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Key Points:
- Model based on LAGEOS, GRACE, and all GOCE data
- Calibrated geoid error at 100 km resolution of 1.7 cm
- Improved geostrophic ocean circulation on 100–200 km scales

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4

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ESA's satellite-only gravity field model via the direct approach based on all GOCE data

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Abstract Gravity field and steady state Ocean Circulation Explorer (GOCE) gravity gradient data of the entire science mission and data from LAGEOS 1/2 and Gravity Recovery and Climate Experiment (GRACE) were combined in the construction of a satellite-only gravity field model to maximum degree 300. When compared to Earth Gravitational Model 2008, it is more accurate at low to medium resolution, thanks to GOCE and GRACE data. When compared to earlier releases of European Space Agency GOCE models, it is more accurate at high degrees owing to the larger amount of data ingested, which was moreover taken at lower altitude. The impact of orbiting at lower altitude in the last year of the mission is large: a model based on data of the last 14 months is significantly more accurate than the release 4 model constructed with the first 28 months. The (calibrated) cumulated geoid error estimate at 100 km resolution is 1.7 cm. The optimal resolution of the GOCE model for oceanographic application is between 100 and 125 km.

1. Introduction

GOCE (Gravity field and steady state Ocean Circulation Explorer) [*Drinkwater et al.*, 2003], European Space Agency (ESA)'s first Earth Explorer, was launched on 17 March 2009 and reentered the atmosphere on 11 November 2013. The Science Mission lasted from 1 November 2009 to 22 October 2013. The orbit was maintained at a constant 255 km mean altitude up to 1 July 2012. GOCE was then lowered 4 times to enhance the gravity signal-to-noise ratio: to 246 km through July 2012, to 240 km through November 2012, to 235 km in February 2013, and to 224 km in May 2013.

The mission objectives are specified at 100 km resolution: geoid (gravity anomaly) accuracy of 1 to 2 cm (1 mGal). GOCE was equipped with a triaxial gravity gradiometer, GPS receiver, laser retroreflector, star sensors, and an ion propulsion engine with variable thrust to reach these goals [*Floberghagen et al.*, 2011]. The High-Level Processing Facility computed the GOCE level 2 products on behalf of ESA. Gravity field model computed by means of the direct numerical approach is one of these products. Its latest release 5 (DIR-R5) is the subject of this paper. This satellite-only gravity field model (GO_CONS_GCF_2_DIR_R5 on http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html) is described and compared with selected other models. DIR-R5, like DIR-R4 [*Bruinsma et al.*, 2013], is constructed with LAGEOS 1/2, Gravity Recovery and Climate Experiment (GRACE), and GOCE data in order to reach high accuracy over the entire spectral range of the model.

NASA's Laser Geodynamics Satellite 1 (LAGEOS 1) was launched in 1976; LAGEOS 2, built by the Italian Space Agency, was launched in 1992. These geodetic satellites orbit at around 5800 and 5600 km altitude, respectively, and are sensitive only to the very low degree coefficients of the gravity field. The twin satellite mission GRACE (Gravity Recovery and Climate Experiment) was launched in March 2002 and is still operating. Its objective is the monthly mapping of the gravity field with a resolution of 400 km [*Tapley et al.*, 2004]. The satellites, separated by approximately 220 km, use a K band microwave ranging system (KBR) to measure this distance with micrometer precision. The science payload of each satellite also comprises a GPS receiver, laser retroreflector, star sensors, and a high-precision three-axis accelerometer.

Earth's geopotential is modeled as a truncated spherical harmonic expansion in the spectral domain. DIR-R5 is developed to degree and order (d/o) 300, corresponding to a resolution on the globe of approximately 67 km (20,000 km/300). The GOCE mission objectives at 100 km resolution are thus specified at d/o 200.

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

	Period	Data Type	NE Maximum d/o	NE d/o Range Used
LAGEOS 1/2	1985 to 2010	satellite laser ranging	30	2–30
GRACE	2/2003 to 12/2012	GPS + KBR	175	2–130
GOCE	11/2009 to 10/2013	SGG Vxx, Vyy, Vzz, and Vxz	300	2–300

2. The DIR-R5 Model

2.1. Satellite Data Processing

For GRACE and LAGEOS, analysis of orbit perturbations is the basis of the estimation of the Stokes coefficients. Satellite tracking data are compared to model-predicted values inferred from a numerically integrated orbit. The differences between observations and modeled quantities, i.e., residuals, are ingested into an iterative least squares adjustment. The tracking data are reduced in orbital arcs of 1 day for GRACE and 10 days for LAGEOS.

GOCE gravity gradient data are directly the second-order derivatives of the gravitational potential. GOCE data processing is therefore fundamentally different from that of GRACE and LAGEOS. The gravity gradients Vxx, Vyy, Vzz, and Vxz, expressed in the gradiometer reference frame [*European GOCE Gravity-Consortium*, 2010], are precise only in the measurement band (MB) from 5 to 100 mHz of the gradiometer. Below and above the MB, the noise increases approximately with f^{-1} and f^2, respectively. Mainly, the long wavelengths of the gravity field model would be affected by colored noise without a filtering step in the processing. The description of the instrumental noise is given by *Pail et al*. [2011]. Measured minus modeled gradients, i.e., satellite gravity gradiometry (SGG) residuals, and the observation equations relating them to the unknown model parameters are both band-pass filtered, after which normal equations are computed. The passband of 8.3–125 mHz applied in the direct approach ensures that the results are largely independent of the temporal variations in the colored noise. The GOCE precise science orbits [*Bock et al*., 2011] were used to geolocate the gradients, which were separately processed for each component in 42 uninterrupted measurement time spans. Table 1 lists the observations and the resulting normal equation (NE) as used in the model construction.

2.2. Composition of DIR-R5 and the Test Models

The LAGEOS 1/2 and GRACE NE is from the Groupe de Recherche de Géodésie Spatiale release 3 GRACE processing (grgs.obs-mip.fr/grace). This release was computed with the version 2 of the GRACE level 1B data. The LAGEOS/GRACE and GOCE NEs were accumulated into one system of normal equations that complete to d/o 300; the used degree range of each NE is shown in the right column of Table 1. The polar gaps in the GOCE data cause the matrix to be ill conditioned at high degrees for low orders, and we apply regularization based on a work of *Metzler and Pail* [2005]. Since regularization of this kind mainly constrains the (near) zonal and (near) sectorial coefficients, Kaula regularization was also applied for degrees 180 to 300 to gradually smooth coefficients of all orders. Then, the regularized normal system was solved by Cholesky decomposition.

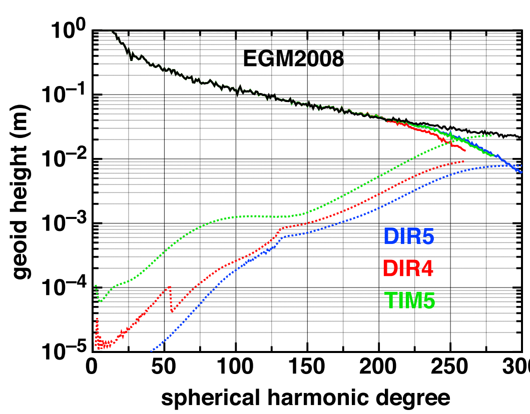

Figure 1. RMS values per degree of signal (solid lines) and error (dotted lines) of the models DIR-R4, DIR-R5, TIM-R5, and EGM2008.

3. Model Evaluation

3.1. Spectral Behavior

Figure 1 shows the RMS values per degree of signal and error of DIR-R5, DIR-R4, the fifth release of ESA's timewise model TIM-R5, and the reference model Earth Gravitational Model 2008 (EGM2008) [*Pavlis et al*., 2012]. The GOCE models have significantly less power than EGM2008 above degree 210–225 and higher, but the enhanced signal content at high degree for release 5 compared with the release 4 model is clear. The signal and error RMS values per degree

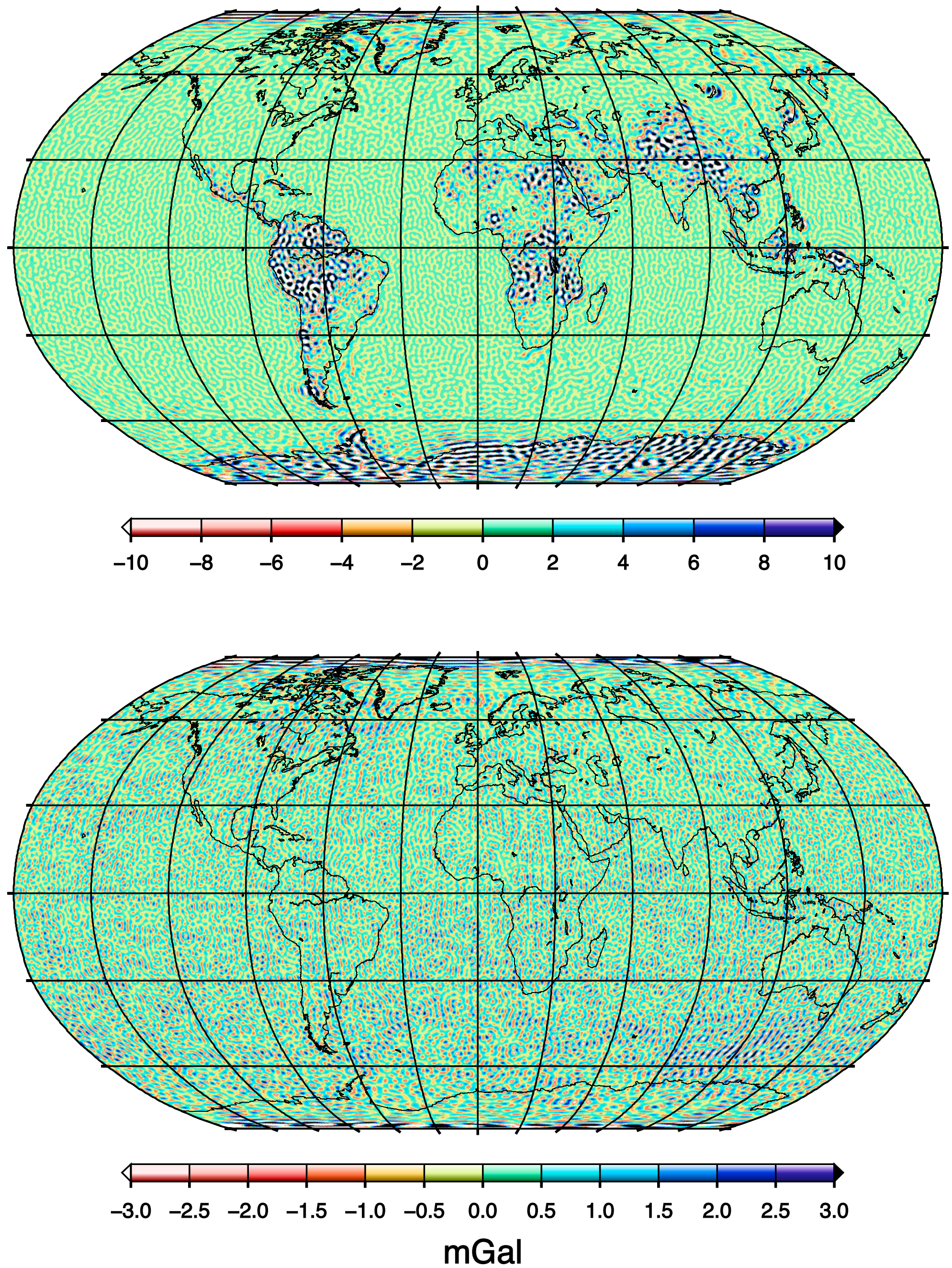

Figure 2. Gravity anomaly difference (mGal) between (top) DIR-R5 and EGM2008 and (bottom) DIR-R5 and DIR-R4 at d/o 200.

curves cross (signal-to-noise ratio of 1) at degrees 291 and 257 for DIR-R5 and TIM-R5, respectively. The cumulated (formal) error of DIR-R5 at degree 200 in terms of geoid height (gravity anomaly) is 0.8 cm (0.2 mGal) compared to 1.3 cm (0.4 mGal) for DIR-R4, i.e., an improvement of about 40% (50%) thanks to using more data and at lower altitude.

The impact of the lower altitude in the last 14 months of the mission is very large. The model based on data after DIR-R4 (DDIR4) is more accurate than DIR-R4, and the less steep curve for degrees higher than 200 is thanks to the data at lower altitude. DIR-R4 and ΔDIR-R4 are based on 28 and 14 months of data, respectively.

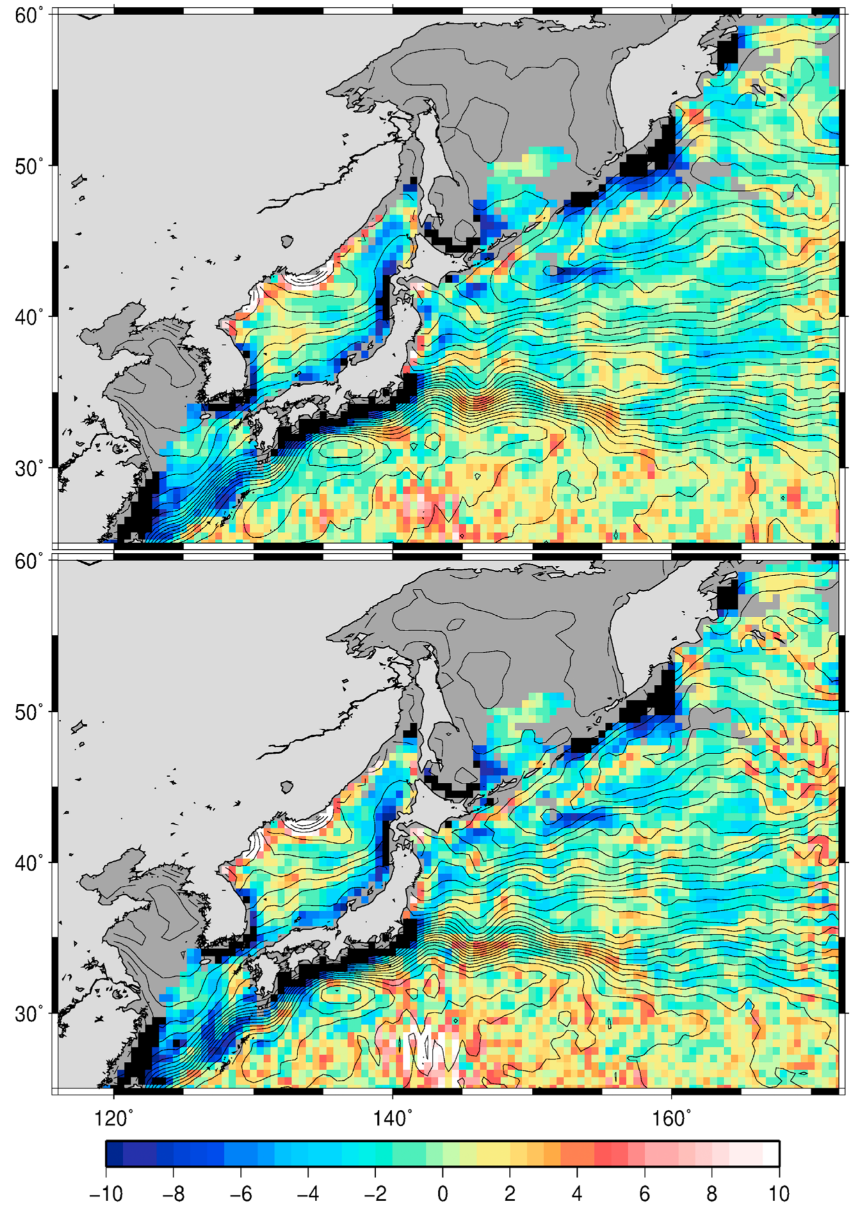

Figure 3. Differences with drifter current intensities for (top) DIR5 and (bottom) DIR4 for the Kuroshio. The MDT contour lines are superposed.

3.2. Comparisons With EGM2008

Figure 2 (top) displays the gravity anomaly difference to d/o 200 between DIR-R5 and EGM2008. The large differences over the continents are improvements thanks to GOCE data over regions for which sparse or low-quality data were available for EGM2008. Conversely, over oceans, North America and Australia for example, excellent data were already assimilated and differences are small. Figure 2 (bottom) shows the difference between DIR-R5 and DIR-R4; it is largest around the magnetic poles because the Vyy component is noisiest there [*Siemes et al.*, 2012]. Otherwise, differences appear to be more or less uniform; i.e., homogeneous improvement is reached, except for some striations in the East Pacific (Figure 3) and west of Australia for example. Figures S1 and S2 in the supporting information show, besides with EGM2008 and DIR-R4, the differences with TIM-R5 as well, for d/o 200 and 240.

Specific comparisons are done for four zones: in the North and South Pacific (PacN, 40°×40° box, and PacS, 20°×15° box), which have very small variations in bathymetry as well as very low current variability, and over

Table 2. RMS of Geoid Height Differences With EGM2008 (cm) Over Oceanic and Continental Zones Evaluated at Four Maximum d/o

	d/o	PacN	PacS	U.S.	Australia
DIR-R4	200	3.2	4.2	4.2	4.4
	220	5.5	6.1	5.7	6.6
	240	9.4	9.3	8.5	11.5
	260	13.9	10.5	15.2	15.3
DIR-R5	200	2.7	2.7	3.4	3.4
	220	4.0	4.5	4.0	4.8
	240	6.3	7.1	6.3	8.2
	260	9.9	8.9	11.8	11.2

continental U.S. and Australia (10°×20°). The results, listed in Table 2 for four maximum d/o of comparisons, show the 20–50% smaller RMS differences of DIR-R5. The TIM-R5 model compares equally well as DIR-R5 to EGM2008, being closer to EGM2008 for two out of four zones (not listed). Computing the difference of DIR-R5 with EGM2008 20° higher (DIR-R5 to d/o 200 minus EGM2008 to d/o 220 and so on) and comparing to the difference of both models for the higher degree (i.e., DIR-R5 minus EGM2008 both to d/o 220) reveals to which degree DIR-R5 contains signal. For the U.S./PacN/PacS/Australia, signal is present to d/o 300/280/260/260. This is in line with the spatial error map based on the variance-covariance matrix, which is zonal with the largest errors between 0° and 40°S, and smaller errors over the Northern Hemisphere due to the lower orbit altitude (noncircular orbit).

3.3. GPS/Leveling Results

An independent comparison is done using geoid heights determined pointwise by GPS positioning and leveling over Germany [*Ihde et al*., 2002] and Japan (courtesy Tokuro Kodama, Geospatial Information Authority of Japan), i.e., the best available GPS/leveling data sets. Table 3 shows the gain in accuracy of DIR-R5 compared with DIR-R4 of 10–30% for Germany and 3–20% for Japan, the highest gain being to d/o 240 in both cases. TIM-R5 is significantly less accurate for Germany, i.e., by far the most accurate data set, but a little more accurate for Japan. The ΔDIR-R4 model is more accurate than DIR-R4 model in this test in line with section 3.1.

3.4. Oceanographic Evaluation

The relative accuracy of the geoid models is assessed through the comparison of the mean geostrophic currents using the method described by *Mulet et al*. [2012a]. In short, mean dynamic topographies (MDT; mean sea surface minus geoid) are computed and filtered at spatial scales ranging from 80 to 200 km with a Gaussian filter, then associated mean geostrophic currents are compared to mean geostrophic currents derived from independent drifting buoy data, available in all oceans, and similarly filtered. The standard deviation of the difference is then calculated. The surface velocities are inferred with an uncertainty of 3 cm s^{-1} from drifter trajectories, after the ageostrophic components, and the time variability measured by altimeters have been removed. The results are listed for 80 (i.e., d/o 250 of the geoid model) to 150 km scales in Table 4. DIR-R5 is a significant improvement over DIR-R4, notably at 80 km. Figure 3 (Figure S3 in the supporting information) illustrates this improvement for the Kuroshio (Gulf Stream), where DIR-R5 shows better consistency with drifters than DIR-R4, in particular in subduction areas (Emperor Chain and Izu Ogasawara Trench) thanks to the use of more GOCE data but mainly because of the lower orbit. DIR-R5 and TIM-R5 give very similar results except that TIM-R5 gives slightly better results for the meridional component up to 100 km, whereas at 80 km, DIR-R5 is overall slightly more accurate. At 100 km, the R5 models give a good estimate of the zonal component with a σ of the difference that is 4 cm s^1 lower than the signal itself (i.e., the standard deviation of the drifters; σ current in Table 4). However, the σ of the difference is equal to the signal for the meridional component, and thus, it is recommended to use GOCE models at 125 km. The minimum σ of the difference with unfiltered velocities from drifters is reached between 100 and 125 km (Figure S4 in the supporting information). EGM2008 gives the best results at

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

	Germany d/o 200/220/240	Japan d/o 200/220/240
EGM2008	4.3	8.2
DIR-R4	5.4/6.0/9.9	7.8/9.2/12.2
DIR-R5	4.8/5.2/6.9	7.6/8.1/9.7
TIM-R5	4.9/5.9/7.8	7.6/8.0/9.1
ΔDIR4	5.0/5.6/7.5	7.8/8.5/10.1

[a]Models were taken to given d/o and completed with EGM2008 to d/o 2190.

Table 4. Standard Deviation of the Measured Current and the Zonal (*u*) and Meridional (*v*) Current Differences in cm/s at Four Scales

	80 km *u/v*	100 km *u/v*	125 km *u/v*	150 km *u/v*
σ current	9.5/6.0	9.3/5.5	8.7/5.0	8.4/4.5
EGM2008	7.0/7.9	5.7/6.3	4.7/5.0	4.0/4.0
DIR-R4	12.4/13.6	6.0/6.3	4.3/4.1	3.9/3.5
DIR-R5	9.8/11.0	5.4/5.7	4.3/4.1	3.9/3.5
TIM-R5	10.0/10.8	5.4/5.5	4.3/4.0	3.9/3.4
ΔDIR4	10.7/12.5	5.6/6.1		

80 km, but the meridional difference is much bigger than the current itself. Compared with EGM2008, GOCE improves the circulation estimate in the 100 to 200 km scale range. Below 200 km resolution, the models have similar performance.

4. Discussion and Conclusions

Germany has the most accurate, but not error free, GPS/leveling data set. It is used to calibrate the DIR-R5 formal errors in a two-step calculation (T. Gruber, personal communication): systematic leveling errors are removed using a planar fit, after which the σ of the difference with DIR-R5 is 2.7 cm. The GPS/leveling geoid error is assumed to be 2.1 cm, which is the sum of the GPS height error (1.5 cm) and the normal height accuracy after planar fit (1.5 cm). Based on these numbers, the DIR-R5 model error at 100 km resolution is estimated at 1.7 cm ($\sqrt{2.7^2 - 2.1^2}$). The formal cumulated error at d/o 200 is 0.8 cm (section 3.1); therefore, the calibration factor is 2. The GOCE mission objectives have been reached according to this evaluation. The DIR-R5 model is significantly more accurate than the previous release, thanks to the assimilation of more and lower altitude data. The impact of the lower orbit on model accuracy is very large: DIR-R4, based on 28 months of data, is significantly less accurate than a model using only the last 14 months. In fact, the mission objectives could be reached in part thanks to ESA's decision to lower the orbit to enhance the gradiometer's signal-to-noise ratio. Comparisons with EGM2008 over four test zones quantified the noise reduction with respect to DIR-R4 and the higher resolution attained with release 5. The model contains signal over the Northern Hemisphere midlatitudes (i.e., lowest part of the GOCE orbit) to d/o 300. Evaluations from degrees 200 to 250 showed equivalent performance of the DIR-R5 and TIM-R5 models.

The optimal resolution of GOCE for oceanographic application is between 100 and 125 km (this was established using a nonideal Gaussian filter). This is not in contradiction with the objective of 1 to 2 cm accuracy at 100 km because the MDT a hundred times smaller than the geoid, causing the inferred currents to be very sensitive to geoid error. Comparison with drifters shows that DIR-R5 is an improvement over EGM2008 between 100 and 200 km scales. The use of GOCE improves the Centre National d'Etudes Spatiales–Collecte Localisation Satellites (CNES-CLS) MDT estimate. For instance, the 3-D reconstruction of the current described by *Mulet et al*. [2012b] gives a mid-ocean geostrophic transport in 2006 at 26.5°N in the Atlantic of −7 sverdrup (Sv) using the CNES-CLS09 MDT (no GOCE) and −12 Sv using the CNES-CLS13 MDT (with GOCE data), which is more consistent with the −14 Sv from the independent Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array array [*Cunningham et al*., 2007] and is due to an improved MDT around the Bahamas. Finally, drifter data are available in all oceans, but they do not cover them completely (e.g., grey areas in Figure 3 and around Antarctica typically).

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References

Bock, H., A. Jäggi, U. Meyer, P. Visser, J. van den IJssel, T. van Helleputte, M. Heinze, and U. Hugentobler (2011), GPS-derived orbits for the GOCE satellite, *J. Geod.*, *85*, 807–818, doi:10.1007/s00190-011-0484-9.

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.

Cunningham, S. A., et al. (2007), Temporal variability of the Atlantic meridional overturning circulation at 26.5° N, *Science*, *317*(5840), 935–938.

Drinkwater, M. R., R. Floberghagen, R. Haagmans, D. Muzi, and A. Popescu (2003), GOCE: ESA's first Earth explorer core mission, in *Earth Gravity Field From Space—From Sensors to Earth Science*, *Space Sci. Ser. ISSI*, vol. 18, edited by G. Beutler et al., pp. 419–432, Kluwer Acad., Dordrecht, Netherlands.

EGG-C (2010), GOCE Level 2 Product Data Handbook, GO-MA-HPF-GS-0110, Issue 4.2, European Space Agency, Noordwijk, Netherlands. [Available at http://earth.esa.int/pub/ESA_DOC/GOCE/Product_Data_Handbook_4.1.pdf.]

Floberghagen, R., M. Fehringer, D. Lamarre, D. Muzi, B. Frommknecht, C. Steiger, J. Piñeiro, and A. da Costa (2011), Mission design, operation and exploitation of the gravity field and steady-state ocean circulation explorer mission, *J. Geod.*, *85*, 749–758, doi:10.1007/s00190-011-0498-3.

Ihde, J., J. Adam, W. Gurtner, B. G. Harsson, M. Sacher, W. Schlüter, and G. Wöppelmann (2002), The height solution of the European Vertical Reference Network (EUVN), Mitteilungen des BKG, Bd. 25, EUREF Publication No. 11/I, Frankfurt a. M., Germany, pp. 53-79.

Metzler, B., and R. Pail (2005), GOCE Data Processing: The Spherical Cap Regularization Approach, *Stud. Geophys. Geod.*, *49*, 441–462.
Mulet, S., M. H. Rio, and S. Bruinsma (2012a), Assessment of the preliminary GOCE geoid models accuracy for estimating the ocean mean dynamic topography, *Mar. Geod.*, *35*, 314–336, doi:10.1080/01490419.2012.718230.
Mulet, S., M.-H. Rio, A. Mignot, S. Guinehut, and R. Morrow (2012b), A new estimate of the global 3D geostrophic ocean circulation based on satellite data and in-situ measurements, *Deep Sea Res., Part II*, *77–80*, 70–81.
Pail, R., et al. (2011), First GOCE gravity field models derived by three different approaches, *J. Geod.*, *85*, 819–823, doi:10.1007/s00190-011-0467-x.
Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor (2012), The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), *J. Geophys. Res.*, *117*, B04406, doi:10.1029/2011JB008916.
Siemes, C., R. Haagmans, M. Kern, G. Plank, and R. Floberghagen (2012), Monitoring GOCE gradiometer calibration parameters using accelerometer and star sensor data: Methodology and first results, *J. Geod.*, *86*, 629–645, doi:10.1007/s00190-012-0545-8.
Tapley, B., S. Bettadpur, M. Watkins, and C. Reigber (2004), The gravity recovery and climate experiment: Mission overview and early results, *Geophys. Res. Lett.*, *31*, L09607, doi:10.1029/2004GL019920.