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Comparative analysis among Asia–Pacific geoid models stored at the ISG repository

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Abstract

Geoid models have important applications in geosciences as well as engineering, for example, for the conversion from ellipsoidal heights observed by GNSS techniques to orthometric heights. To meet the user's demands, the International Service for the Geoid (ISG, <https://www.isgeoid.polimi.it/>) provides access to a repository of local, regional, and continental geoid models through its website. Among hundreds of worldwide models, there are many covering countries in the Asia–Pacific area. The focus of this study is about this region, performing a series of analyses to assess the geoid models stored in the ISG repository through some relative comparisons. In particular, three kinds of analyses are performed with the purpose of: (a) investigating the evolution in time of a geoid series referring to the same country, (b) comparing the information provided by local and regional geoid models on overlapped areas, and (c) assessing the agreement between local and global models. These analyses are firstly performed on sample models, providing a detailed description, and then applied to all Asia–Pacific geoid models currently stored in the ISG repository, providing summary statistics.

Keywords: Earth gravity field, Geoid, ISG, Asia–Pacific

1 Introduction

The International Service for the Geoid (ISG) is an official service of the International Association of Geodesy (IAG), performing activities under the coordination of the International Gravity Field Service (IGFS). These activities are mainly devoted to maintaining a worldwide local and regional geoid model repository and to supporting agencies or scientists in computing local and regional geoid models, especially in developing countries, by organizing special training courses and international schools on geoid determination. ISG is based in Italy, with its main centre at Politecnico di Milano, and the services are managed and provided by its internal staff with the support of individual scientists at the international level.

As for the geoid repository, ISG collects models worldwide, validates them when possible, and disseminates

them to users mainly through its official website. Since the summer of 2020, a Digital Object Identifier (DOI) service is offered as well, making it possible to assign a DOI to the models of the geoid repository. This service has been established in collaboration with GFZ (GeoForschungsZentrum) Data Services and allows geoid models to be cited in publications, e.g., Barzaghi et al. (2020).

More in detail, ISG manages and preserves an openly accessible repository of continental, regional, and national geoid models at a worldwide scale. The geoid repository aims at storing and redistributing geoid models in the original data format together with a standardized ASCII format developed for purposes, also including useful metadata for gravity related analysis and allowing data interoperability. Most models in the repository can be freely downloaded, some of them require the author's permission to be accessible, and few are private and cannot be distributed. Consequently, the current 242 geoid models of the repository are classified as public (181), on-demand (22), or private (39), respectively. Moreover,

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168 of them are based on gravity data only (i.e., the so-called gravimetric models), 8 are based on GPS/levelling data only (i.e., the so-called geometric models), and 66 based on gravity data and fitted to GPS/levelling data (i.e., the so-called hybrid models). About 500 users per month visit the repository that has almost worldwide coverage, with resolution grids up to 0.5 arcminutes. As for the Asia–Pacific region, there are 58 geoid models, among which 47 are classified as public, 2 as on-demand, and 9 as private. These statistics reflect the status of the repository at the date of May 31, 2021. Each model of the repository has a dedicated web page on the website, containing all the available information, like, e.g., names of the authors, publication year, key references, and a brief description of the input data, the adopted computational method, and kind of output, in addition to the data file (when the model is classified as public) both in the original and standardized ASCII format. Furthermore, when a DOI is assigned to a model, the latter is made available also through the catalogue of GFZ Data Services, where a dedicated landing page is present, cross-referencing the data and the ISG webpage. More details about the structure of the service can be found in Reguzzoni et al. (2021).

This work aims at performing some analyses and comparisons on the geoid models that cover the Asia–Pacific area and are available in the ISG repository, thus providing a picture of the geoid knowledge over this area.

1.1 Comparative analysis

The large number of geoid models stored in the ISG repository offers the possibility of assessing them through relative comparisons. For instance, possible mismatches between geoid models referring to the same area can be revealed by analysing their residuals. Inconsistencies and/or disagreements can be detected between models computed at different epochs, with different techniques or published by different authors.

An overview of the Asia–Pacific models that are currently available at the ISG repository clearly shows that two classical methods are prevalently used for the geoid computation, namely Stokes's integration (Stokes 1849) and Least Squares Collocation (Moritz 1980; Tscherning 2013). The former is typically implemented by Fast Fourier Transform (Sideris 2013) after proper modifying Stokes's kernel (e.g., Wong and Gore 1969). Both methods are generally applied in the framework of the so-called remove-restore approach (Denker 2013), where the long-wavelength gravity signal is modeled by a global gravity model given as a truncated series of spherical harmonic coefficients (Pavlis 2013) and the short-wavelength contribution is taken from a digital terrain model by computing the so-called residual terrain correction (Forsberg

1984). Even if they are not used for the geoid models under consideration for this work, it is worth recalling that there are many other methods and approaches for local geoid computations and some comparative studies have been performed on test areas to assess them, for example the Auvergne test (Duquenne 2006) or the more recent Colorado experiment (Wang et al. 2021). Results from these tests are published and freely available at the ISG website (www.isgeoid.polimi.it/Projects/Auvergne_test.html, www.isgeoid.polimi.it/Projects/colorado_experiment.html) and the readers can refer to the cited literature for detailed descriptions of the geoid computation methods.

Since the Asia–Pacific models we are going to analyse cover a time span of almost 30 years (from 1993 to 2020), besides the differences in the processing methods one cannot disregard the technological advancements and the increasing data availability during the years, leading to an improved quality of the input observations as well as more updated and accurate global gravity models as the reference for the long-wavelength components of the gravity signal. In this respect, the older Asia–Pacific models are mainly referred to EGM96 (Lemoine et al. 1998) and EGM2008 (Pavlis et al. 2012), while the most recent ones also exploits the information coming from the GOCE gravity mission (Drinkwater et al. 2003; Pail et al. 2011). For these reasons, cross-checking regional geoid models like those stored at ISG repository is meaningful for taking trace of the evolution of gravity models at different scales, from local to regional and even up to global scales.

In this study, three kinds of analyses are provided: (a) the assessment of the evolution in time of a geoid series referring to the same country, (b) the comparison of local and regional geoid models on overlapped areas, (c) the agreement between local and global models computed over the same area.

The computation of the residuals between geoid undulations from different models of the repository requires some preliminary processing. In particular, geographical coverage, spatial resolution, reference frames, and height datums must be consistent. Therefore, the models to be compared are firstly masked only over overlapping areas. Then, the grid of the model with the lower resolution is taken as reference, and the other models are interpolated (or downsampled, when possible) over this reference grid. The interpolation of geoid undulations on the coarser grid makes this approach conservative, avoiding the possibility of adding gross artefacts related to the interpolation method, and allowing to neglect possible small inconsistencies. Obviously, this step is skipped in the case of coincident grids. In the case of comparison with respect to global models, this problem does not

exist because the latter are modelled through a truncated spherical harmonic expansion, and the geoid undulation can be directly synthesized on the same grid of the local geoid under assessment. Finally, regarding possible misalignments due to different reference frames and/or datums, they can be assumed to be negligible after removing the best fitting plane on the computed residuals. Considering some test cases, the results of these comparative analyses are presented and discussed in detail in the next section. The same analyses have also been carried out for all the geoid models currently stored in the ISG repository and covering the Asia–Pacific area. For the sake of brevity, the overall results are presented in the form of tables only, summarizing the information that can be inferred from the ISG repository.

2 Results and discussion

This section presents and comments the numerical results on the relative assessments introduced in the previous sections.

2.1 Local geoid series comparison

Geoid model series referring to Philippines and surrounding seas (PGM series) has been chosen as an example of the assessment regarding the evolution in time of local geoid models. The models of this series included in the ISG repository are PGM2014 (Forsberg et al. 2014), PGM2016 (Gatchalian et al. 2016), and PGM2018 (see <http://www.namria.gov.ph/projects.aspx>). These models were computed by the National Mapping and Resource Information Authority (NAMRIA) of the Republic of the Philippines with the technical assistance of the National Space Institute of the Denmark Technical University (DTU-Space). Table 1 summarizes their main characteristics and statistics.

As one can see, spatial coverage and resolution are identical for the PGM gravimetric geoid series. Therefore,

Table 1 Characteristics and statistics of the PGM gravimetric geoid series, considered as an example of the assessment of the evolution of local geoid models in time

	PGM2014	PGM2016	PGM2018
Model type	gravimetric	gravimetric	gravimetric
Reference ellipsoid	GRS80	GRS80	GRS80
Spatial resolution	1.5'	1.5'	1.5'
Latitude coverage	4°N–22°N	4°N–22°N	4°N–22°N
Longitude coverage	112°E–128°E	112°E–128°E	112°E–128°E
Mean	39.061 m	38.261 m	38.261 m
STD	18.361 m	18.361 m	18.360 m
Min	− 9.020 m	− 9.820 m	− 9.826 m
Max	76.429 m	75.630 m	75.630 m

the preprocessing step for harmonizing the grids is not required. Statistics reveal a bias of about 80 cm between the first PGM2014 and the subsequent PGM models (see Mean, Min and Max rows in Table 1) while maintaining the same overall variability, being the standard deviations almost identical to the millimeter level (see STD row in Table 1). This bias is consistent with the shift of 80 cm applied to PGM2014 by the authors to approximately fit the Manila tide gauge datum (see Forsberg et al. 2014).

From this preliminary analysis on the PGM gravimetric model series, it is very hard to detect localized differences and refinements applied in the latest edition of the PGM model (PGM2018) that has a declared accuracy of 1.2 cm against 30 cm of the first PGM2014. A cross-comparison among them is then required to this aim. In Table 2 the statistics of the residuals between subsequent PGM models, reduced for the fitting plane as described in the previous section, are reported.

From these statistics, PGM2014 and PGM2016 show a very good agreement, with a sub-centimetric standard deviation, and main differences localized in the area of Surigao del Norte (10°N, 125°E) and the southern peaks like Mount Apo (7°N, 125°E), as shown in Fig. 1. These small differences on land are due to the performed re-computation after adding new land gravity data, as reported also in Gatchalian et al. (2016). The latest PGM2018 shows higher residuals with respect to the previous geoid models, up to almost 3 cm of standard deviation. The map of residuals highlights a significantly high frequency difference related to the topography and bathymetry signal. This is probably thanks to new satellite gravity and altimetry data and densified land gravity data that were used to update the model. For instance, Philippine and Sulu trenches are well identifiable (along the eastern Philippines and in the Sulu Sea between Borneo and Philippines), as well as the undersea structures around Scarborough Shoal in the South China Sea.

The ISG geoid repository currently stores many other geoids referring to the same country and being subsequent editions they can be analysed with the procedure just described for the Philippines. For the sake of brevity, in the following Table 3, other geoid series comparisons are reported in terms of residuals statistics among subsequent geoid models. The residuals have been computed for geoid series comprising at least three gravimetric or

Table 2 Statistics on the residuals of the comparisons among the models of the PGM gravimetric geoid series

Model A	Model B	STD (A-B)	Min (A-B)	Max (A-B)
PGM2014	PGM2016	0.008 m	− 0.388 m	0.424 m
PGM2016	PGM2018	0.028 m	− 0.184 m	0.456 m

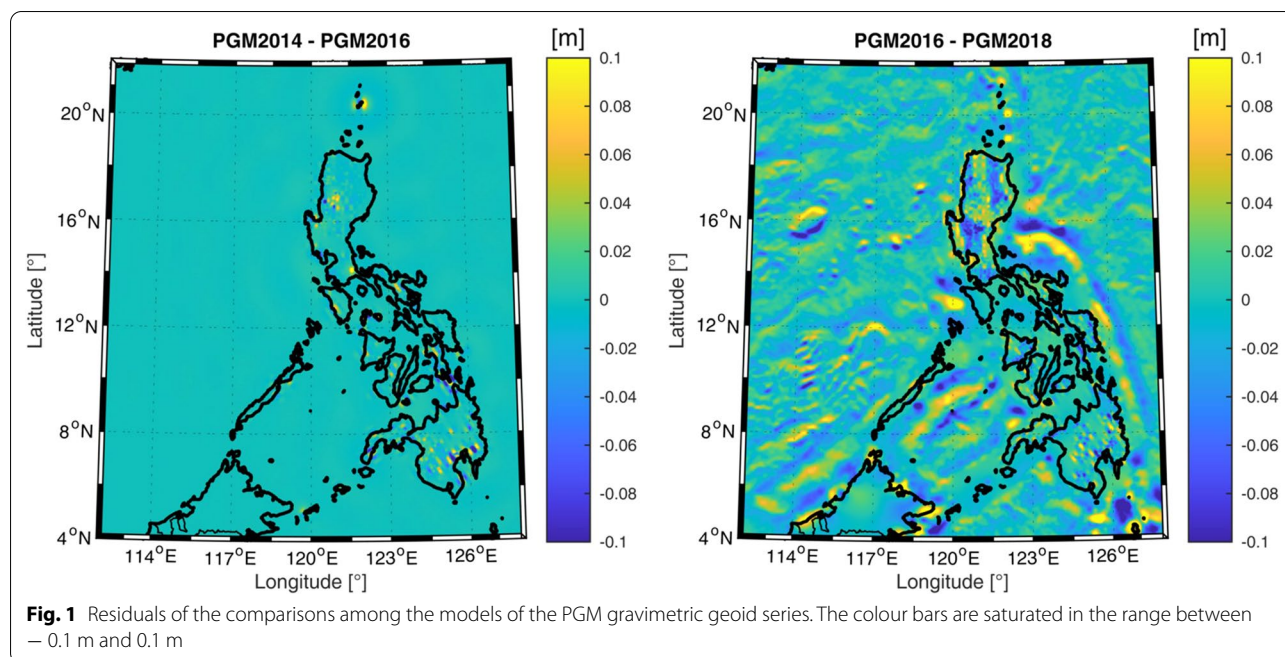


Table 3 Statistics on the residuals of national geoid series comparisons, for all the series stored in the ISG geoid repository

Country/region	Model A	Model B	STD (A-B)	Min (A-B)	Max (A-B)
Australia (gravimetric)	AUSGEOID93	AUSGEOID98	0.345 m	-2.455 m	2.814 m
	AUSGEOID98	AUSGEOID09	0.202 m	-1.854 m	0.858 m
	AUSGEOID09	AUSGEOID2020	0.083 m	-0.328 m	0.570 m
Japan (hybrid)	GSIGEO96	GSIGEO2000	0.148 m	-0.796 m	1.032 m
	GSIGEO2000	GSIGEO2011	0.100 m	-0.535 m	0.710 m
Hawaiian Islands (gravimetric)	GEOID93	GEOID96	0.352 m	-1.315 m	1.668 m
	GEOID96	GEOID99	0.188 m	-0.750 m	0.608 m
	GEOID99	USGG03	0.001 m	-0.031 m	0.002 m
	USGG03	USGG09	0.116 m	-0.828 m	0.977 m
	USGG09	USGG12	0.041 m	-0.318 m	0.078 m
Hawaiian Islands (hybrid)	GEOID03	GEOID09	0.117 m	-0.861 m	0.989 m
	GEOID09	GEOID12B	0.041 m	-0.353 m	0.084 m
New Zealand (gravimetric)	NZGEOID05	NZGEOID09	0.111 m	-2.067 m	2.201 m
	NZGEOID09	NZGEOID2016	0.092 m	-1.026 m	1.401 m
	NZGEOID2016	NZGEOID2017	0.074 m	-0.493 m	0.809 m

hybrid models, neglecting possible mismatches between geoids and quasi-geoids.

As one can see, the standard deviation of the residuals decreases gradually with updating the model, thus indicating a progressive refinement of the model in that area. Only the geoid series referring to the Hawaiian Islands shows particularly low residuals between the 1999 and 2003 editions. The reason is that these two gravimetric models are the same for the Hawaiian Islands but for the reference frame (Roman et al. 2004). However, the effect

of this frame transformation is substantially cancelled when removing the fitting plane from the residuals.

2.2 Local and regional geoid comparison

The regional South East Asia (SEA) geoid model (Kadir et al. 1999) have been compared with the overlapping local geoids of Brunei (Lyszkowicz et al. 2014) and the previously analysed PGM2018. SEA is the only regional/continental model that is available in the ISG repository for the Asian area, and Brunei and PGM

Table 4 Characteristics of the SEA, PGM2018, and Brunei geoid models, used as input for the local and regional geoid comparison example

	South East Asia (SEA)	PGM2018	Brunei
Model type	gravimetric	gravimetric	gravimetric
Reference ellipsoid	GRS80	GRS80	GRS80
Spatial resolution	30'	1.5' (downsampled to 30')	2' (downsampled to 30')
Latitude coverage	25°N–15°S (clipped over PGM2018/Brunei)	4°N–22°N	3.5°N–5.5°N
Longitude coverage	90°E–140°E (clipped over PGM2018/Brunei)	112°E–128°E	113.5°E–116°E

Table 5 Statistics on the residuals of the comparison of SEA regional geoid model with respect to PGM2018 and Brunei local geoid models

Model A	Model B	STD (A–B)	Min (A–B)	Max (A–B)
SEA	PGM2018	1.193 m	– 6.590 m	3.963 m
SEA	Brunei	0.498 m	– 0.788 m	1.590 m

series models are the only ones included in the SEA extensions. Due to the different native spatial resolutions and coverage, two grids with the same coarser resolution of SEA, and smaller coverages of Brunei and PGM2018 have been considered. Over these grids, SEA has been simply clipped while the two local geoids have been downsampled to a resolution of 30' (being their native grids overlapped to that of SEA), making the geoid models consistent among them before being compared. Table 4 summarizes the characteristics of these geoids.

The following Table 5 reports the statistics of the residuals of the two local geoids with respect to the regional one, after reducing for the fitting planes too.

Referring to the comparison between SEA and PGM2018, the residuals show a standard deviation of about 1.19 m, with values ranging between about – 6.59 m and 3.96 m. As one can see in Fig. 2, the main differences are localized in Philippines, Sulu trenches, and Borneo area (showing SEA under-estimated values) and Philippines mainland (showing SEA over-estimated values). In Brunei, the standard deviation of residuals is about 0.5 m. These residuals are quite higher if compared to the expected accuracy (declared by authors) of PGM2018 and Brunei geoids, namely 0.012 m and 0.3 m, respectively. This would suggest, for instance, that for regional investigations in this area, it would be preferable to patch together the available local geoids using SEA just as a common reference or, still better, considering recent global models (SEA is dated back to 1999). For this purpose, Fig. 3 also shows the residuals of PGM2018 and Brunei models with respect to EGM2008 (Pavlis et al.

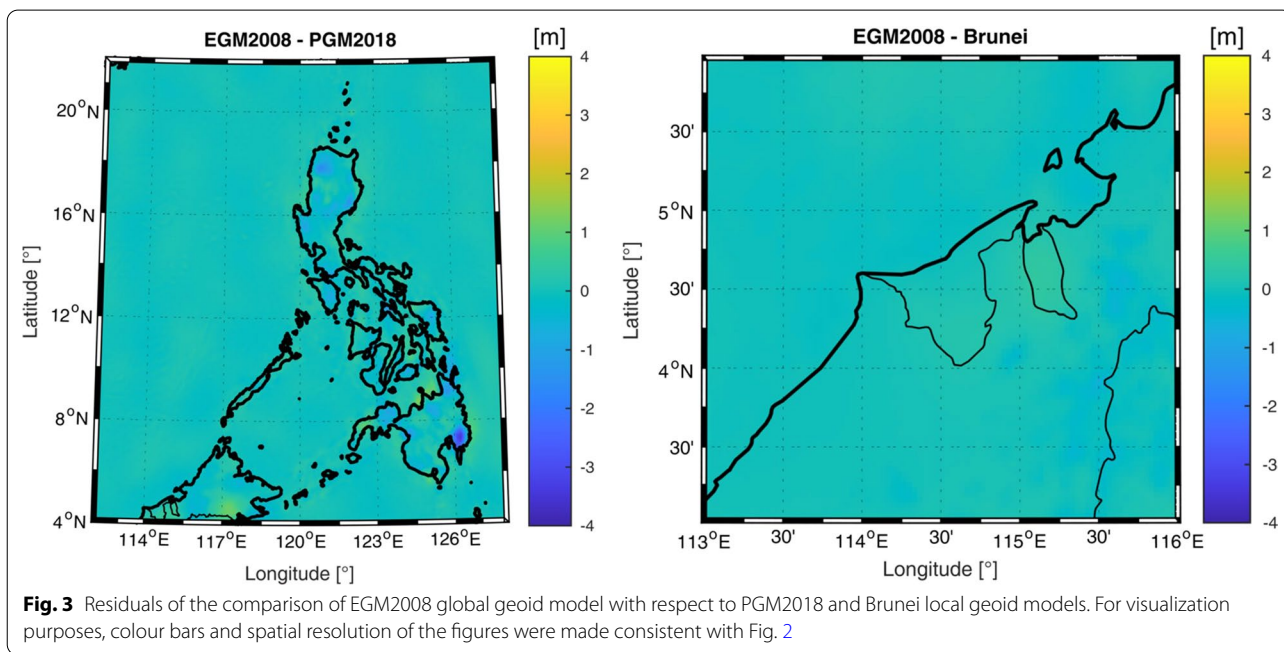
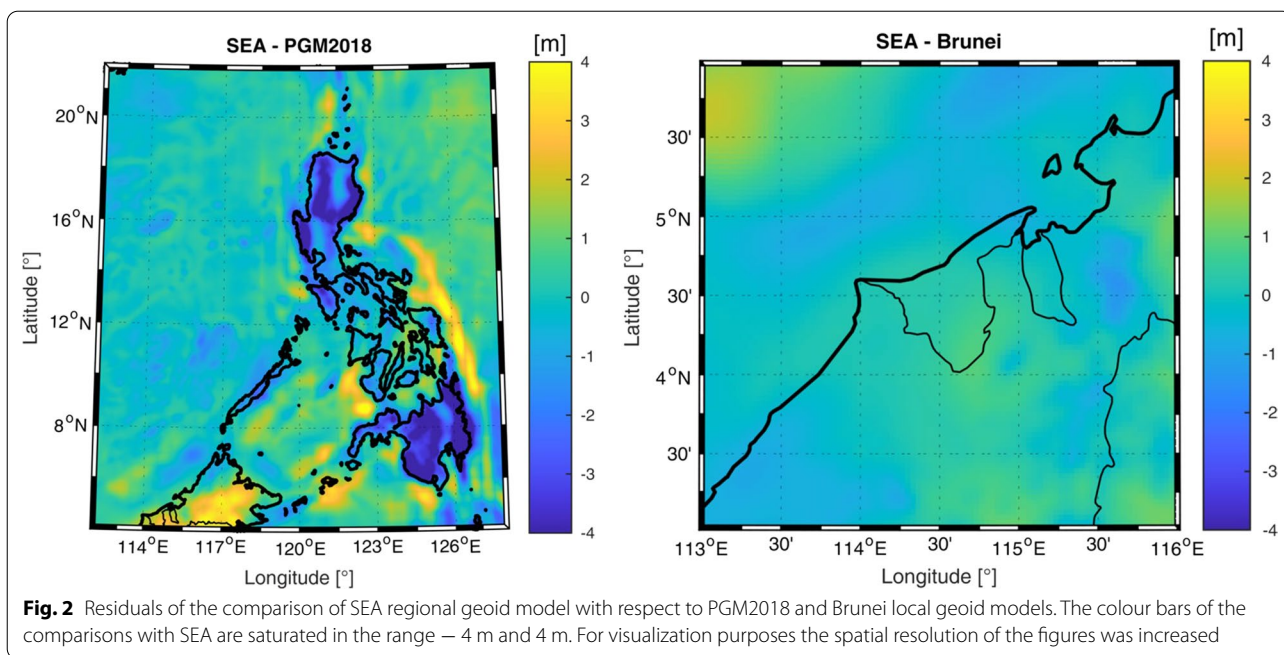
2012). As one can see, the agreement with EGM2008 is considerably higher for both PGM2018 (STD 0.184 m) and Brunei (STD 0.103 m). In the subsequent sections, comparisons with global models will be further detailed.

2.3 Local and global geoid comparison

To validate a local solution when regional or continental models are not available or they are obsolete, like in the example of the previous section, the comparison with a global model may be useful. In this respect, the Taiwanese geoid model TWGEOID2018 (Hwang et al. 2020), in its gravimetric and hybrid versions, has been evaluated with respect to EGM2008 and EIGEN6C4 (Förste et al. 2014) global models. The geoid undulations from EGM2008 and EIGEN6C4 were computed at their full resolution on the same grid points of TWGEOID2018, by exploiting the online computational tools of the International Centre for Global Earth Models (ICGEM) (Ince et al. 2019). Table 6 summarizes the main characteristics (spatial resolution and spatial coverage) and statistics of TWGEOID2018, and the geoid undulations computed from global models.

As for the mean value, the statistics of Table 6 are quite contradictory, in the sense that the TWGEOID2018g gravimetric geoid is fully consistent with EIGEN6C4, even if it was computed by using EGM2008 for the modelling of the long-wavelength behaviour (Hwang et al. 2020). On the other hand, the mean of the TWGEOID2018h hybrid geoid is closer to the EGM2008 value rather than the one of EIGEN6C4. As for the variability, the hybrid solution has a standard deviation more similar to the reference global models (about 0.01 m and 0.03 m lower with respect to EGM2008 and EIGEN6C4, respectively), while the gravimetric solution looks a slightly smoother model.

When analysing the residuals, whose statistics are reported in Table 7, slightly better matching between TWGEOID2018 and EGM2008 is revealed, accordingly to the input data used for its computation. In particular, the residuals with respect to EGM2008 of both the gravimetric and hybrid local geoid models of Taiwan show a



standard deviation of about 0.16 m, 0.02 m less than in comparison with EIGEN6C4. This also reflects on the minimum values of the residuals, but not on the maximum ones, being all practically equivalent.

Figure 4 presents the spatial distribution of the aforementioned residuals in the case of the Taiwanese gravimetric model (TWGEOID2018g), since the hybrid one shows a practically identical behaviour. The main

differences are located on Chinese mainland on the West side and on Japanese Yaeyama Islands on the East side, where the local Taiwanese geoid model seems to provide more detailed information than the global models. Residuals against EIGEN6C4 show also that the negative maximum differences are mainly located in the sea in front of the Quanzhou area (25°N, 120°E). This is probably related to the gravity data used for

Table 6 Characteristics and statistics of the TWGEOID2018 geoid model (gravimetric and hybrid versions) and the EGM2008 and EIGEN6C4 global models (over the Taiwan area), considered in the local and global geoid comparison example

	TWGEOID2018g	TWGEOID2018h	EGM2008	EIGEN6C4
Model type	Gravimetric geoid	Hybrid geoid	Geoid	Geoid
Reference ellipsoid	GRS80	GRS80	GRS80	GRS80
Spatial resolution	30''	30''	30''	30''
Latitude coverage	21°N–27°N	21°N–27°N	21°N–27°N	21°N–27°N
Longitude coverage	118°E–125°E	118°E–125°E	118°E–125°E	118°E–125°E
Mean	18.726 m	19.932 m	19.726 m	18.721 m
STD	4.947 m	5.037 m	5.043 m	5.069 m
Min	5.599 m	5.533 m	4.456 m	4.394 m
Max	30.999 m	31.472 m	30.053 m	30.084 m

computing the TWGEOID2018 models, which cover only the Taiwan Island, with gaps in the region with higher residuals (see Hwang et al. 2020).

As previously stated, this kind of relative assessment between local and global geoid models can reveal useful information for conducting more refined analyses.

Table 7 Statistics on the residuals of the comparison of the TWGEOID2018 geoid model (gravimetric and hybrid versions) with respect to EGM2008 and EIGEN6C4 global models (over the Taiwan area)

Model A	Model B	STD (A-B)	Min (A-B)	Max (A-B)
TWGEOID2018g	EGM2008	0.157 m	− 0.423 m	0.804 m
TWGEOID2018g	EIGEN6C4	0.181 m	− 0.565 m	0.803 m
TWGEOID2018h	EGM2008	0.161 m	− 0.417 m	0.809 m
TWGEOID2018h	EIGEN6C4	0.181 m	− 0.563 m	0.808 m

For the sake of brevity, just the case of the Taiwanese TWGEOID2018 geoid model has been described in detail, while Table 8 summarizes the statistics of the residuals computed by applying the same procedure to all the local geoid models stored in the ISG repository, covering the Asia–Pacific area.

As one can see, the agreement between local and global geoid models is different depending on the considered area.

For example, in the case of the Australian geoid series, residuals with respect to EGM2008 and EIGEN6C4 show very similar standard deviations, while in Guam and Northern Mariana Islands, these global models performed differently.

In the Xinjiang and Tibet area, the local geoid model is much more adherent to EGM2008 than EIGEN6C4, with statistics about 3 times better. This result matches what

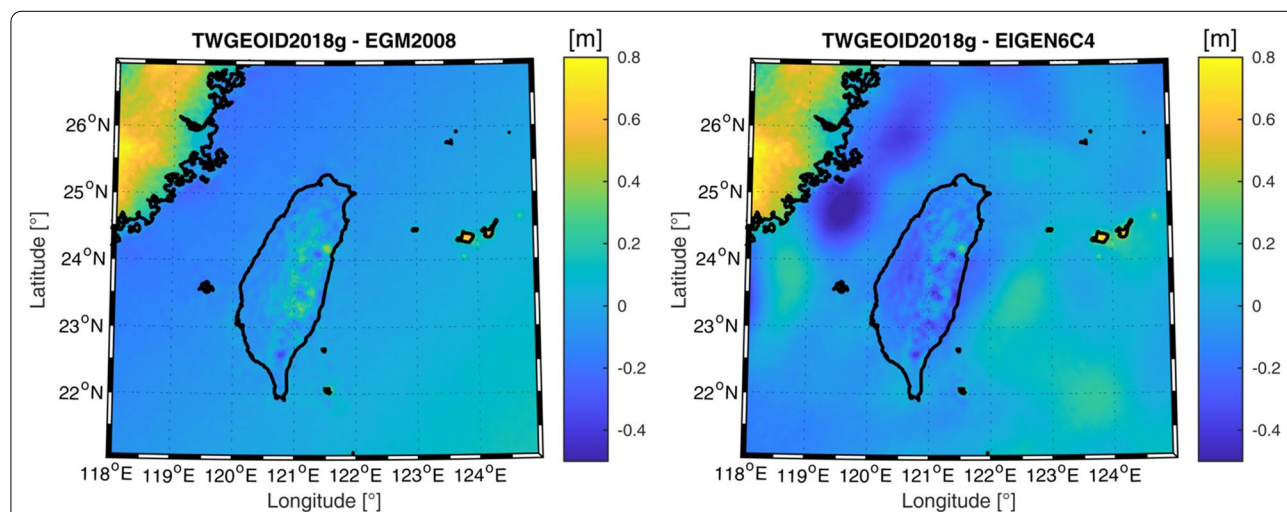


Fig. 4 Residuals of the comparison of the TWGEOID2018 geoid model (gravimetric version) with respect to EGM2008 and EIGEN6C4 global models (over the Taiwan area). The results of the same comparison computed with the hybrid version of the TWGEOID2018 geoid model are not reported, because they show an almost identical behaviour

Table 8 Statistics on the residuals of the comparison between the Asia–Pacific geoid models available in the ISG repository with respect to EGM2008 and EIGEN6C4 global models

Country or region	Model name (type)	STD [m]		Min [m]		Max [m]	
		EGM2008	EIGEN6C4	EGM2008	EIGEN6C4	EGM2008	EIGEN6C4
American Samoa Islands	USGG2009 (g)	0.012	0.060	− 0.066	− 0.256	0.261	0.416
	USGG2012 (g)	0.028	0.057	− 0.108	− 0.259	0.322	0.455
	GEOID09 (h)	0.012	0.059	− 0.068	− 0.257	0.268	0.413
	GEOID12B (h)	0.028	0.057	− 0.108	− 0.260	0.324	0.455
Australia	AUSGEOID93 (g)	0.349	0.350	− 3.222	− 3.094	2.248	2.076
	AUSGEOID98 (g)	0.438	0.435	− 11.391	− 11.386	2.556	2.460
	AUSGEOID09 (h)	0.086	0.094	− 0.553	− 0.747	1.908	1.922
	AUSGEOID2020 (h)	0.073	0.075	− 0.506	− 0.487	0.464	0.525
Brunei	Brunei (g)	0.103	0.169	− 0.447	− 0.378	0.570	0.585
Xinjiang and Tibet	Xinjiang and Tibet (g)	0.149	0.430	− 0.973	− 4.251	1.338	3.274
Guam and Northern Mariana Islands	USGG2009 (g)	0.097	0.044	− 0.468	− 0.106	0.589	0.263
	USGG2012 (g)	0.099	0.036	− 0.497	− 0.102	0.546	0.211
	GEOID09 (h)	0.097	0.044	− 0.469	− 0.108	0.588	0.281
	GEOID12B (h)	0.100	0.036	− 0.497	− 0.103	0.547	0.225
Hawaiian Islands	GEOID93 (g)	0.301	0.300	− 1.669	− 1.689	1.791	1.733
	GEOID96 (g)	0.195	0.197	− 1.281	− 1.299	0.984	0.944
	GEOID99 (g)	0.116	0.121	− 0.848	− 0.807	1.024	0.980
	USGG03 (g)	0.116	0.121	− 0.848	− 0.807	1.024	0.980
	USGG09 (g)	0.019	0.050	− 0.171	− 0.239	0.137	0.241
Japan	USGG12 (g)	0.052	0.059	− 0.089	− 0.143	0.331	0.314
	JGEOID2000 (g)	0.821	0.828	− 4.312	− 4.235	2.822	3.019
	JGEOID2008 (g)	0.204	0.223	− 3.058	− 3.049	2.154	1.964
	GSIGEO96 (h)	0.197	0.184	− 1.248	− 1.115	1.077	1.233
	GSIGEO2000 (h)	0.196	0.197	− 0.842	− 0.922	1.384	1.343
New Zealand	GSIGEO2011 (h)	0.138	0.136	− 0.594	− 0.506	1.038	0.946
	NZGEOID05 (g)	0.465	0.466	− 6.487	− 6.448	2.224	2.191
	NZGEOID09 (g)	0.059	0.075	− 1.246	− 1.253	1.439	1.529
	NZGM10 (g)	0.084	0.097	− 1.379	− 1.390	1.272	1.362
	NZGEOID2016 (g)	0.077	0.073	− 0.562	− 0.543	1.235	1.117
Papua New Guinea	NZGEOID2017 (g)	0.042	0.033	− 0.559	− 0.493	0.562	0.521
	PNG94 (g)	1.071	1.077	− 6.684	− 6.575	3.013	3.015
	PNG08 (g)	0.141	0.241	− 1.035	− 2.355	0.773	1.864
Philippines	PGM2014 (g)	0.185	0.153	− 1.368	− 0.957	3.499	2.876
	PGM2016 (g)	0.185	0.153	− 1.375	− 0.957	3.441	2.794
	PGM2018 (g)	0.184	0.151	− 1.374	− 0.959	3.436	2.789
	PGM2016 (h)	0.200	0.178	− 1.461	− 1.020	3.337	2.690
	PGM2018 (h)	0.219	0.183	− 1.390	− 1.048	3.396	2.746
Russia	RGG2003 (g)	0.913	0.399	− 13.996	− 13.948	28.546	37.487
	RGG2003 (g-clean)	0.911	0.393	− 6.752	− 7.060	8.203	9.633
Tahiti	Tahiti (g)	0.060	0.103	− 1.828	− 1.910	0.460	0.593
Taiwan	TAIWAN (g)	0.523	0.479	− 1.747	− 1.804	1.946	1.744
	TWGEOID2018g (g)	0.157	0.181	− 0.423	− 0.565	0.804	0.803
	TWGEOID2018h (h)	0.161	0.181	− 0.417	− 0.563	0.809	0.808
Vietnam	Vietnam (g)	0.238	0.142	− 1322	− 0.906	1.098	0.683

The type of the model is defined by the g and h letters, referring to gravimetric and hybrid models, respectively

Table 9 Mean values of the Asia–Pacific geoid models available in the ISG repository, as well as those of EGM2008 and EIGEN6C4 global models computed on the same grids

Country or region	Model name (type)	Mean [m]		
		ISG model	EGM2008	EIGEN6C4
American Samoa Islands	USGG2009 (g)	26.715	26.200	26.202
	USGG2012 (g)	26.698	26.200	26.202
	GEOID09 (h)	26.907	26.200	26.202
Australia	GEOID12B (h)	26.886	26.200	26.202
	AUSGEOID93 (g)	25.957	25.688	25.689
	AUSGEOID98 (g)	28.910	28.892	28.892
	AUSGEOID09 (h)	29.192	28.900	28.901
Brunei	AUSGEOID2020 (h)	24.368	23.925	23.925
	Brunei (g)	43.557	42.563	42.606
China (Xinjiang and Tibet)	Xinjiang and Tibet (g)	45.265	45.775	45.771
Guam and Northern Mariana Islands	USGG2009 (g)	49.944	55.287	55.364
	USGG2012 (g)	49.937	55.287	55.364
	GEOID09 (h)	48.638	49.411	49.411
	GEOID12B (h)	48.966	49.417	49.417
Hawaiian Islands	GEOID93 (g)	6.646	5.751	5.755
	GEOID96 (g)	6.396	5.751	5.755
	GEOID99 (g)	6.306	5.751	5.755
	USGG03 (g)	6.309	5.751	5.755
	USGG09 (g)	6.170	5.751	5.755
	USGG12 (g)	6.181	5.751	5.755
Japan	JGEOID2000 (g)	25.992	25.749	25.751
	JGEOID2008 (g)	26.251	25.749	25.751
	GSIGEO96 (h)	34.275	33.619	33.612
	GSIGEO2000 (h)	33.642	32.855	32.851
	GSIGEO2011 (h)	34.966	34.204	34.198
New Zealand	NZGEOID05 (g)	24.805	24.885	24.886
	NZGEOID09 (g)	25.062	24.885	24.886
	NZGM10 (g)	22.285	22.122	22.122
	NZGEOID2016 (g)	25.030	24.885	24.886
	NZGEOID2017 (g)	25.041	24.885	24.886
Papua New Guinea	PNG94 (g)	71.553	70.818	70.820
	PNG08 (g)	72.068	71.420	71.421
Philippines	PGM2014 (g)	39.175	37.906	37.905
	PGM2016 (g)	38.409	37.906	37.905
	PGM2018 (g)	38.409	37.906	37.905
	PGM2016 (h)	39.581	37.905	37.905
	PGM2018 (h)	45.461	43.990	43.988
Russia	RGG2003 (g)	− 3.281	− 3.179	− 3.179
	RGG2003 (g-clean)	− 3.279	− 3.179	− 3.179
Tahiti	Tahiti (g)	4.396	3.426	3.376
Taiwan	TAIWAN (g)	19.729	18.726	18.721
	TWGEOID2018g (g)	19.932	18.726	18.721
	TWGEOID2018h (h)	19.932	18.726	18.721
Vietnam	Vietnam (g)	17.536	17.535	17.536

The type of the model is defined by the g and h letters, referring to gravimetric and hybrid models, respectively

can be found in Shen and Han (2013), where the procedure of the Xinjiang and Tibet geoid model computation is described, highlighting the contribution of the use of EGM2008, and therefore justifying the agreement with this global model. On the other hand, Kostelecky et al. (2015) states that the main difference between EGM2008 and EIGEN6C4 is the inclusion of GOCE mission data in the EIGEN6C4 model. In their evaluation, they see long wavelength differences between the two models in remote areas of the Earth (as mountainous Tibet areas could be considered), where a scarce or bad terrestrial data coverage is present, and, for these regions, they assume a positive effect of introducing the GOCE data. This would lead thinking that, despite worse statistics, in most challenging areas, EIGEN6C4 might be a better reference for local model assessment.

Regarding the Russian quasi-geoid model RGG2003 (Medvedev and Nepoklonov 2003), statistics reveal anomalous values. Minimum and maximum values are of the order of tenths of meters, although the standard deviation is comparable to those of the other geoid models. This leads assuming the presence of outliers in the dataset. A possible strategy to find out them can be the inspection of the histogram of the residuals. Tails are expected to tend toward zero, without significant peaks or isolated values that could be considered anomalous. Once detected, the corresponding values could be removed and, eventually, interpolated if needed. With such a simple procedure, correcting just 4 points out of 651,689, the range of residuals significantly decreases, leaving the standard deviation almost unchanged, as shown in Table 8.

For the sake of completeness, the mean values of both local and global geoid models are reported in Table 9. These values clearly show how the adopted height datums are different and represent an important input towards the realization of a unified vertical reference system.

3 Conclusions

This work analysed the state-of-the-art geoid modelling in the Asia–Pacific region by considering the models that are stored in the repository of ISG, which represents the reference geoid archive for the geodetic community in the framework of IAG. It comes out that a significant portion of the region is covered by at least a model, or even more when considering series of solutions computed by the same institution in the years or by different authors exploiting different techniques. Altogether, 58 models covering more than 60% of Asia–Pacific area are available. Starting from this collection of models, some comparative statistical analyses were performed, basically showing that:

- in all geoid series, there is a time trend with smaller and smaller corrections, suggesting that recent solutions include improvements with a sort of convergence to an “optimal” one;
- at the regional/continental level, only a model for South-East Asia is currently included in the ISG repository, but this model is quite out-of-date, and the performances of more recent global models look better;
- in general, local/national solutions agree quite well with global ones (EGM2008 and EIGEN6C4 were considered in this analysis), with discrepancies ranging from a few to some tens of centimetres in terms of standard deviation.

As for the future perspectives, some effort will be dedicated to enlarging the ISG repository in the Asia–Pacific region, especially covering China, Mongolia, Korean Peninsula, Indonesia, India, and the South-West Asia. Exploiting this enlarged archive and, maybe, updating some old solutions, national geoid models might also be used to address the problem of the height datum unification in the framework of IAG activities for the definition and realization of an International Height Reference System (IHR).

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Author contributions

All authors contributed equally to the study conception, design, material preparation, data collection, analysis, first draft preparation and comment of its subsequent versions. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analysed during this study and included in this published article can be accessed through the International Service for the Geoid repository (<https://www.isgeoid.polimi.it/>) under different policies, specified on the website.

Declarations

Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

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