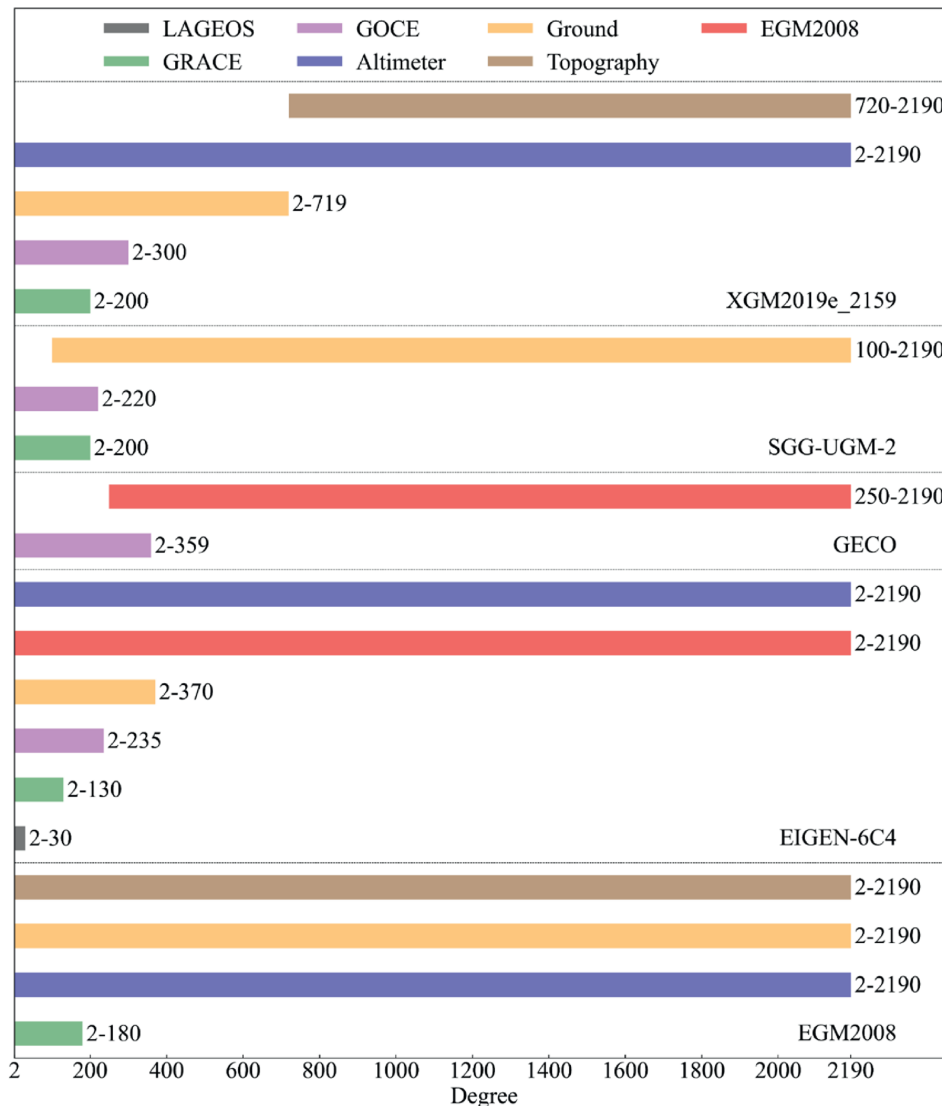


Fig. 1. Data sources for the combined gravity field model.

Table 1

Links for accessing airborne gravity data.

Name	Data acquisition links
AFI	https://doi.org/10.5285/BC55DF03-CAC4-4384-BFA7-57B65D969B48
AntGG	https://doi.org/10.1594/PANGAEA.848168
AGAP	https://doi.org/10.5285/8E5F910B-11D6-4A9D-BDF7-175C9B98CFB8
Brunt	https://doi.org/10.5285/79e63097-f5dc-41ff-8ca5-36BCE4f95a6ff
DUFKE	https://doi.org/10.5285/6BF4FF06-31C4-41F4-B88C-6378122B7D5
ICEGRAV	https://doi.org/10.5285/28E3B21F-BF4B-46A6-8559-F69D69C63A48
IGGRV1B	https://doi.org/10.5067/PEN1C60T9EAV
FISS	https://doi.org/10.5285/B3E51C6E-20FD-4E3A-BE47-0ED2EFCAA0AB
JRI	https://doi.org/10.5285/F3A55F48-1B9B-4DA2-987D-BE63B6BF5061
MAMOG	https://doi.org/10.5285/BC870F9E-4200-4AE2-8DB0-6CB80B870C09
PolarGap	https://doi.org/10.5285/6be0a803-78d4-4ca9-be02-3838866763c3
SPARC	https://doi.org/10.5285/5388DB62-4A5E-4072-9B01-3A65785D80A0
TORUS	https://doi.org/10.5285/5DE1230C-33F5-4586-821B-E6C40316D6BD
WISE/ISODYN	https://doi.org/10.5285/81B419C4-0055-435A-9BED-F583F64BD25A

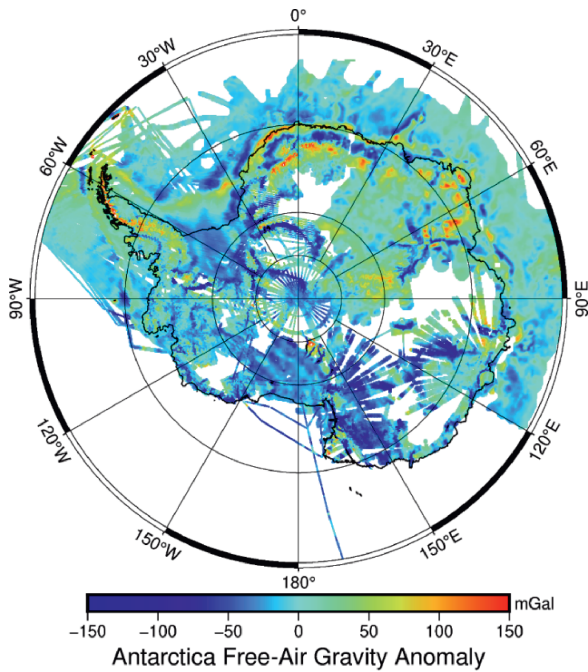


Fig. 2. Distribution of airborne gravity data in the Antarctic region. The figure shows the distribution of airborne gravity data above 60°S in the Antarctic region. The latitude circles marked in the figure correspond to 60°S, 70°S, and 80°S, moving inward from the outermost boundary.

theory) [53]. Since the free air anomaly obtained from airborne gravity measurements is the gravity disturbance, it is necessary to calculate the gravity disturbance based on the gravity field model, in order to compare it with the measured gravity values and assess the model's accuracy. The formula for calculating the gravity disturbance using the gravity field model is as follows [54]:

$$\delta g(r, \varphi, \lambda) = \frac{GM}{r^2} \sum_{n=n_{\min}}^{n_{\max}} \left(\frac{R}{r}\right)^n (n+1) \sum_{m=0}^n (\Delta \bar{C}_{n,m} \cos m\lambda + \Delta \bar{S}_{n,m} \sin m\lambda) \bar{P}_{n,m}(\sin \varphi) \quad (1)$$

where δg is the gravity disturbance at the calculation point, r, φ and λ are the latitude and longitude of the calculation point; R is the mean radius of the Earth; GM is the product of the gravitational constant and the Earth's mass; n is the model degree, m is the model order, and $n_{\max}$ and $n_{\min}$ are the maximum and minimum model degrees; $\bar{C}_{n,m}$ and $\bar{S}_{n,m}$ are the fully normalized gravity field model coefficients; P_{nm} are the fully regularized Legendre functions.

3.2. Gravity field model evaluation

This study selects the Root Mean Square Error (RMSE) as the accuracy evaluation metric for gravity field models, and its calculation formula is as follows:

$$\text{RMSE} = \sqrt{\frac{1}{k} \sum_{i=1}^k (\delta g_i - faa_i)^2} \quad (2)$$

In the formula, k represents the number of observations, faa_i is the free air anomaly at the i -th point obtained from airborne gravity measurements, and δg_i is the gravity disturbance value calculated at the i -th point from the model using Eq. (1). The value of RMSE reflects the accuracy of the gravity field model. A smaller RMSE indicates that the gravity disturbance computed by the model is closer to the actual airborne gravity anomaly, thus implying higher model accuracy.

Furthermore, to perform a more systematic evaluation of the gravity field model and assess its differences at lower degrees, the coefficient difference spectrum and degree variance were also used for spectral domain analysis. The coefficient difference spectrum represents the spectral domain differences of spherical harmonic coefficients at corresponding degrees, and is mathematically expressed as:

$$\Delta \bar{C}_{n,m} = \bar{C}_{n,m}^{\text{model}} - \bar{C}_{n,m}^{\text{reference}} \quad (3)$$

$$\Delta \bar{S}_{n,m} = \bar{S}_{n,m}^{\text{model}} - \bar{S}_{n,m}^{\text{reference}} \quad (4)$$

In the formula, $\bar{C}_{n,m}^{\text{model}}$ and $\bar{S}_{n,m}^{\text{model}}$ are the spherical harmonic coefficients of the model to be evaluated, and $\bar{C}_{n,m}^{\text{reference}}$ and $\bar{S}_{n,m}^{\text{reference}}$ are the spherical harmonic coefficients of the reference model. n is the model degree, and m is the model order. The coefficient difference spectrum directly calculates the difference between the spherical harmonic coefficients, providing an intuitive way to reveal the model bias at each degree.

Degree variance is an important metric in gravity field spectral analysis, used to quantify the signal strength or error distribution of the gravity field model at different degrees. By summing the squared differences of all spherical harmonic coefficients at a particular degree, the overall difference between two models in that frequency band can be shown. The mathematical expression for the degree variance of the spherical harmonic coefficient difference is as follows:

$$E_n^2 = \sum_{m=0}^n (\Delta \bar{C}_{n,m}^2 + \Delta \bar{S}_{n,m}^2) \quad (5)$$

$\Delta \bar{C}_{n,m}$ and $\Delta \bar{S}_{n,m}$ are the results obtained by taking the difference between the spherical harmonic coefficients of the gravity

field model and the reference gravity field model. n represents the degree of spherical harmonic expansion.

When using the coefficient difference spectrum and degree variance for model performance evaluation, it is crucial to choose a high-precision reference model as the truth. When the reference model's accuracy is sufficiently high, the coefficient difference spectrum and degree variance between the model and the reference model can effectively characterize the performance differences of various gravity field models.

4. Gravity field accuracy analysis

This study systematically evaluates the accuracy of global gravity field models using airborne gravity measurement data from the Antarctic region. The theoretical gravity disturbances at the height of the airborne measurements were first calculated for each gravity field model. These were compared with the measured airborne gravity data, and the differences between the model and observed values were computed. The spatial distribution patterns of model errors were analyzed, achieving an accuracy characteristic analysis in the spatial domain. Based on this, the overall accuracy of different gravity field models was quantitatively assessed using the Root Mean Square Error (RMSE). Additionally, the degree variance and coefficient difference spectrum were used to evaluate the degree of agreement between the models and the reference model at different degrees, revealing the error characteristics of the gravity field models from the spectral domain. Furthermore, the trend of RMSE variation with truncation degree for the combined gravity field models was analyzed, which highlights the regularity of model accuracy variation with respect to degree.

4.1. Spatial distribution patterns of gravity field models

In this study, the accuracy of six satellite gravity field models, (DIR_R6, SPW_R5, TIM_R6, TIM_R6e, GOCO06s, and GOSG02S), along with five combined gravity field models (EGM2008, EIGEN-6C4, SGG-UGM-2, GECO, and XGM2019e), was evaluated using airborne gravity data as the reference in the Antarctic region. Among these, the XGM2019e gravity field model has three different versions with varying highest degrees (760, 2190, and 5540). To facilitate comparison with other combined gravity field models, it was necessary to maintain the highest degree consistent with others. Therefore, this study selected the XGM2019e_2159 version, which has a maximum degree of 2190.

Using Eq. (1), gravity disturbances were calculated for each model up to their maximum degree, and the model results were compared with the airborne gravity data. The spatial difference characteristics between the model inversion values and the measured values were revealed (Fig. 3). The results show that the errors for all models were mainly concentrated in the range of -30 to 30 mGal, with regional differences: the coastal areas from 0°E to 90°E exhibited dense negative large errors (blue areas), while the land areas from 90°E to 180°E and 90°W to 180°W mainly exhibited positive large errors (red areas). Comparing with the Antarctic topographic map (Fig. 3(l)), it can be observed that the areas with high errors correspond spatially with regions of intense topographic fluctuations.

The XGM2019e_2159 model (Fig. 3(k)) demonstrated superior accuracy compared to other models. Its error distribution was overall smoother, and high-error points were significantly reduced. This is mainly due to the incorporation of airborne gravity data in this model, while other models predominantly rely on satellite gravity data. Because satellite data has relatively low spatial resolution, it is challenging to precisely reflect the gravity

field details of complex terrain areas, resulting in large deviations between the model inversion values and the airborne data. While TIM_R6e (Fig. 3(d)) also includes airborne gravity data, its resolution limitations prevent it from fully capturing the high-frequency signals associated with the terrain.

In oceanic regions, the error characteristics of the combined gravity field models and satellite gravity field models exhibited significant differences. The former, benefiting from the inclusion of high-precision satellite altimetry data, showed a much smoother error distribution in the oceanic regions. In contrast, the latter, due to the resolution limitations of satellite data, exhibited larger error fluctuations in the oceanic areas.

Tables 2 and 3 summarize the evaluation results of the satellite gravity field models and combined gravity field models in the Antarctic region.

As shown in Table 2, among the satellite gravity field models, the TIM_R6e model exhibits the best performance with a total RMSE of 20.81 mGal, followed by GOCO06s (21.27 mGal), DIR_R6 (21.28 mGal), GOSG02S (21.66 mGal), TIM_R6 (22.09 mGal), and SPW_R5 (22.37 mGal). Except for SPW_R5, all satellite gravity field models use the sixth-generation data released by the European Space Agency (ESA). The differences in model accuracy can partially reflect the influence of various regularization methods, which in turn helps evaluate the applicability of these methods. TIM_R6e incorporates high-precision airborne gravity data, while GOCO06s and DIR_R6 integrate satellite data such as GRACE, resulting in higher accuracy compared to models constructed using only GOCE data, with the main improvements observed south of 83.3°S . This suggests that incorporating additional detailed gravity field measurement data as constraints is the most direct and effective method to improve the accuracy of gravity field models. The pure GOCE model GOSG02S and TIM_R6 also exhibit accuracy differences in the Antarctic region (Table 2), which can be attributed to the use of different regularization methods. TIM_R6 applies a zero-gravity anomaly observation equation constraint (assuming that gravity anomalies in the polar region tend toward zero), effectively suppressing model uncertainty in sparse high-latitude regions (south of 83.3°S), slightly improving its accuracy compared to GOSG02S, which uses Tikhonov regularization (34.11 mGal vs. 34.27 mGal). However, this strong constraint causes over-smoothing of the real signals in middle and low latitudes (north of 83.3°S), resulting in significantly increased errors, leading to an overall lower accuracy than GOSG02S.

In the combined gravity field models (see Table 3), the XGM2019e_2159 model leads significantly with a total RMSE of 10.52 mGal, showing an improvement of 52.1% over the second-best model, GECO (21.97 mGal). The ranking of the other models is as follows: SGG-UGM-2 (23.63 mGal), EIGEN-6C4 (23.52 mGal), and EGM2008 (24.29 mGal). It can be seen that TIM_R6e and XGM2019e_2159 are the most accurate models in the satellite gravity field models and combined gravity field models, respectively. This is related to the data used in constructing the models in the Antarctic region. Both TIM_R6e and XGM2019e_2159 incorporated airborne gravity data from the Antarctic region, while other models typically relied on more limited gravity data in the region, such as low-resolution GRACE data or regularization-based constraints.

In the combined gravity field models, the accuracy of XGM2019e_2159 is significantly higher than that of the satellite gravity field models, while the other combined gravity field models, despite being expanded to the 2190th degree, exhibit similar accuracy to the satellite gravity field models. This is because during the modeling process of EGM2008, SGG-UGM-2, GECO, and EIGEN-6C4, only satellite gravity measurements were used in the Antarctic region. Table 4 summarizes the evaluation

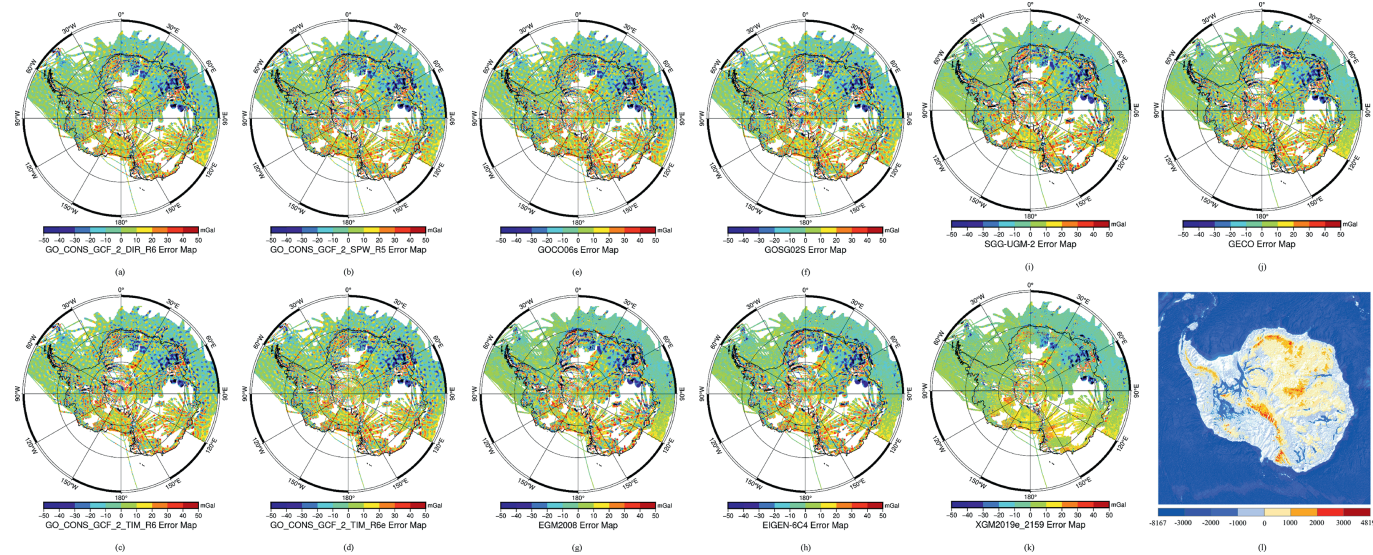


Fig. 3. Error distribution map of the gravity field model in the Antarctic region. (a) to (f) show the error distribution maps of the satellite gravity field models, while (g) to (k) show the error distribution maps of the combined gravity field models. The figure shows the distribution of error data above 60°S in the Antarctic region. The latitude circles marked in the figure correspond to 60°S, 70°S, and 80°S, moving inward from the outermost boundary. (l) A topographic map of Antarctica.

results for the combined gravity field models truncated to the satellite contribution degree. The results show that, except for XGM2019e_2159, the remaining combined gravity field models, when expanded to the satellite contribution degree, show accuracy differences within 1 mGal compared to the maximum degree of 2190. In the Antarctic region, XGM2019e_2159 benefits from the higher-resolution airborne gravity data as a supplement, which significantly improves the accuracy when expanded to higher degrees. Other combined gravity field models primarily rely on satellite gravity in the Antarctic region and only incorporate altimetry data as a supplement in the oceanic regions. Therefore, as the degree increases, there is no significant increase in the signal. Consequently, for applications in the Antarctic gravity field, except for XGM2019e_2159, the models can be truncated to the satellite gravity measurement contribution degree.

In addition, all gravity field models show significant differences in accuracy inside and outside the 83.3°S latitude band. The accuracy is notably higher in regions north of the 83.3°S latitude

(outside the latitude band) compared to those south of it (inside the latitude band) (Table 2, Table 3, and Table 4). For pure GOCE models (Tables 5 and 6), there are no direct satellite observations in the polar regions, leading to poorer accuracy in these areas. However, for models that integrate other data sources (such as GRACE data, particularly airborne gravity data), the accuracy in the polar regions has been relatively improved. Consequently, the accuracy of integrated models in the polar regions is generally higher than that of the pure GOCE models, with a smaller accuracy gap when compared to regions outside the polar areas.

4.2. Coefficient difference analysis of gravity field models

As shown in Tables 2 and 3, TIM_R6e and XGM2019e_2159 are the most accurate models among satellite gravity field models and combined gravity field models, respectively. When the

Table 2
Accuracy of satellite gravity field models in the Antarctic region (RMSE in mGal).

Model	Degree	RMSE (Total)	RMSE (Lat > 83.3°S)	RMSE (Lat < 83.3°S)
GOSG02S	300	21.66	34.27	20.74
GOCO06s	300	21.27	29.42	20.72
DIR_R6	300	21.28	29.65	20.72
TIM_R6	300	22.09	34.11	21.23
SPW_R5	330	22.37	34.19	21.53
TIM_R6e	300	20.81	26.74	20.44

Table 3
Accuracy of combined gravity field models in the Antarctic region (RMSE in mGal).

Model	Degree	RMSE (Total)	RMSE (Lat > 83.3°S)	RMSE (Lat < 83.3°S)
EGM2008	2190	24.29	34.16	23.63
SGG-UGM-2	2190	23.63	33.69	22.94
GECO	2190	21.97	33.23	21.18
EIGEN-6C4	2190	23.52	33.85	22.81
XGM2019e_2159	2190	10.52	17.02	10.04

Table 4
The accuracy of the gravity field model truncated to satellite degrees compared with the highest precision.

Model	Degree	RMSE (Total)	RMSE (Lat > 83.3°S)	RMSE (Lat < 83.3°S)
EGM2008	359	24.58	34.21	23.93
	2190	24.29	34.16	23.63
SGG-UGM-2	220	24.72	33.99	23.28
	2190	23.63	33.69	22.94
EIGEN-6C4	370	23.81	33.78	23.14
	2190	23.52	33.85	22.81
GECO	359	22.27	33.26	21.50
	2190	21.97	33.23	21.18
XGM2019e_2159	300	19.60	26.51	19.07
	2190	10.52	17.02	10.04

Table 5
Accuracy of Pure GOCE Models (RMSE in mGal).

Model	RMSE (Lat > 83.3°S)	RMSE (Lat < 83.3°S)	Data Resource
TIM_R6	34.11	21.23	GOCE
SPW_R5	34.19	21.53	GOCE
GOSG02S	34.27	20.74	GOCE

Table 6
Accuracy of GOCE Models with additional data fusion (RMSE in mGal).

Model	RMSE (Lat > 83.3°S)	RMSE (Lat < 83.3°S)	Data Resource
SGG-UGM-2	33.69	22.94	GOCE, GRACE, etc.
EIGEN-6C4	33.85	22.81	GOCE, GRACE, etc.
XGM2019e_2159	17.02	10.04	GOCE, GRACE, airborne gravity data, etc.
GOCO06s	29.42	20.72	GOCE, GRACE, etc.
DIR_R6	29.65	20.72	GOCE, GRACE, etc.
TIM_R6e	26.74	20.44	GOCE, airborne gravity data

XGM2019e_2159 model is truncated to a degree of 300, its root mean square error (RMSE) is 19.60 mGal, which is slightly higher than that of the TIM_R6e model. Therefore, in this study, XGM2019e_2159 truncated to 300° is selected as the reference model, and the accuracy of the satellite gravity field models at various degrees is assessed by calculating the coefficient difference degree variance between the satellite gravity field models and the XGM2019e_2159 model.

Fig. 4 shows the coefficient difference distribution between the satellite gravity field models and the XGM2019_2159 model.

As can be seen from the figure, except for GOCO06s, all other models show significant differences with the reference model at lower degrees, manifested as a narrow wedge-shaped pattern. This difference is attributed to the polar gap. Sneeuw and Gelderen mentioned in their paper that the affected coefficient region appears as a narrow wedge, and this “polar gap wedge” widens as the polar gap increases [55]. Since one of the data sources for the XGM2019e_2159 model is the GOCO06s model, the coefficient difference is small, and no obvious “polar gap wedge” appears in the coefficient difference spectrum. Pure GOCE models, such as GOSG02S, TIM_R6, and SPW_R5, are significantly affected by the polar gap and exhibit clear wedge-shaped coefficient difference spectra. TIM_R6e and DIR_R6, which respectively incorporate airborne gravity data and GRACE satellite data, show significant improvements in the coefficient difference spectra at higher and lower degrees, exhibiting smaller coefficient differences.

Based on XGM2019e_2159, this study further investigates the error distribution of different combined gravity field models at various degrees. Fig. 5 shows the coefficient difference distribution between XGM2019e_2159 and the remaining four models from 0° to 360°. From Fig. 5(a), it can be seen that EGM2008 shows

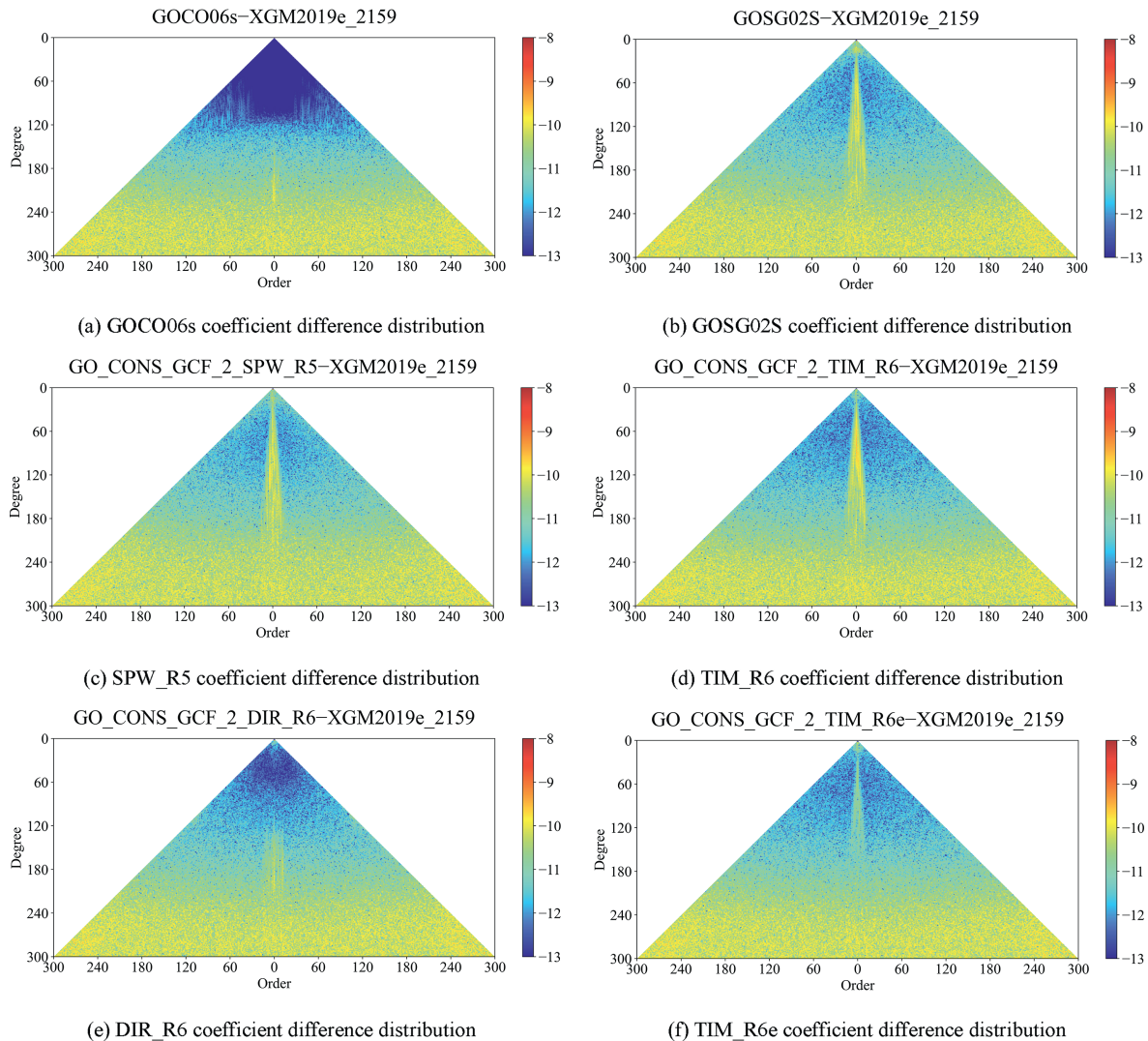


Fig. 4. Coefficient difference distribution between Satellite Gravity Field Models and XGM2019_2159 Model (The color code uses a logarithmic scale with base 10, representing the logarithmic value of the absolute coefficient difference). The vertical axis represents the SH-degree, and the horizontal axis represents the SH-order. On the left side, the differences in the S coefficients are shown, and on the right side, the differences in the C coefficients are displayed.

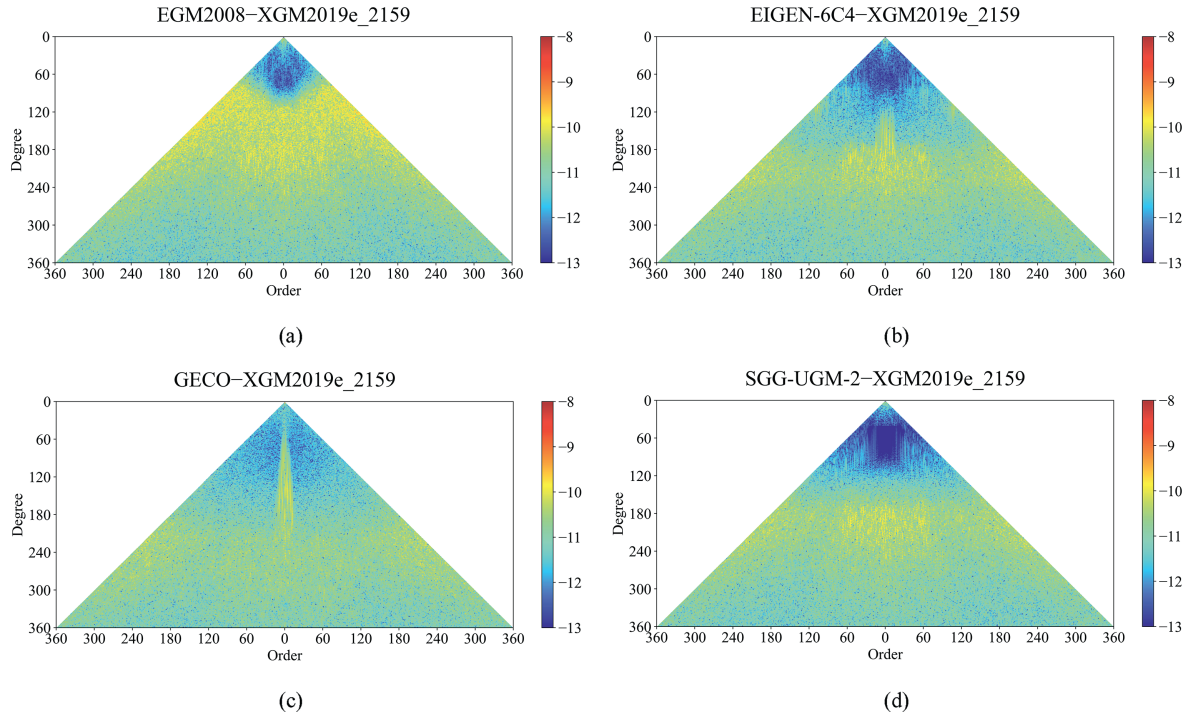


Fig. 5. Coefficient difference distribution between synthetic gravity field models and XGM2019e_2159 from 0° to 360° (The color code uses a logarithmic scale with base 10, representing the logarithmic value of the absolute coefficient difference of spherical harmonic coefficients).

larger coefficient differences with XGM2019e_2159 at lower degrees, mainly because EGM2008 did not incorporate GOCE satellite data during its construction, leading to differences due to varying data sources. By introducing GOCE data, EIGEN-6C4, SGG-UGM-2, and GECO show reduced coefficient differences compared to EGM2008. In addition, the coefficient difference spectrum of GECO and XGM2019e_2159 shows a “polar gap wedge” in the first 200° , which is the result of the correction brought by the GOCE data to EGM2008. EIGEN-6C4 does not exhibit the influence of the polar data gap at lower degrees, as the first 130° are primarily contributed by GRACE data. From degree 130 to 180, the contribution of GOCE data is evident in the coefficient difference spectrum. SGG-UGM-2 and XGM2019e_2159 use the same generation of GRACE data (ITSG-Grace2018) for the first 200° . GRACE contributions dominate the first 120° , with minimal differences. However, after degree 120, the differences in the coefficient spectrum increase due to variations in the types and weights of satellite data sources.

4.3. The accuracy variation of the integrated gravity field model with truncation degree

This paper further evaluates the quality of the combined gravity field models as they change with the truncation degree by comparing the coefficient differences between the combined gravity field models and XGM2019e_2159. As shown in Fig. 6, the variance of the coefficient differences between the combined gravity field models and XGM2019e_2159 changes with the degree. From the figure, it can be seen that significant differences occur between the combined gravity field models in the range of 20° – 240° , with the largest variance difference occurring with EGM2008. Additionally, before 140° , the variance difference

between SGG-UGM-2 and XGM2019e_2159 is the smallest. Between 140° and 160° , the variance difference between EIGEN-6C4 and XGM2019e_2159 is the smallest. Between 160° and 240° , the variance difference between GECO and XGM2019e_2159 is the smallest. After 240° , the variance of EGM2008, EIGEN-6C4, and SGG-UGM-2 gradually becomes consistent, while the variance difference between GECO and XGM2019e_2159 is the largest from 240° to 360° .

These differences are mainly attributed to the varying data sources for the low-degree combined gravity field models (Fig. 1). In the first 120° , GRACE data dominates, and because GECO lacks GRACE data and EGM2008 uses an older version of GRACE data, the precision of both is relatively low in this frequency band. In the 120° – 160° range, both GOCE and GRACE data contribute, but since EGM2008 has not incorporated GOCE data and GECO lacks GRACE observations, their precision in this range is still visibly lower than that of the other models. EIGEN-6C4 and SGG-UGM-2 both integrate GRACE and GOCE data and thus perform better, with SGG-UGM-2 showing the highest precision in this range due to its use of the same generation of GRACE data (ITSG_Grace2018) as XGM2019e_2159. In the 160° – 240° range, the contribution of GOCE data dominates. Since GECO, EIGEN-6C4, and SGG-UGM-2 use different versions of GOCE data, their contributions range from 359° , 235° , and 220° , respectively. Thus, GECO, which includes the most extensive GOCE data range, provides the best precision. After the 240° th degree, contributions from ground data and satellite altimetry become more significant. GECO's coefficients from 0° to 360° were obtained by joint adjustment with GOCE TIM R5 and EGM2008, while both EIGEN-6C4 and SGG-UGM-2 used EGM2008 as a data source and incorporated different satellite altimetry data, resulting in different precision.

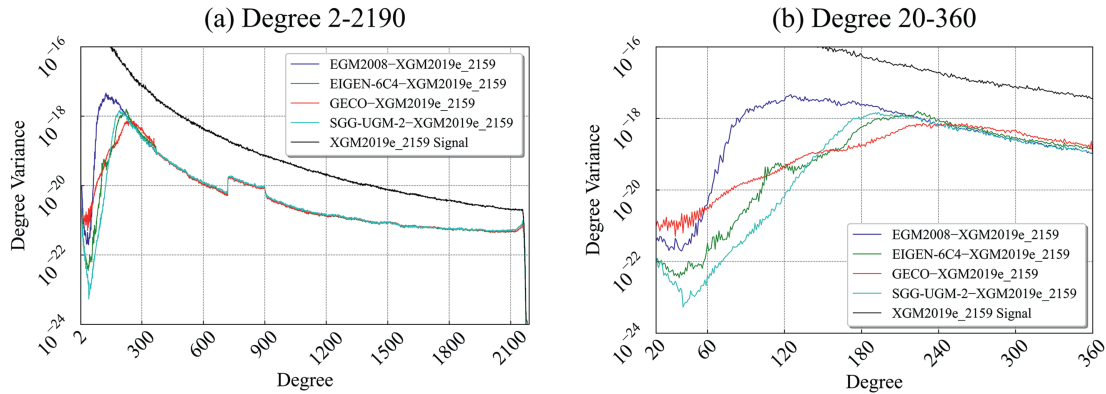


Fig. 6. Comparison of the degree variance differences of other models with the combined gravity field model XGM2019e_2159. (a) shows the entire spherical harmonic spectrum covered by the models, while (b) focuses on the degree range where the differences are most significant, from 20° to 360°.

Additionally, the variance of the coefficient differences in the combined models exhibits a jump between the 720th and 900th degrees, likely due to the fact that higher-degree signals in the reference model XGM2019e_2159 after the 720th degree predominantly come from the Earth2014 terrain gravity data. In contrast, other combined models use actual gravity measurements for this frequency band. The coefficient difference variance for the combined gravity field models at higher degrees shows smaller differences, mainly because EIGEN-6C4, GECO, and SGG-UGM-2 all use EGM2008 as a data source above the resolution of satellite models, making them more reliant on this model. After the 360th degree, the variance difference between SGG-UGM-2 and the other three models becomes relatively large, as SGG-UGM-2 uses newly derived ocean gravity anomaly data.

In conclusion, the precision differences in fusion gravity field models are mainly due to the low-degree spherical harmonic coefficients. EGM2008, which has the largest coefficient difference with XGM2019e_2159, provides the lowest precision among all combined gravity field models. EIGEN-6C4, SGG-UGM-2, and GECO have improved precision compared to EGM2008 in Antarctica. Among them, GECO performs better than EIGEN-6C4, SGG-UGM-2, and EGM2008, a conclusion confirmed by numerous studies [33, 40, 56]. GECO shows better precision in regions with sparse ground gravity data, such as Antarctica, compared to other GOCE-based synthetic gravity field models. EIGEN-6C4 and SGG-UGM-2 have similar precision, mainly because both use similar data combination methods and input data. Since EIGEN-6C4 uses more satellite gravity data (such as LAGEOS), the low-degree coefficients are slightly better than those in SGG-UGM-2, resulting in relatively higher precision.

To further evaluate the precision of the combined gravity field models at different degrees, this study calculates the gravity anomaly at aviation altitude for models expanded to different degrees and compares it with actual measured data. The RMSE of the differences is calculated to further assess the precision of the combined gravity field models, with the results shown in Fig. 7.

From Fig. 7, the following patterns can be summarized. 1) The precision of all combined gravity field models increases initially, then decreases, and later increases again with higher degrees,

reaching its peak at the highest degree of 2190. 2) Except for the XGM2019e_2159 model, the precision of the other synthetic gravity field models remains largely unchanged between degrees 300 and 1800. 3) All synthetic gravity field models show significant precision improvement from degree 2159 to 2190.

The first two points are mainly caused by the contribution of different data sources at various degrees during the model calculation process. Firstly, for the first 300 or so degrees, there is satellite data in the Antarctic region, and as the degree increases, the resolution of the model improves, allowing for better reflection of gravity perturbations in Antarctica. However, after the satellite data contribution is taken into account, except for XGM2019e_2159, the other synthetic gravity field models use gravity anomaly grids based on EGM2008. Since EGM2008 does not have effective data in Antarctica, no additional signals are introduced. The XGM2019 model, however, was constructed independently of EGM2008, using land-based observed gravity anomalies (including Antarctic airborne gravity data) and DTU13 satellite altimetry gravity anomalies, and a 15' global geographical grid (at 30 km from the equator). Therefore, as the model degree increases, it becomes more detailed in capturing surface features, which leads to an improvement in model precision.

The third point is mainly due to the global gravity field modeling method. In the calculation of high-degree combined gravity field models, the ellipsoidal harmonic coefficients are first calculated up to degree 2159, and then transformed into spherical harmonic coefficients using the conversion method proposed by Jekeli [57]. During the conversion process, when the n -th degree truncated spherical harmonic field is extended to the ellipsoid, the high-degree terms $(\frac{R}{r})^n$ grow exponentially with increasing degree, with the impact being most significant in polar regions. To address this issue, additional correction terms are included in the conversion from ellipsoidal to spherical harmonic coefficients, and the expanded spherical harmonic coefficients are carried out up to degree 2190 [58]. Therefore, in practical applications, models such as XGM2019e_2159 need to be expanded up to degree 2190 to avoid errors introduced by the conversion from ellipsoidal harmonics to spherical harmonics in high-latitude regions.

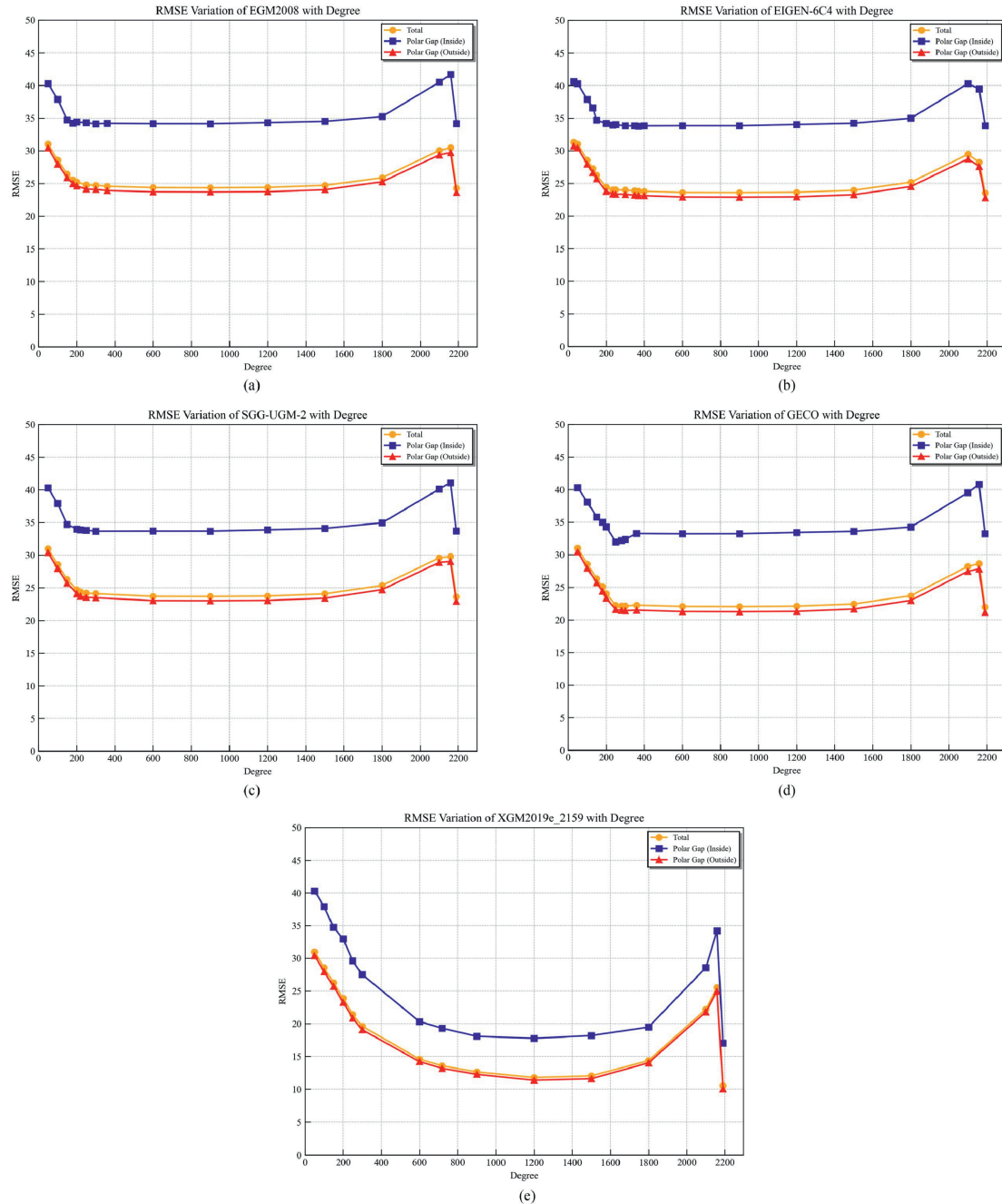


Fig. 7. Precision variation of combined gravity field models in Antarctica with truncation degree.

5. Conclusions and outlook

Research on the Antarctic gravity field holds significant scientific and practical value. As a key physical representation of the distribution of Earth's internal and surface materials, Antarctic gravity field data can reveal dynamic processes such as ice sheet mass migration and crustal tectonic movements. These data provide core support for understanding global sea-level change mechanisms and the interaction between ice sheets and climate. Existing gravity field models heavily rely on satellite gravity observations in the Antarctic region. However, due to the orbital inclination limitation (96.7°) of the GOCE satellite, there is data missing in the polar regions above latitudes 83.3°N and 83.3°S , leading to ill-posed problems in the gravity field inversion process.

While some researchers have attempted to address these data gaps using regularization methods (such as Tikhonov and spherical cap regularization) or by integrating multi-source data (e.g., TIM_R6e using airborne gravity data, DIR_R6 using GRACE data), the applicability of these methods and their effectiveness in improving the accuracy of the Antarctic gravity field remain insufficiently validated. Furthermore, although current ultra-high-degree combined gravity field models (such as EGM2008, EIGEN-6C4) integrate multi-source data to enhance model resolution, they still primarily rely on satellite data in the Antarctic region. Only XGM2019e integrates some airborne gravity observations. Due to the resolution limitation of satellite gravity data, models such as EGM2008 and EIGEN-6C4 exhibit uncertainty in accuracy in the Antarctic.

The AntGG, PolarGap, and British Antarctic Survey's released airborne gravity datasets provide new insights for assessing the quality of global gravity field models in the Antarctic region. This paper, based on these airborne datasets, systematically evaluates the accuracy of six GOCE satellite gravity field models (DIR_R6, SPW_R5, etc.) and five combined gravity field models (XGM2019e, GECO, etc.) in the Antarctic region. The accuracy differences of existing global gravity field models in the Antarctic are assessed from both spatial and spectral domains. The overall accuracy of the models is evaluated using the root mean square error (RMSE) indicator, which reveals the error distribution pattern of different models in the Antarctic. Additionally, spectra of spherical harmonic coefficient differences and the variance of coefficient differences are used to uncover the signal contribution characteristics and error properties of each model in different frequency bands. Furthermore, by analyzing the RMSE trend of combined gravity field models with respect to truncation degree, the relationship between model accuracy and expansion degree is revealed.

From a spatial distribution perspective, the accuracy of global gravity field models is lower within the 83.3°S latitude circle due to data gaps in the polar regions. The inclusion of additional data can effectively mitigate the impact of these gaps on model accuracy, especially when high-precision airborne gravity data is added (e.g., TIM_R6e has an RMSE of 26.74 mGal, compared to 34.11 mGal for TIM_R6, representing a 21.6 % improvement in accuracy). Furthermore, appropriate regularization can also lead to accuracy improvements, as demonstrated by the Tikhonov regularization method used in GOSG02S, which relatively improves the model's accuracy in the Antarctic region. The error distribution of gravity field models in the Antarctic is highly consistent with the topography, with larger errors observed in areas with more pronounced terrain variations. This is mainly because the gravity models in the Antarctic region rely primarily on lower-resolution satellite gravimetry data, which are not able to capture the gravity field details in areas with significant terrain variation. XGM2019_2159 and TIM_R6e have incorporated airborne gravity data in the Antarctic region, with the former significantly smoothing out errors, while the latter is constrained by its own model resolution, making it unable to fully represent the high-frequency signals related to the terrain. In addition, in the oceanic regions, the combined gravity field models benefit from the inclusion of high-precision satellite altimetry data, which results in a more uniform error distribution in these regions. In contrast, satellite gravity field models exhibit significant error fluctuations in the oceanic regions due to their resolution limitations.

From the perspective of spectral characteristics, XGM2019e_2159 significantly outperforms other models, thanks to its inclusion of high-precision airborne gravity data and its high resolution. Moreover, the inclusion of airborne gravity data in the middle and high degrees contributes to XGM2019e_2159's higher accuracy in these degrees. For combined gravity field models other than XGM2019e_2159, the low-degree satellite data is the primary source of accuracy differences in the Antarctic, and using combined gravity field models (other than XGM2019e_2159) with satellite data contribution up to a certain degree does not significantly improve accuracy by increasing the expansion degree to the highest levels. If high-degree spherical harmonic coefficients from models like XGM2019e_2159 are used in practical applications, they need to be expanded to the 2190th degree in high-latitude regions to avoid errors introduced during the conversion from ellipsoidal harmonics to spherical harmonics.

The study's results indicate that the application of gravity field models in the Antarctic requires certain strategies. For applications that require high precision, such as geological surveys, high-

degree combined models like XGM2019e_2159, which incorporate airborne gravity data, should be prioritized. For large-scale studies such as ice sheet and ice cap mass changes, satellite gravity field models can be chosen to save computational resources. Furthermore, Antarctic gravity field modeling should focus on the synergy between multi-source observational data and regularization methods. Airborne gravity data, with its high precision, captures high-frequency gravity field signals related to terrain in areas with significant topographic variations, thereby enhancing the model's spatial resolution and accuracy. To address the issue of insufficient satellite gravity observation coverage in the Antarctic, effectively utilizing airborne gravity measurements and other real-world gravity data can substantially improve gravity field inversion quality. Regularization methods in Antarctic gravity field modeling aim to resolve instability in inversion due to insufficient data, ensuring the reliability of inversion results. The design of regularization methods should consider geological features, climate change, and other factors to improve the model's adaptability to complex environments and develop regularization methods that are more suitable for special geographic environments, such as the polar regions. The conclusions of this research highlight the accuracy and applicability of global gravity field models in Antarctica, providing experimental references for their use in the region and scientific evidence for constructing high-precision gravity field models in Antarctica.

CRediT authorship contribution statement

Xinhong Xiao: Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Meng Yang:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization. **Qinglu Mu:** Writing – review & editing, Validation, Supervision. **Wei Feng:** Writing – review & editing. **Min Zhong:** Writing – review & editing.

Declaration of competing interest

Wei Feng is an Editorial Board Member for Geodesy and Geodynamics and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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