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The new ESA satellite-only gravity field model via the direct approach

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[1] Reprocessed Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) gravity gradient data were combined with data from Laser Geodynamics Satellite (LAGEOS) 1/2 and Gravity Recovery and Climate Experiment (GRACE) to generate a satellite-only gravity field model to degree 260 using the direct approach, named DIR-R4. When compared to Earth Gravitational Model 2008 (EGM2008), it is more accurate at low to medium resolution thanks to GOCE and GRACE data. When compared to earlier releases of ESA GOCE models, it is more accurate at high degrees owing to the larger amount of data ingested. It is also slightly more accurate than ESA's fourth release of the time-wise model (TIM-R4), as demonstrated by GPS/leveling, orbit determination tests, and an oceanographic evaluation. According to the formal, probably too optimistic by a factor of 2–2.5, cumulated geoid (1.3 cm) and gravity anomaly (0.4 mGal) errors at 100 km resolution, the GOCE mission objectives have been reached. **Citation:** Bruinsma, S. L., C. Förste, O. Abrikosov, J.-C. Marty, M.-H. Rio, S. Mulet, and S. Bonvalot (2013), The new ESA satellite-only gravity field model via the direct approach, *Geophys. Res. Lett.*, *40*, 3607–3612, doi:10.1002/grl.50716.

1. Introduction

[2] The ESA Earth Explorer satellite GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) [*Drinkwater et al.*, 2003] was launched on 17 March 2009 and started its science phase in November 2009 at a constant altitude of 255 km. The mission objectives are geoid accuracy of 1–2 cm and gravity anomaly accuracy of 1 mGal at a resolution of 100 km, which corresponds to spherical harmonic degree 200. GOCE is equipped with a triaxial gravity gradiometer, a GPS receiver, a laser retroreflector, star sensors, and ion propulsion to achieve this unprecedented performance. The High-Level Processing Facility (HPF) generates ESA GOCE level-2 products and, notably, the gravity field models, the latest release of which is the subject of this paper. The satellite-only gravity field model by means of the direct approach, named DIR-R4 in the following (GO_CONS_GCF_2_DIR_R4 on http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html), is presented and compared with other selected models. DIR-R4 is constructed with Laser Geodynamics Satellite (LAGEOS) 1/2, GRACE (Gravity Recovery and Climate Experiment), and reprocessed GOCE data, which, in combination, assures high accuracy from low to high resolution.

[3] NASA's Laser Geodynamics Satellite 1 (LAGEOS-1) was launched in 1976; LAGEOS-2 was built by the Italian Space Agency and launched in 1992. These spherical satellites orbit at around 5800 and 5600 km altitudes, respectively. They contribute to the knowledge of the very low degree coefficients of the gravity field thanks to the quality of the laser tracking data provided by the International Laser Ranging Service [*Pearlman et al.*, 2002].

[4] The twin GRACE satellites, launched in March 2002, have, for objective, to map monthly gravity fields with a resolution of 400 km [*Tapley et al.*, 2004]. The satellites are on the same orbit, separated by approximately 220 km; this distance is measured with micrometer precision using a K-band microwave ranging (KBR) system. Furthermore, the science payload of each satellite consists of a GPS receiver, a laser retroreflector, star sensors, and a high-precision three-axis accelerometer.

[5] The geopotential is represented as a spherical harmonic expansion in the spectral domain. Stokes coefficients C and S are estimated up to degree and order (d/o) 260, corresponding to a resolution on the globe of approximately 77 km (20,000 km/degree).

2. The DIR-R4 Model

2.1. Satellite Data Processing

[6] The estimation of the Stokes coefficients from GRACE and LAGEOS observations is done using the dynamic approach, i.e., based on the analysis of orbit perturbations. The satellite tracking data are compared to model-predicted values inferred from a numerically integrated orbit using a priori gravitational and nongravitational background models (LAGEOS) or accelerometer data (GRACE). The difference between the observations and the modeled quantities, i.e., the residuals, is ingested into an iterative least squares adjustment. The tracking data are reduced in batches of 1 day (GRACE) or 10 days (LAGEOS), i.e., in 1 and 10 day arcs. Normal equations (NEs) are formed for each arc, which,

Table 1. Data and Normal Equations (NE) Used in the Model Construction

	Period	Data Type	NE Max d/o	NE d/o Range Used
LAGEOS-1/2	1985–2010	SLR	30	2–30
GRACE	2/2003 to 1/2011	GPS + KBR	160	2–54
	10/2003 to 9/2012	GPS + KBR	180	55–130
GOCE	11/2009 to 7/2012	SGG V_{xx}, V_{yy}, V_{zz}, V_{xz}	260	2–260

Additional supporting information may be found in the online version of this article.

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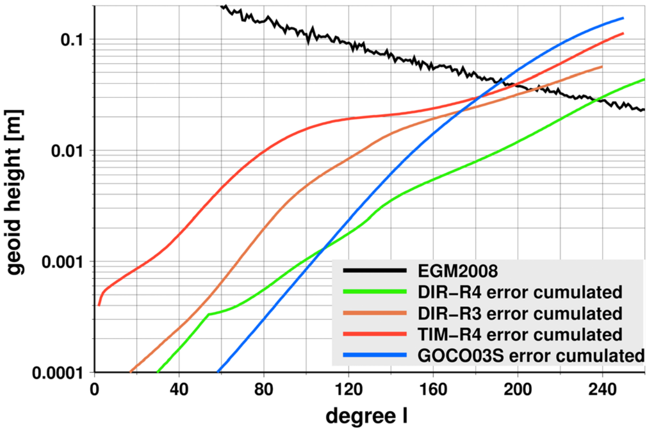

Figure 1. Cumulated formal errors in terms of geoid heights. The degree amplitudes of EGM2008 (black) are given as reference.

ultimately, are all summed into one equation system. For a detailed description of the GRACE data processing, we refer to *Bruinsma et al.* [2010] and *Dahle et al.* [2012].

[7] Reprocessed GOCE satellite gravity gradient (SGG) data are precise only in the measurement bandwidth (MBW) of 5–100 mHz, in which the noise is nearly white. The errors increase approximately with $1/f$ below (which causes large errors in the long-wavelength part of the spherical harmonics) and f^2 above the MBW (colored noise), respectively. For a more detailed description of the instrumental noise, we refer to *Pail et al.* [2011]. All signals outside the MBW are suppressed with an autoregressive moving average filter to obtain results that are largely independent of the variability in the colored noise. The measured minus modeled quantities, i.e., the SGG residuals, are filtered together with the observation equations that relate these quantities to the unknown model parameters. A filter with a passband of 8.3–125 mHz of order 12 was applied. The

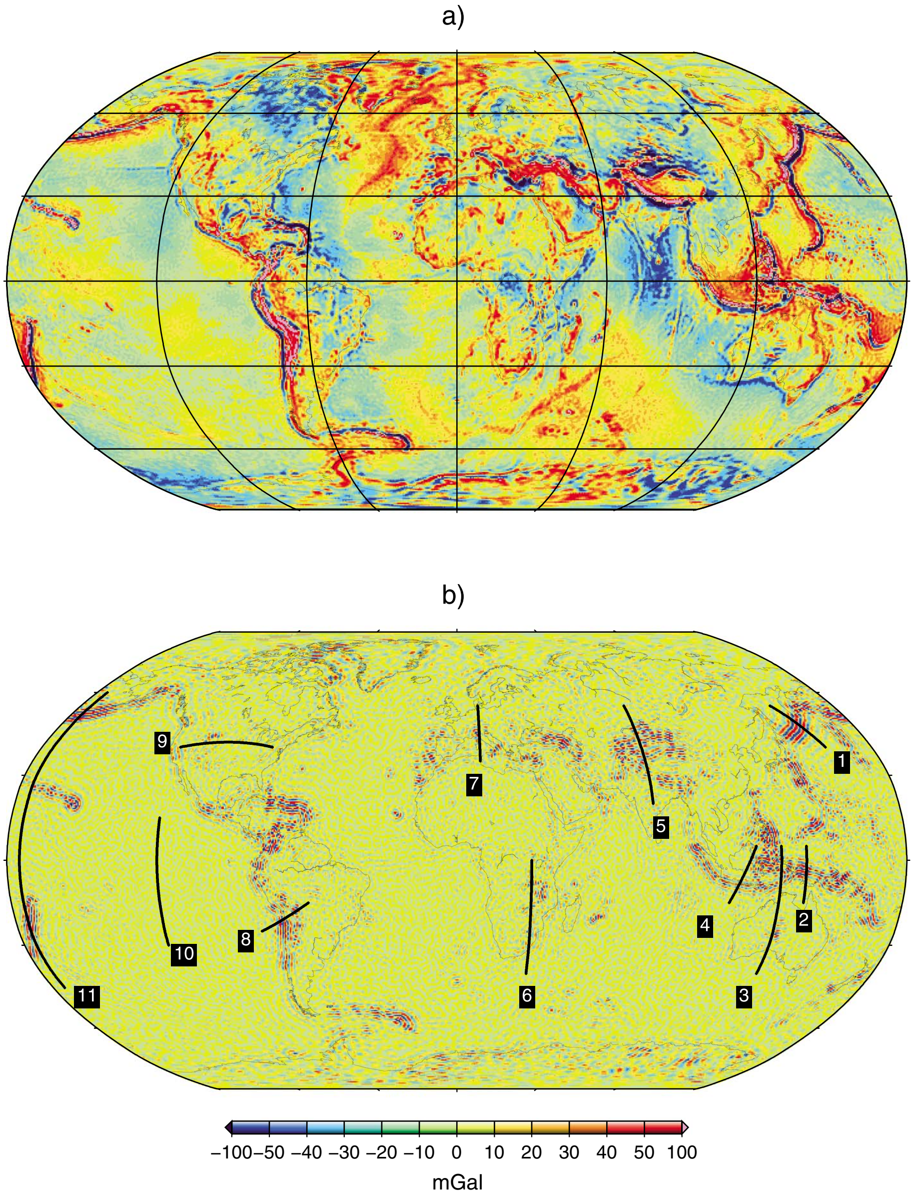

Figure 2. (a) FA gravity anomaly computed from the DIR-R4 model (d/o 260). (b) Difference between Figure 2a and the FA gravity anomaly derived from the ITG-Grace2010s model (d/o 150).

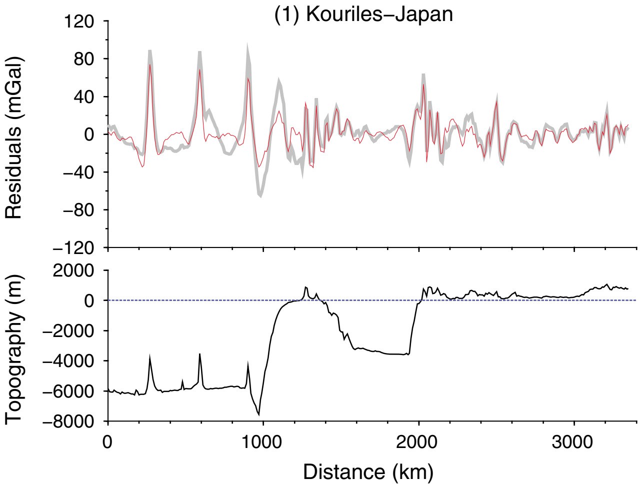

Figure 3. The differences between (red) DIR-R4 and (grey) ITG-Grace2010s with the reference model EGM2008 for profile 1.

high-pass cutoff frequency is selected within the gradiometer MBW because of the higher accuracy of the GRACE K-band data in the low-to-medium spectral range. The second-order derivatives of the gravitational potential, namely, V_{xx}, V_{yy}, V_{zz}, and V_{xz}, are used (i.e., SGG observations) in the gradiometer reference frame (GRF) [*EGG-C*, 2010]. GOCE SGG normal equations are computed separately for each component in batches of 33 uninterrupted measurement time spans, using the precise science orbits to geolocate the gradients. Table 1 lists the ingested data and the resulting normal equation (NE).

2.2. Composition of DIR-R4

[8] The LAGEOS-1/2 NE and the GRACE NE to d/o 160 are from the Groupe de Recherche de Géodésie Spatiale (GRGS) release 02 GRACE processing [*Bruinsma et al.*, 2010], whereas the GRACE NE to d/o 180 is from the GFZ release 05 processing [*Dahle et al.*, 2012]. The GRACE normal equations were then combined, taking d/o 2–54 from GRGS release 2 and d/o 55–180 from GFZ GRACE release 05. Such a blended composition was chosen because the GRGS coefficients for the wavelengths below degree 55 are more accurate than those of GFZ release 05. This was verified through satellite orbit computation. The release 05 NEs are significantly more accurate for degrees 54 and up, which shows as noise reduction over deserts and oceans.

Table 2. RMS Differences (mGal) Along Profiles Between the FA Gravity Anomalies Derived From ITG-Grace2010s, DIR-R3, DIR-R4, and TIM-R4, With EGM2008

	ITG-Grace	DIR-R3	DIR-R4	TIM-R4
No.	d/o Max = 150/180	d/o Max = 240	d/o Max = 240/260	d/o Max = 240/250
1	14.2/14.6	10.4	10.9/8.8	10.7/10.1
2	11.1/12.9	9.1	8.5/8.6	8.5/7.8
3	15.9/17.5	11.8	11.7/12.2	12.0/11.6
4	15.5/17.8	14.4	12.7/13.6	13.3/13.5
5	26.8/23.8	22.3	21.2/20.2	21.1/19.8
6	17.4/18.0	14.9	14.6/13.6	14.5/14.1
7	17.7/16.9	14.6	12.5/13.7	13.3/13.8
8	15.9/15.1	11.5	11.4/11.9	11.6/11.9
9	19.1/16.7	14.8	14.5/13.9	14.5/14.4
10	3.9/6.3	4.0	4.2/4.4	4.3/4.3
11	17.4/18.0	14.9	14.6/13.6	14.5/14.1

Table 3. RMS of GPS/Leveling Minus Model-Derived Geoid Heights (cm)[a]

	Region (Number of Points)				
	USA (6169)	Australia (201)	Germany (675)	Canada (1930)	Europe (1234)
EGM2008	31.8	23.6	14.2	22.9	27.0
TIM-R4	32.8	26.6	18.0	25.2	28.6
DIR-R3	35.2	28.1	21.2	27.8	30.5
DIR-R4	32.7	26.3	16.8	24.7	28.4
GOCO03s	34.8	28.0	21.9	27.2	30.8

[a] Models were taken to d/o 240 and completed to d/o 360 with EGM2008. References for most of the GPS/leveling data sets can be found in *Förste et al.* [2008].

[9] Finally, the LAGEOS, GRACE, and GOCE contributions were accumulated into one system of normal equations complete to d/o 260; Table 1 (far right column) lists the degree range used in each NE. This normal matrix is ill conditioned due to the polar gaps in the GOCE data. Hence, the spherical cap regularization as proposed by *Metzler and Pail* [2005] was applied, in which the geopotential function is given as an analytical continuous function in the polar caps only. The regularization is applied as a normal equation, which mainly constrains the (near)zonal and (near)sectorial coefficients. The stabilizing function in the right-hand side of the regularized normal system [*Metzler and Pail*, 2005, equation (27)] was chosen as a spherical harmonic expansion of the potential based on an a priori gravity field model that was constructed with the GRACE/LAGEOS NE up to d/o 130 and filled with zero values to d/o 260. The resulting regularized normal system was solved by means of Cholesky decomposition, in which Kaula regularization was applied for degrees 200–260.

3. Model Evaluation

3.1. Spectral Behavior

[10] Figure 1 shows the spectral cumulated formal errors of DIR-R4 in comparison to the previous release (DIR-R3), the fourth release of the time-wise model TIM-R4, and the combined satellite-only model GOCO03S [*Mayer-Gürr et al.*, 2012]. The spectrum of Earth Gravitational Model 2008 (EGM2008) [*Pavlis et al.*, 2012] is given as reference. The formal error of DIR-R4 is significantly smaller than that of DIR-R3 thanks to using more and more precise data (i.e., reprocessed GOCE and GRACE). The peak in the DIR-R4 formal error at degree 55 is due to the transition in the

Table 4. Mean RMS of Fit (cm) of GOCE, Starlette, and LAGEOS Dynamic Orbits

	GOCE	Starlette	LAGEOS
EGM2008	2.8	1.6	1.7
TIM-R4	1.5	2.0	1.6
DIR-R3	1.6	2.1	1.1
DIR-R4	1.6	1.5	1.1
GOCO03s	1.6	1.4	2.4

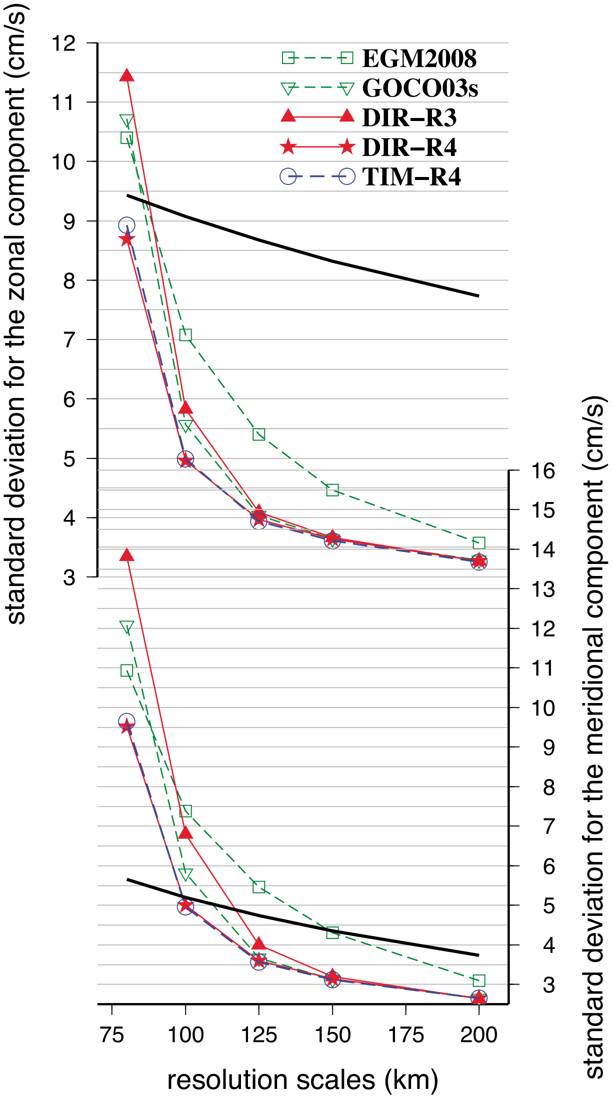

Figure 4. Standard deviation of the measured current (thick line) and its difference with derived currents at specific scales (symbols), in centimeters per second.

GRACE normal equations from release 2 of GRGS to release 5 of GFZ because the error in the GRACE release 5 NE from GFZ is significantly smaller. This is thanks to using reprocessed GRACE data, compared to the older release from GRGS. The cumulated error of DIR-R4 at degree 200 in terms of geoid height (gravity anomaly) is 1.3 cm (0.4 mGal) compared to 3 cm for DIR-R3, i.e., an improvement of about 50%.

3.2. Gravity Anomaly Comparisons

[11] Figure 2a displays the free-air (FA) gravity anomalies computed with the GRACE/GOCE model DIR-R4 to d/o 260; Figure 2b shows the difference with the best GRACE model, ITG-Grace2010s [*Mayer-Gürr et al*., 2010], to d/o 150. The largest differences are mostly observed over areas that are characterized by steep gradients that cannot be resolved with GRACE. To demonstrate the added value of GOCE for solid Earth applications, 10 profiles from DIR-R4, DIR-R3, TIM-R4, and ITG-Grace2010s are compared to the reference model EGM2008. The profiles shown in Figure 2b are representative of both various Earth features (e.g., subduction trenches, shallow seas, and ocean-continent transitions) and level of gravity information in EGM2008 (i.e., available surface data as described in *Pavlis et al.* [2012]). A reference profile (#10), where gravity anomalies are well known from altimetry, shows good agreement. Figure 3 shows profile 1 as an example, for which the accord with EGM2008 is significantly improved for the DIR-R4 model. All RMS differences are listed in Table 2, for the maximum model resolution as well as at d/o 240 for the GOCE models, in order to compare at the same resolution.

[12] Obviously, the improvements are due to GOCE providing gravity information in the d/o 150–240–260 range. This intermediate spectral range was not well constrained by GRACE or surface gravity data (better at characterizing higher-frequency variations). GOCE models thus provide a global and accurate gravity reference for this bandwidth, making surface and satellite measurements match together better when mapping gravity anomalies from long to short wavelengths. It will be particularly useful to constrain gravity anomaly models based on realistic Earth models such as recently proposed by *Balmino et al*. [2012].

[13] Figure 2 and Table 2 reveal also that major improvements are obtained along active continental margins, where subduction or collision processes between tectonic plates take place. The structure of these plate boundaries, which extends for most of them over continental and oceanic domains, is usually poorly constrained due to the lack of homogeneous gravity data over such transitions.

3.3. GPS/Leveling Results

[14] An independent comparison can be made using geoid heights determined pointwise by GPS positioning and leveling. Table 3 lists the results for EGM2008 and the satellite-only models DIR-R4, TIM-R4, GOCO03s, and DIR-R3 using data sets for different regions of the world. The height anomalies were calculated from the models and reduced to geoid heights. The coefficients of the GOCE models were taken to d/o 240 and completed to d/o 360 with EGM2008. Table 3 shows the significant gain in accuracy of DIR-R4 compared with DIR-R3 and its better performance when compared to TIM-R4 and GOCO03s.

3.4. Precise Orbit Determination Results

[15] The long-to-medium wavelength accuracy of models can be evaluated through dynamic orbit computation. We computed 60 GOCE orbits of 1.25 day length, 20 Starlette 6 day arcs, and 30 LAGEOS 10 day arcs. For GOCE, the level-2 kinematic science orbits were used as observations. LAGEOS and Starlette were fitted to satellite laser ranging data. Besides the ESA models DIR-R3, DIR-R4, and TIM-R4, results from GOCO03s and EGM2008 are listed in Table 4. The best fit results, overall, are obtained with the DIR-R4 model. The best results for GOCE are obtained with TIM-R4, which used GOCE GPS satellite-to-satellite tracking (SST) data employing a novel short-arc method [*Mayer-Gürr et al*., 2005]; GOCE SST data were not used in DIR-R4.

3.5. Oceanographic Evaluation

[16] The relative accuracy of geoid models is assessed through the computation of the ocean mean dynamic topography (MDT; mean sea surface minus geoid) and the

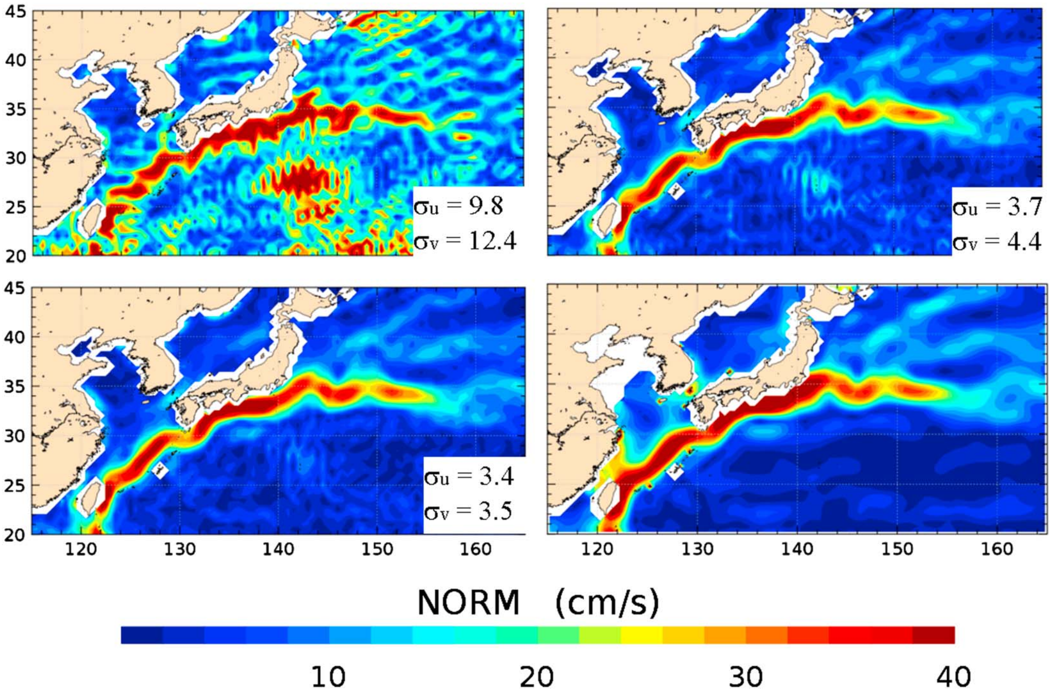

Figure 5. Mean current intensity in the Kuroshio at 100 km resolution from (top left) ITG-Grace2010s, (top right) EGM-DIR3, (bottom left) EGM-DIR4, and (bottom right) in situ velocities. σ_u (resp. σ_v) stands for standard deviation of the difference with measured zonal (resp. meridional) velocities.

corresponding mean geostrophic currents using the method described in *Mulet et al.* [2012]. The mean currents are filtered at spatial scales ranging from 80 to 200 km and compared to mean geostrophic currents derived from independent in situ data at the same resolution. In situ mean currents are obtained by averaging the surface velocities deduced from the trajectories of drifting buoys after the ageostrophic components have been removed as well as the time variability measured by altimeters. The error in the in situ mean currents, counting both the buoy measurement accuracy and the processing errors, is estimated at 3 cm/s [*Hansen and Poulain*, 1996; *Poulain et al*., 2012].

[17] Figure 4 shows the RMS differences between the in situ mean velocities and the mean velocities obtained using geoid solutions at different resolutions for the zonal (u) and meridional (v) components. For DIR-R4 and TIM-R4, the RMS difference at the target resolution of GOCE of 100 km is 5 cm/s, which is a significant improvement compared to earlier GOCE solutions. RMS differences at 100 km resolution for ITG-Grace2010s are 17 and 18 cm/s for u and v, respectively. This highlights the huge step achieved at 100 km resolution in the computation of the ocean circulation thanks to GOCE. Figure 5 (Figure S1 in the supporting information) illustrates this for the Kuroshio (Gulf Stream). At 80 km resolution, RMS differences to in situ observations increase to around 9 and 9.5 cm/s for the u and v components, respectively, with slightly better results for DIR-R4 than for TIM-R4. However, at that resolution, the RMS differences for the meridional component exceed the variability of the observed current.

4. Discussion and Conclusions

[18] The DIR-R4 model is significantly more accurate than its predecessor mainly due to more than doubling the amount of GOCE mission data used, which are, moreover, of better quality thanks to the reprocessing by ESA. It is also more accurate than ESA's GOCE-only TIM-R4 model, as may be seen in Tables 2 and 4. The noise over the oceans is also smaller: RMS of 13.2 cm versus 13.9 cm when compared with EGM2008 to d/o 250. The added value of GOCE over both continents and oceans is demonstrated by a comparison of DIR-R4 with ITG-Grace2010s results in Table 2 and section 3.5. Taking into account the error in the in situ velocities of 3 cm/s, GOCE data now allow for a description of the ocean circulation at 100 km with accuracy of $\varepsilon_v = \sqrt{5^2 - 3^2} \approx 4\,\mathrm{cm/s}$ (the corresponding MDT being consequently known at accuracy better than $\varepsilon_h = \varepsilon_v / \sqrt{2} \approx 3\,\mathrm{cm}$). This value is consistent with the expected 1–2 cm error level for the GOCE geoid at 100 km resolution coupled with a centimeter error level of the altimeter mean sea surface [*Schaeffer et al*., 2012].

[19] According to our formal error estimates, which may be too optimistic by a factor of 2–2.5, the mission objectives as specified at the horizontal resolution of 100 km have been reached. This fourth ESA/GOCE satellite-only gravity field model now provides the best reference for geodesy, oceanography, and solid Earth studies.

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