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Comparison of global geomagnetic field models and evaluation using marine datasets in the north-eastern Atlantic Ocean and western Mediterranean Sea

Jean-François Oehler* , Didier Rouxel and Marie-Françoise Lequentrec-Lalancette

Abstract

Many models describing the Earth's magnetic field exist and are maintained by international research organizations. However, no clear general overview of the cross-compared quality of these models is available. An evaluation of the internal component and of the anomaly field as estimated by a selection of nine geomagnetic models with global coverage is presented here. Anomaly field models are also compared with an external, independently processed marine dataset extracted from Shom's (the French Hydrographic and Oceanographic Service) geophysical database. The comparative study shows that internal geomagnetic fields computed outside the provisional domain, up to degrees 12 or 13 of spherical harmonics (SH), can be considered as equivalent. Relative amplitude differences with the World Magnetic Model 2015 (WMM2015) and the 12th generation of the International Geomagnetic Reference Field (IGRF-12) taken as references are lower than 10 nT. For an extent reduced to the north-eastern Atlantic Ocean and western Mediterranean Sea, anomaly field models up to SH degree 720 and the 3rd version of the Earth Magnetic Anomaly Grid (EMAG2v3) at the equivalent 0.5° resolution are the closest models to the filtered marine data. However, they are significant spatial discrepancies and standard deviations of differences between models and data are about 65 nT. The 3-arc-minute World Digital Magnetic Anomaly Map (WDMAM) best reflects the unfiltered marine data, but with significant standard deviations of about 70 nT. Results demonstrate that any model can be used with insignificant errors to compute raw anomalies from total field measurements by removing the internal component of the Earth's magnetic field. In addition, they suggest that the priority should be given to WDMAM for levelling and evaluating marine datasets and for computing enhanced high-resolution regional magnetic maps.

Keywords: Geomagnetic field models, Spherical harmonics, Internal component, Anomaly field, Marine data, Comparative analysis

Introduction

Global geomagnetic models mathematically describe the Earth's magnetic field (see Langel 1987; Backus et al. 1996). The geomagnetic field is the sum of three contributions: (1) the main (or internal) field originating from the Earth's core (dynamo effect), which is variable in time (secular variations) and represents about 95% of the total field at the surface; (2) the anomaly field from crustal,

mantle or anthropic sources; and (3) the external field from the upper atmosphere and magnetosphere, which is highly dependent on solar activity.

Many geomagnetic models exist and are being developed, maintained and updated by several research organizations all over the world and have been published in scientific literature. The scope of applications is very broad, ranging from fundamental research to geophysical surveying and object detection. At Shom (the French Hydrographic and Oceanographic Service), only internal and anomaly field models are currently used. The internal World Magnetic Model (WMM, see references

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in Table 1) is used for applications in sea and air navigation, as required by NATO's standards (Defense Mapping Agency 1993). The International Geomagnetic Reference Field (IGRF, Table 1) is the reference model adopted by the scientific community to correct the main field and derive magnetic anomalies. Global anomaly field models, such as the Earth Magnetic Anomaly Grid (EMAG) or the World Digital Magnetic Anomaly Map (WDMAM) (Table 1), are used to level and evaluate marine datasets. They can also be used for computing enhanced regional magnetic maps.

Whether models are sometimes assessed through intrinsic comparisons with data used to produce them or extrinsically against concurrent models before dissemination to the scientific community, the only study dealing with the comparison of a wide range of recent versions of geomagnetic models relates to the evaluation of candidate models for the production of the reference model IGRF-12 from IAGA (Thébault et al. 2015a, b). IGRF-12 commonly corresponds to a weighted average of several internal models expressed in spherical harmonics (SH) to degree 13 and provided by a number of different international research laboratories and institutions. Thébault et al. (2015b) observe deviations between the ten candidate models. However the root mean square vector difference field between models as defined by the authors are generally less than 10 nT. They conclude that the internal models submitted are relatively homogeneous. The present paper gives additional results to the evaluation performed for IGRF-12. Its aim is to present an evaluation from the selection of nine magnetic models with global coverage that are compared for the same spectral

content, and with an external, independently processed marine dataset. The selected models characterize not only the internal component of the Earth's magnetic field up to SH degree 14 (IGRF-12, WMM2015 and COV-OBS.x1) but also, the combination of the internal component and the anomaly field with SH degrees up to 65 and 720 (CM4, POMME-9, EMM2015 and HDGM2016), and only the anomaly field through high-resolution grids (EMAG2v3 and WDMAM; see references in Table 1). External contributions to the Earth's magnetic field are not considered here.

The selected models are freely available in digital form. They describe at least the intensity of the total magnetic field and span the period 2010–2015. Exceptions are made for CM4 which is estimated only before July 2002, for WMM2015 which is considered to be valid only between 2015 and 2020, and for the licensed HDGM2016 which has been purchased by Shom for their own studies.

Most models (WMM2015, EMM2015, HDGM2016, POMME-9, see references in Table 1) are calculated using a serial approach (Thébault et al. 2010). It consists of a computation of Gauss coefficients by inversion to independently estimate the internal and anomaly components of the magnetic field on one hand, and (when appropriate) the external component on the other hand. Components are then aggregated to obtain the final model. The CM4 model results from a comprehensive approach (Sabaka et al. 2004, 2015) where all components are directly co-estimated. COV-OBS.x1 is an original model, as it is the only one estimated using a stochastic method (Gillet et al. 2013, 2015). Models are mainly built from recent satellite data from

Table 1 Main characteristics of the evaluated global geomagnetic field models

Model	Editor	Creation date	HS degree	Temporal coverage	References
IGRF-12	IAGA	December 2014	13	1900–2020	Thébault et al. (2015a, b) and Lowes (2000)
WMM2015	NOAA/NCEI/BGS	December 2014	12	2015–2020	Chuillat et al. (2015) and Alken et al. (2015)
COV-OBS.x1	ISTerre/DTU Space	2015	14	1840–2020	Gillet et al. (2013, 2015)
CM4	PGL/NASA/DTU Space	2004	65	1960–2002	Sabaka et al. (2004, 2015)
POMME-9	NOAA/CIRES/GFZ	April 2015	133	2000–2015	Maus et al. (2006, 2010)
EMM2015	NOAA/NCEI/CIRES	Mai 2015	720	2000–2015	Maus (2010), Chuillat et al. (2015) and Alken et al. (2015)
HDGM2016	NOAA/NCEI	March 2016	720	1900–2017	Maus (2010), Chuillat et al. (2015) and Alken et al. (2015)
Model	Editor	Creation date	Grid resolution	References	
EMAG2v3 (MSL)	NOAA/NCEI	June 2016	2 arc min	Meyer et al. (2016, 2017) and Maus et al. (2007, 2009)	
WDMAM (v2) (MSL)	IAGA/CGMW	2015	3 arc min	Lesur et al. (2016) and Dyment et al. (2015)	

MSL mean sea level

SWARM (ESA), OERSTED (DTU Space), CHAMP (GFZ) and SAC-C (NASA) programs and monthly or annual averages from magnetic observatories. High-resolution models with an anomaly component (i.e. EMM2015 and HDGM2016) are based on EMAG2 version 2 anomaly grid (Maus et al. 2009) and therefore indirectly include marine, land-based and airborne measurements. EMAG2 version 3 (EMAG2v3) and WDMAM version 2 (see references in Table 1) are very high-resolution anomaly grids (with grid spacings of 2 and 3 arc minutes, respectively) calculated at the mean sea level. The short-wavelength field is computed from processed and levelled marine, land-based and airborne measurements, and precompiled anomaly grids. The long-wavelength field is corrected by substituting the longest wavelengths (greater than about 300 km) with models derived from satellite data (MF7 for EMAG2v3 and GRIMM_L120 for WDMAM). EMAG2v3 is calculated from observed data using a kriging process without a priori geologic structure and ocean-age information. WDMAM results from overlap management by attributing an order of precedence for each dataset and weighted averaging in conflicting areas. A forward model of marine magnetic anomalies, built from an age map of the ocean floor, relative plate motions and a geomagnetic polarity time scale, is used to fill data gaps and compute the model over all oceanic areas.

The main purpose of the present work is to evaluate the internal component and anomaly field as estimated by the selected models (Fig. 1), with particular concern on the discrepancies between them, and ultimately to identify the best candidates adapted for Shom’s applications. The anomaly field is also evaluated with processed data extracted from Shom’s marine magnetic database, which are an independent source of measurements. Results are shared with the scientific community as they are an

overview of the cross-compared quality of geomagnetic models with ground-truthing data.

Methods, models and data processing

Evaluation method

Several comparative scenarios are developed to study the differences between SH models. We chose to independently consider: (1) the intensity, inclination and declination (when available) of the total field for the internal component, up to SH degrees 12 and 13, and (2) the intensity of the anomaly field, up to SH degree 720 (Fig. 1). Two geospatial extents are considered: (1) a global scale (land and ocean areas), at 1° grid spacing and (2) an area of interest covering the north-eastern Atlantic Ocean and the western Mediterranean Sea (hereafter referred to as the NEAWM area with an extent of N20°-N70°; W50°-E20°) at 0.5° grid spacing. Three dates (01/01/2000 for CM4 only, 01/01/2010 except for WMM2015 and 01/01/2015) are also selected.

The three global HDGM2016, EMAG2v3 and WDMAM anomaly models are evaluated by comparing them with marine data for the NEAWM area only (mainly for computational reasons) at 0.5° and at full grid spacing for EMAG2v3 and WDMAM. Therefore, either wavelengths lower than 55 km (equivalent to SH deg. 720) or the full spectral content of the data and models are considered for the comparison (Fig. 1).

Difference grids and differences between models and measurements are spatially and statistically analysed. Energy spectrums are computed and compared for each model.

Model calculations

Grids, respectively, showing intensity of the total magnetic field, inclination and declination (when available), are estimated at mean sea level, directly from Gauss

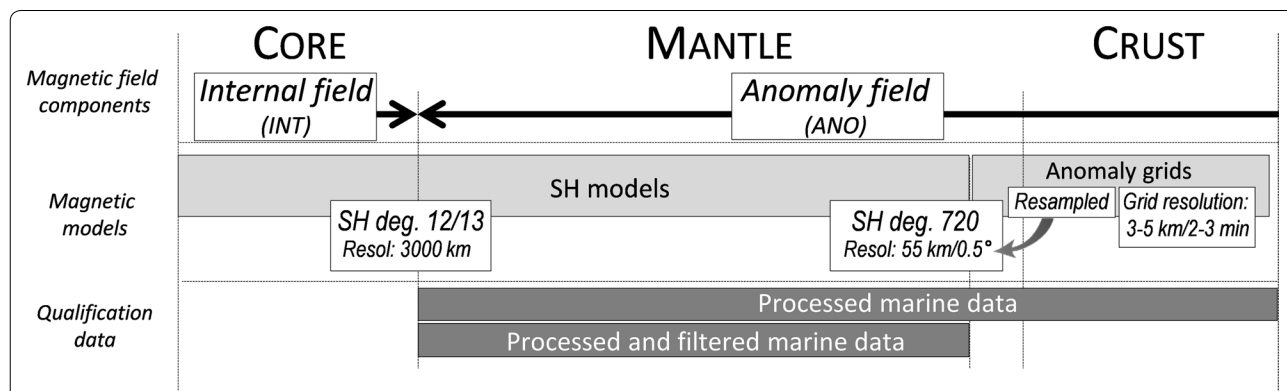


Fig. 1 Summary diagram illustrating the definition of the magnetic components of the Earth’s magnetic field used in the study, the associated geomagnetic models and the data used for evaluation, according to SH degrees and spatial resolutions

coefficients integrated into Shom's processing tools for IGRF-12, WMM2015 and HDGM2016 models (and also the HDGM2016 core sub-model estimated considering only coefficients up to SH degrees 13) or by using computation programs published and associated with EMM2015, COV-OBS.x1, CM4 and POMME-9 models. Scripts were developed to iteratively execute programs that allow point estimation and thus to compute values on 1° and 0.5° grids. EMAG2v3 and WDMAM anomaly grids were also computed by resampling full-resolution published datasets for the targeted 0.5° grid spacing (Fig. 1).

For all models except WMM2015, the computed grids are filtered using the Oasis montaj software-MAG-MAP extension (©Geosoft) to estimate grids describing the internal component of the models only with SH degrees lower than 12 or 13 (Fig. 1). Tests show that the differences between filtered field intensity grids and the WMM2015 or IGRF-12 estimated grids taken as a reference are minimized using the following parameters, which are generalized in our study: (1) removing/restoring the average tendency, (2) padding/unpadding using the maximum entropy method (Burg 1975), and (3) applying an order-12 Butterworth filter and a cut-off wavelength equivalent to the next higher SH degree (i.e. about 3080 km for SH degree 12 and 2860 km for SH degree 13). Statistics are then computed with a global extent reduced by 30° in latitude and 20° in longitude to avoid edge-filtering artefacts. Similarly, the NEAWM 0.5° grids are calculated at a global scale before filtering then reduced to the targeted extent.

Finally, anomaly grids are calculated conventionally by IGRF removal. By definition, only the main internal component of the Earth's magnetic field is consequently removed from anomaly grids. Contributions from mantle and crustal sources are kept in the signal (Fig. 1). IGRF removal is done according to the epoch (i.e. 2010.0 or 2015.0). This can explain why small differences can be observed for the same anomaly field model at two different dates.

Evaluation of the models with marine data

Marine magnetic data acquired during 71 surveys were extracted from Shom's geophysical database (Fig. 2 and Table 2). About half of them consist of in-house surveys. The others are published by other organizations (i.e. the French National Oceanographic Data Centre (SISMER) and the NOAA National Centers for Environmental Information (NCEI)). Data cover the NEAWM area as patches on the following five geographical sub-areas of interest: (1) mid-Atlantic ridge between 20°N and 45°N, (2) Canary Islands to offshore west Portugal, (3) Bay of Biscay, (4) English Channel to North Sea, and (5) western

Mediterranean Sea. They were chosen to characterize a wide range of geodynamic and geomagnetic contexts, from shallow continental shelves and margins to deep abyssal plains, including the Atlantic mid-oceanic ridge. Data are processed following Shom's methodology (Shom 2007). They are made up of magnetic anomalies corrected only from the IGRF's main theoretical field (IGRF anomaly) and, from low frequency diurnal variations (LF anomalies) or from low frequency diurnal and high frequency agitation variations (LF+HF anomalies). It should be noted here that the processing technique applied to the data used to build the EMAG2v3 and WDMAM models greatly differs from the one used at Shom. The former uses the CM4 model to correct the total field for internal and external components (see Quesnel et al. 2009; Maus et al. 2009), while the latter uses IGRF reference models and measurements from the nearest permanent magnetic observatory (in distance and in latitude). In Shom's methodology, diurnal variations are thus obtained by (1) filtering the total field measured at the observatory with a low-pass Gaussian filter that only keeps signals with periods of over 5 h, (2) removing the IGRF's main theoretical field at the station and (3) removing a constant local magnetic response estimated by averaging the residual signal over a relatively long period of time (1–6 months). Agitation variations are calculated by subtracting the previous diurnal variations from the total field measured at the observatory.

Shom's datasets were resampled every 200 m along profiles by a weighted average method. To compare marine data with models defined up to SH degree 720 or subsampled to 0.5°, the highest frequencies (<55 km) are filtered with an order 8 Butterworth filter after removing the average tendency and padding the data.

Results and discussion

Model comparison

Intensity of the internal magnetic field

The intensity of the internal field estimated using global geomagnetic models is evaluated both up to SH degree 12 with WMM2015 as a reference and SH degree 13 with IGRF-12 as reference (see Additional file 1; Fig. 3). Considering this parameter alone, the WMM2015, EMM2015, HDGM2016(core), POMME-9, CM4 and IGRF-12 models can be considered as equivalent. Mean differences are relatively low, generally smaller than 5 nT. Mean standard deviation is less than about 10 nT both on a global scale and for the NEAWM area. For a given resolution, the spatial distribution of the differences is quite similar (see Fig. 3a for the characteristic tendency in SH degree 12 and Fig. 3b, c in SH degree 13). The spectral content of the models is also consistent overall, both at global scale and for the NEAWM

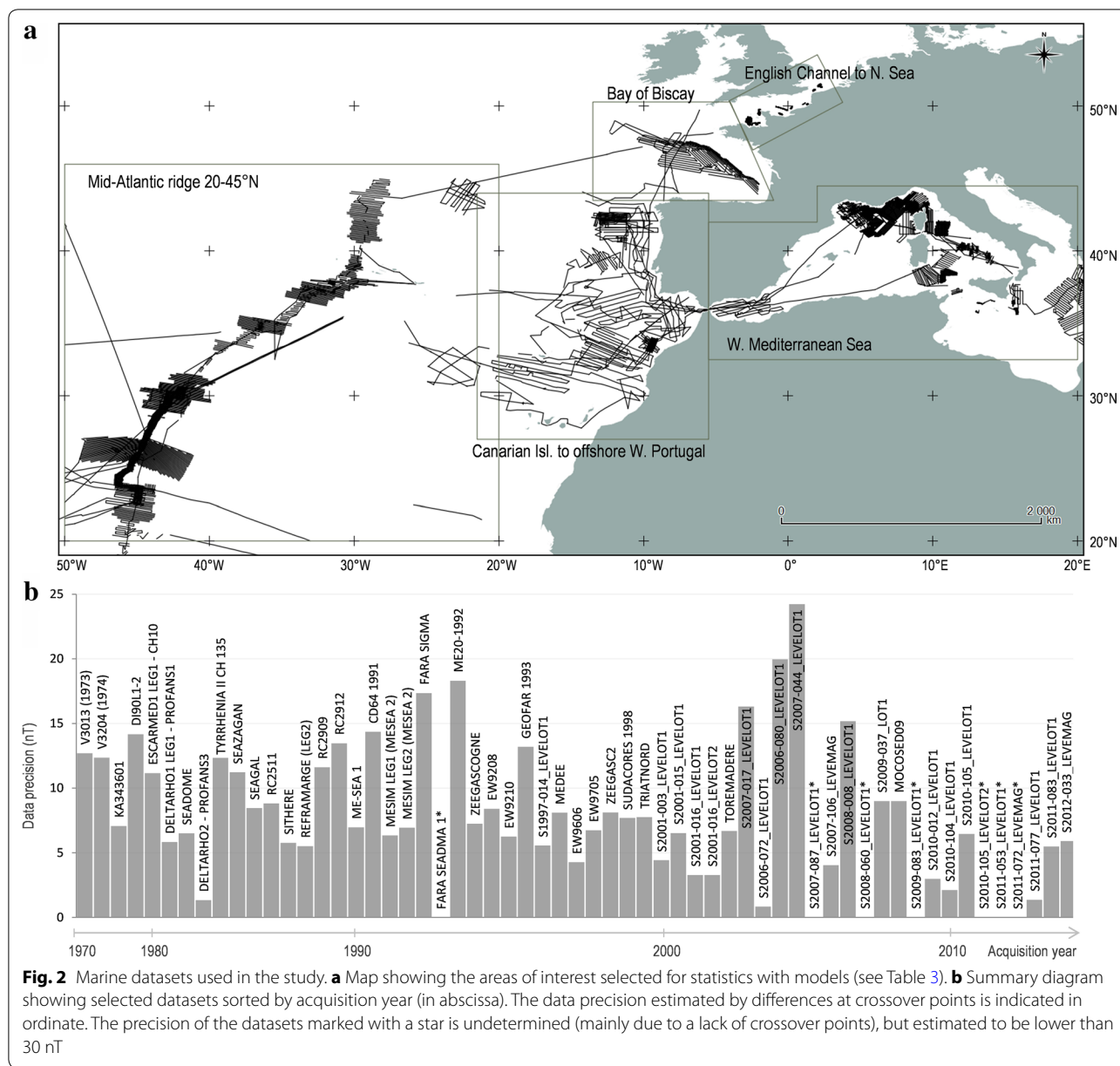


Table 2 Number of surveys and magnetic measurements (after filtering and sub-sampling) used in the study

Area of interest	Number of surveys	Number of magnetic measurements
NEAWM area (i.e. full dataset)	71	1,070,035
Mid-Atl. ridge 20–45°N	17	362,564
Canarian Isl. to offshore west Portugal	16	227,584
Bay of Biscay	5	47,609
English Channel to North Sea	26	138,024
W. Mediterranean Sea	23	294,254

area. Several spatial and amplitude discrepancies can be observed however: (1) Differences computed for SH degree 12 models are a few nanoteslas greater than those for SH degree 13. Moreover, maps of differences in SH degree 12 exhibit higher wavelengths and a noticeable inverse polarity (see for example, the south of Africa or the alternation of positive and negative differences in SH degree 12 maps. All these observations are consistent with the lower degree of spherical harmonics; and (2) the COV-OBS.x1 model seems to be relatively equivalent to HDGM2016, EMM2015 and POMME-9 models for the

date 01/01/2010 with average differences of a few nanoteslas. However, the 01/01/2015 forecast for the COV-OBS.x1 model is not robust and seems to be inconsistent with other models (see Fig. 3d). Mean differences are one to two orders of magnitude higher and are estimated to be about 97 ± 260 nT at a global scale and -4 ± 140 nT for the NEAWM area.

These results are coherent with the conclusions of Thébault et al. (2015b) for the evaluation of candidate models for IGRF-12. The authors underline that all submitted models are not different enough to be rejected with differences generally much less than 10 nT. Amongst them, parent or derived models are used in the present study (i.e. CM, COV-OBS, WMM); the other ones are identified as CHAOS5 from DTU Space (Finlay et al. 2015) or as one-time initiatives for example from BGS (Hamilton et al. 2015), GFZ (Lesur et al. 2015) and IPGP/CEA/LPG Nantes (Fournier et al. 2015; Vigneron et al. 2015; Saturnino et al. 2015). Based on the works of Thébault et al. (2015b), the internal component to SH degree 13 of all these models can be considered as equivalent.

Inclination and declination of the internal and anomaly fields

Inclination and declination grids estimated from global magnetic models are compared with those calculated from IGRF-12 taken as the reference (see Additional file 2; Figs. 4 and 5). Differences between HDGM2016 and EMM2015 are also evaluated.

Differences in inclination and declination between internal HDGM2016core, WMM2015 and IGRF-12 are almost negligible, with means and standard deviations estimated at less than 0.01° .

Anomalously high differences in inclination and declination, up to $0.7^\circ \pm 0.7^\circ$ on average, are observed between EMM2015 and both IGRF-12 and HDGM2016. Those can be explained by doubtful negative inclination and declination values (i.e. located south of the geomagnetic equator for inclination and in the main part of the Atlantic and Indian Oceans and northeast Asia for declination, see Additional file 3) given by the lithospheric EMM2015 model. Additional tests did not identify any problems for the previous version of the product (EMM2010). Inclination and declination parameters are reflected correctly with results close to other models. Defaults, probably due to digital coding, are only observed for the 2015 version. However, for the NEAWM area, inclination

values estimated from EMM2015 are consistent with those of the HDGM2016 model. Differences between HDGM2016 and IGRF-12 are small on average with 0.1° and 0.2° standard deviations for inclination and declination, respectively. They are obviously high locally with extrema of up to 6° . Discrepancies for POMME-9 are about half in amplitude (standard deviations estimated at 0.05° and 0.1° for inclination and declination, respectively) which is consistent overall considering the model's low resolution.

Intensity of the anomaly field

The intensity of the anomaly field estimated using the HDGM2016, EMM2015, EMAG2v3 and WDMAM models is evaluated up to SH degree 720 or with the equivalent 0.5° grid spacing (see Additional file 4; Figs. 6 and 7).

HDGM2016 and EMM2015 up to SH degree 720 can be considered as equivalent. Firstly, differences between these two models are small for all dates and extents, estimated at about few nanoteslas. They appear to be relatively higher for the date 01/01/2015 (only about 1 nT higher on average). The difference map suggests a long-wave residual signal that can be explained by the use of more complete SWARM datasets for the HDGM2016 model, whereas only data up to 2014.8 are considered for EMM2015 (Fig. 6a). Secondly, spectral content is consistent for both models at a global scale and for the NEAWM area (Fig. 6b). Finally, differences with EMAG2v3 and WDMAM are comparable with standard deviations of about 75 nT for EMAG2v3 and 110 nT for WDMAM. Statistics thus show that differences between SH models and anomaly grids, at 0.5° in resolution, are one and a half times higher for WDMAM. Differences between EMAG2v3 and WDMAM are on average estimated at 5 ± 100 nT with extrema higher than 1300 nT mainly located in the mid-Atlantic ridge. These values can be explained by WDMAM's richer spectral content compared to the other models (Fig. 7d).

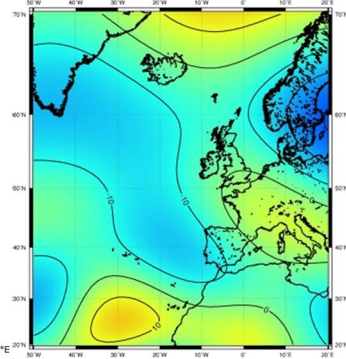
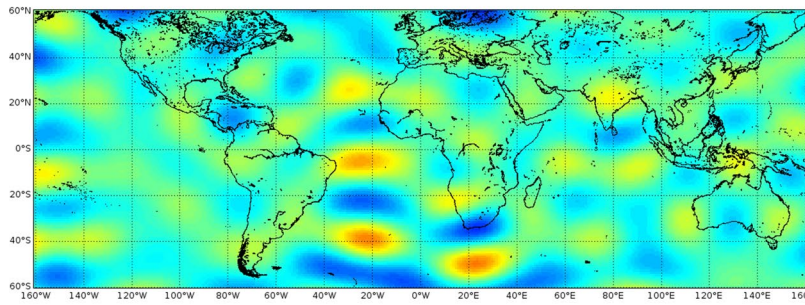
Comparison with marine datasets

Statistics on differences between the HDGM2016, EMAG2v3 and WDMAM models and marine data are summarized in Table 3. Maps of the most significant differences between HDGM2016 (estimated up to SH degree 720 with 0.5° grid spacing) and processed filtered marine data or WDMAM (with full grid spacing of 3 arc minutes) and unfiltered data are shown in Fig. 8.

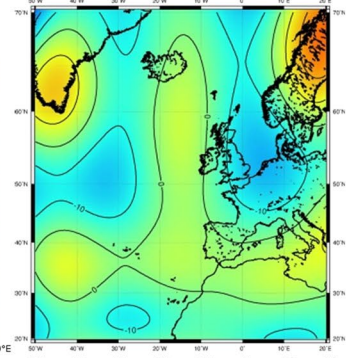
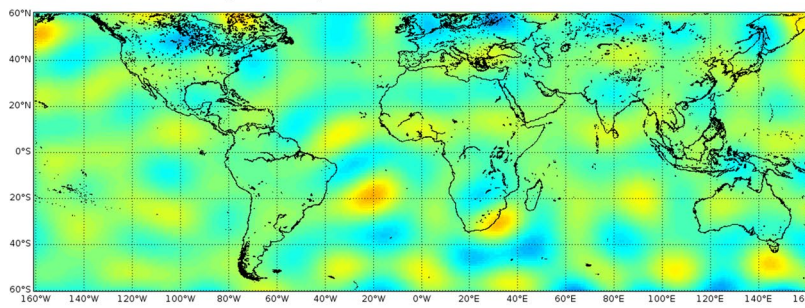
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Fig. 3 Map of differences in intensity values of the internal (INT) field estimated from WMM2015 (a), CM4 (b), HDGM2016 (c), COV-OBS.x1 (d) and IGRF-12 (reference) models up to SH degrees 12 and 13, at a global scale reduced by 30° in latitude and 20° in longitude (left, grid spacing: 1°) and for the NEAWM area (right, grid spacing: 0.5°)

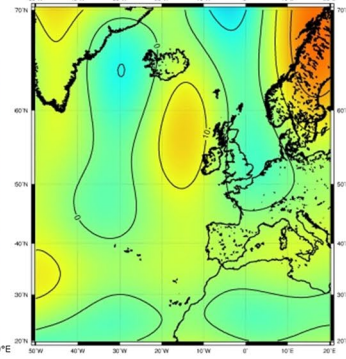
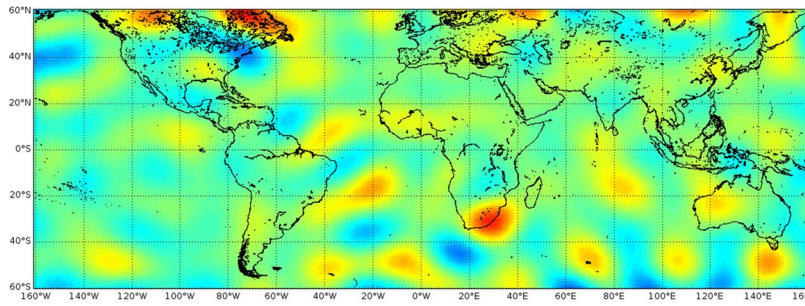
a WMM2015-IGRF-12, INT/12, 01/01/2015



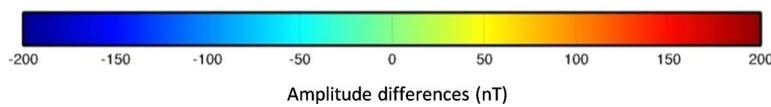
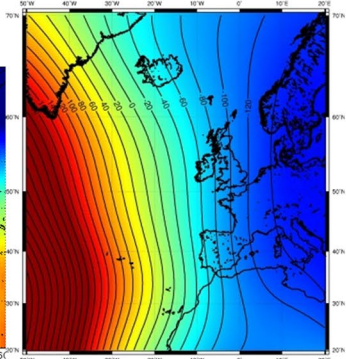
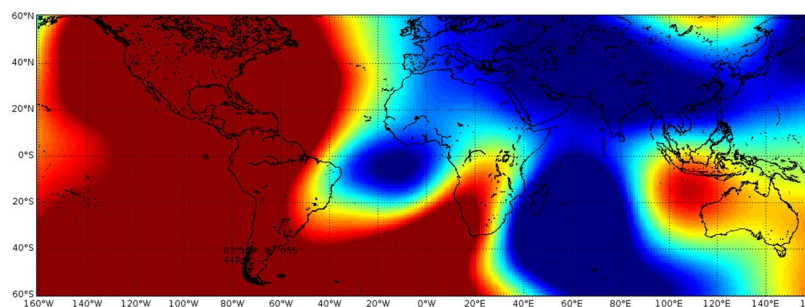
b CM4-IGRF-12, INT/13, 01/01/2000

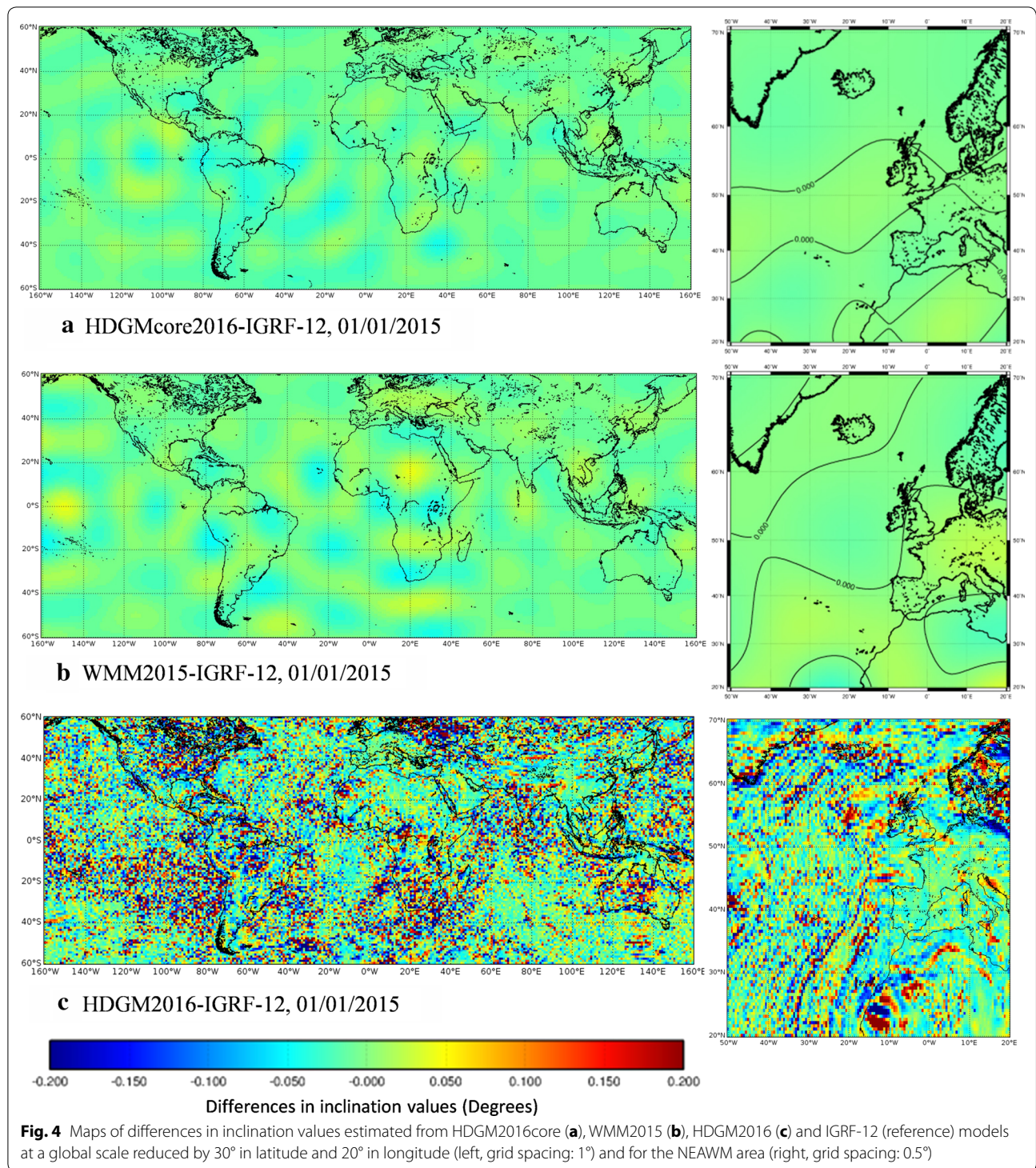


c HDGM2016-IGRF-12, INT/13, 01/01/2015



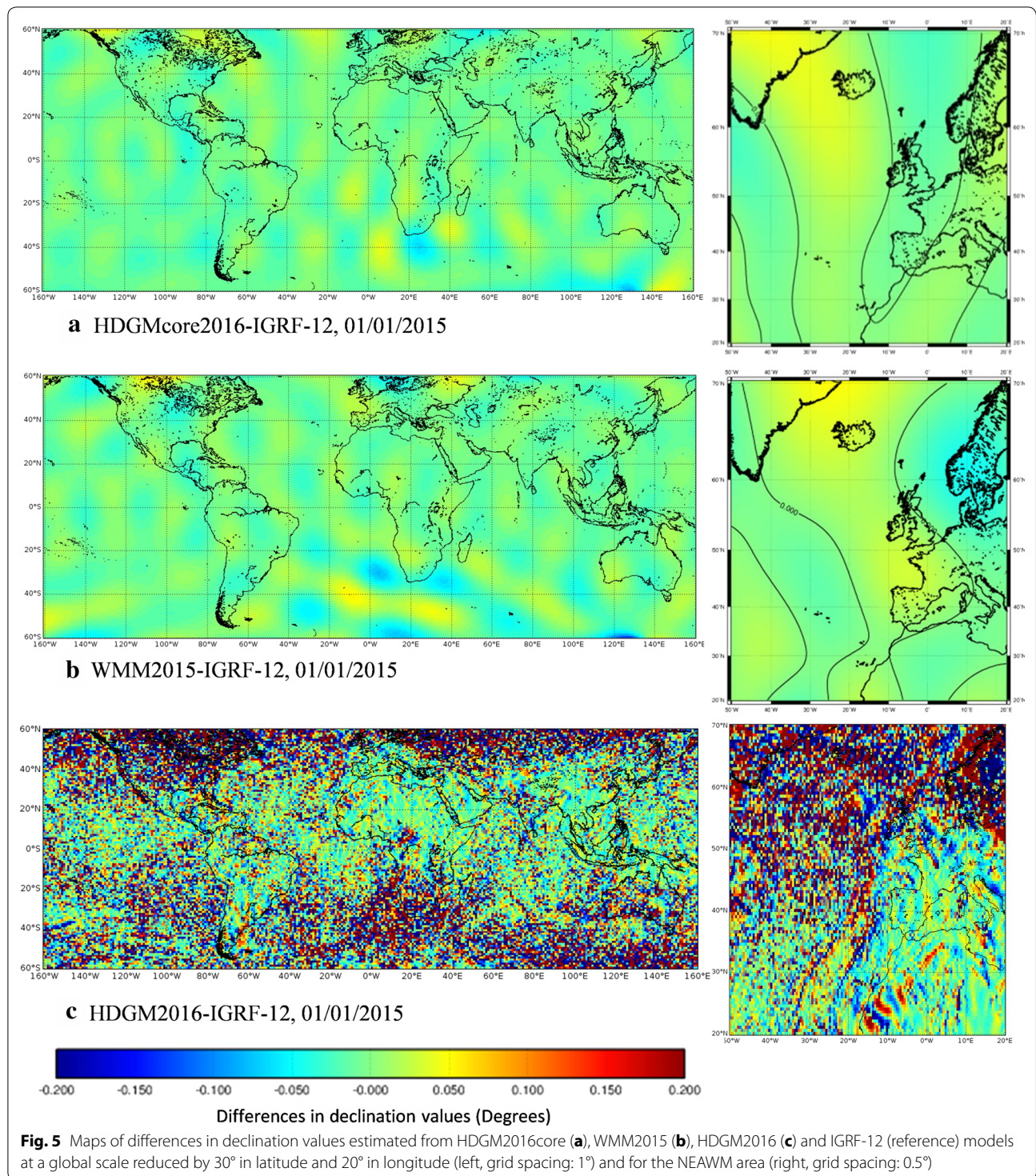
d COV-OBS.x1-IGRF-12, INT/13, 01/01/2015





Up to SH degree 720 (or through equivalent grid spacing of 0.5°), differences between global anomaly models and filtered marine data are minimized for HDGM2016 (for all dates) and EMAG2v3. Statistics are relatively similar for both models whether for the NEAWM area

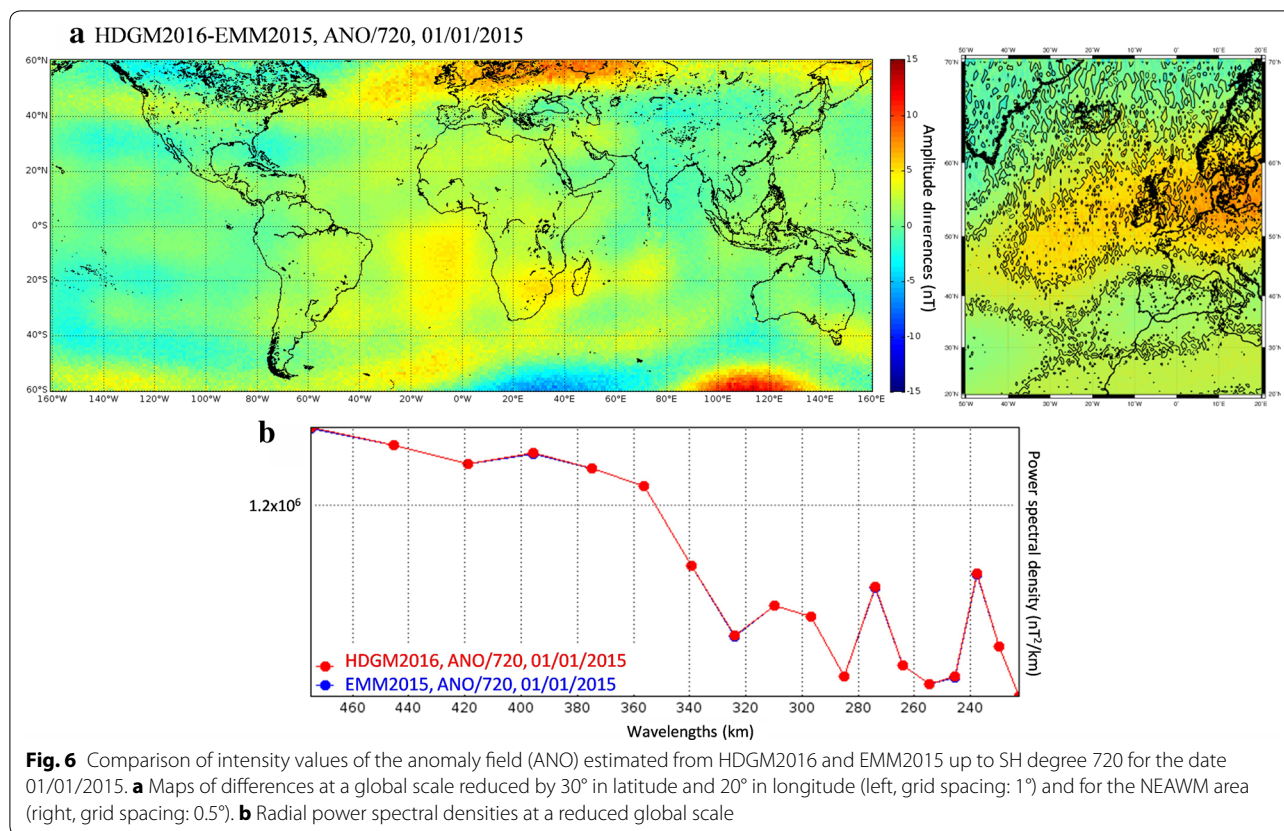
or geographical sub-areas. Mean differences for the NEAWM area are estimated at about a few nanoteslas with relatively high standard deviations of about 65 nT. Differences seem to be more significant for WDMAM with about 80 nT in standard deviations for the NEAWM



area. Most significant discrepancies are observed along the mid-Atlantic ridge where HDGM2016 and EMAG2v3 appear to be much closer to the marine data than WDMAM, with increases of more than 30 nT. High differences are also correlated with strong magnetic

gradients observed along the Tore-Madeira rise (see Fig. 8), where HDGM2016, EMAG2v3 and WDMAM models are statistically equivalent.

In contrast, at full grid spacing, the 3 arc minutes WDMAM model is closer to unfiltered marine data.



Apart from the English Channel to North Sea sub-area, differences between WDMAM and data decrease as resolution increases. Considering all data for the NEAWM area, standard deviations decrease from about 80 nT at 0.5° in resolution to about 70 nT for high resolution. By contrast, differences with the 2 arc minutes EMAG2v3 model significantly increase for the mid-Atlantic ridge and English Channel to North Sea sub-areas and consequently for the NEAWM area. Standard deviations for the NEAWM area are estimated at about 90 nT for high resolution compared to about 70 nT at 0.5° in resolution.

Best statistics observed for EMAG2v3 for 0.5° grid spacing and for WDMAM at full resolution are notable, as both models are globally based on the same datasets and precompiled grids. A noteworthy difference is the use of more realistic synthetic magnetic anomalies generated from ocean spreading (Lesur et al. 2016) for WDMAM, in unsurveyed areas. This may partly explain the more favourable statistics for the 3-arc-minute WDMAM model in the mid-Atlantic ridge and the Canary Islands to offshore west Portugal sub-areas. Whatever the resolution, differences between models and data on the Bay of Biscay and the western Mediterranean Sea sub-areas

are relatively high (with standard deviations of about 35–50 nT). It is not disturbing considering the precision of the marine data (see Fig. 2). On the contrary, EMAG2v3 and WDMAM inadequately characterize the magnetic signal at high resolution in the English Channel to North Sea continental shelf. The main differences in this area can be explained by the exclusive assimilation of the French longer-wave aeromagnetic data in the global anomaly models (Le Mouél 1970).

Limitations of the comparative study

The following limitations should be kept in mind when analysing these results:

- The study only focusses on the intensity of the magnetic field or of the anomaly field and the inclination/declination parameters calculated for the dates 01/01/2010, 01/01/2015 and for the CM4 model, 01/01/2000. It gives an overview of the behaviour of the models, but the study could benefit from a larger temporal coverage.
- The comparison of the internal component of the geomagnetic field is performed by filtering the spectral content of the considered models with a Butter-

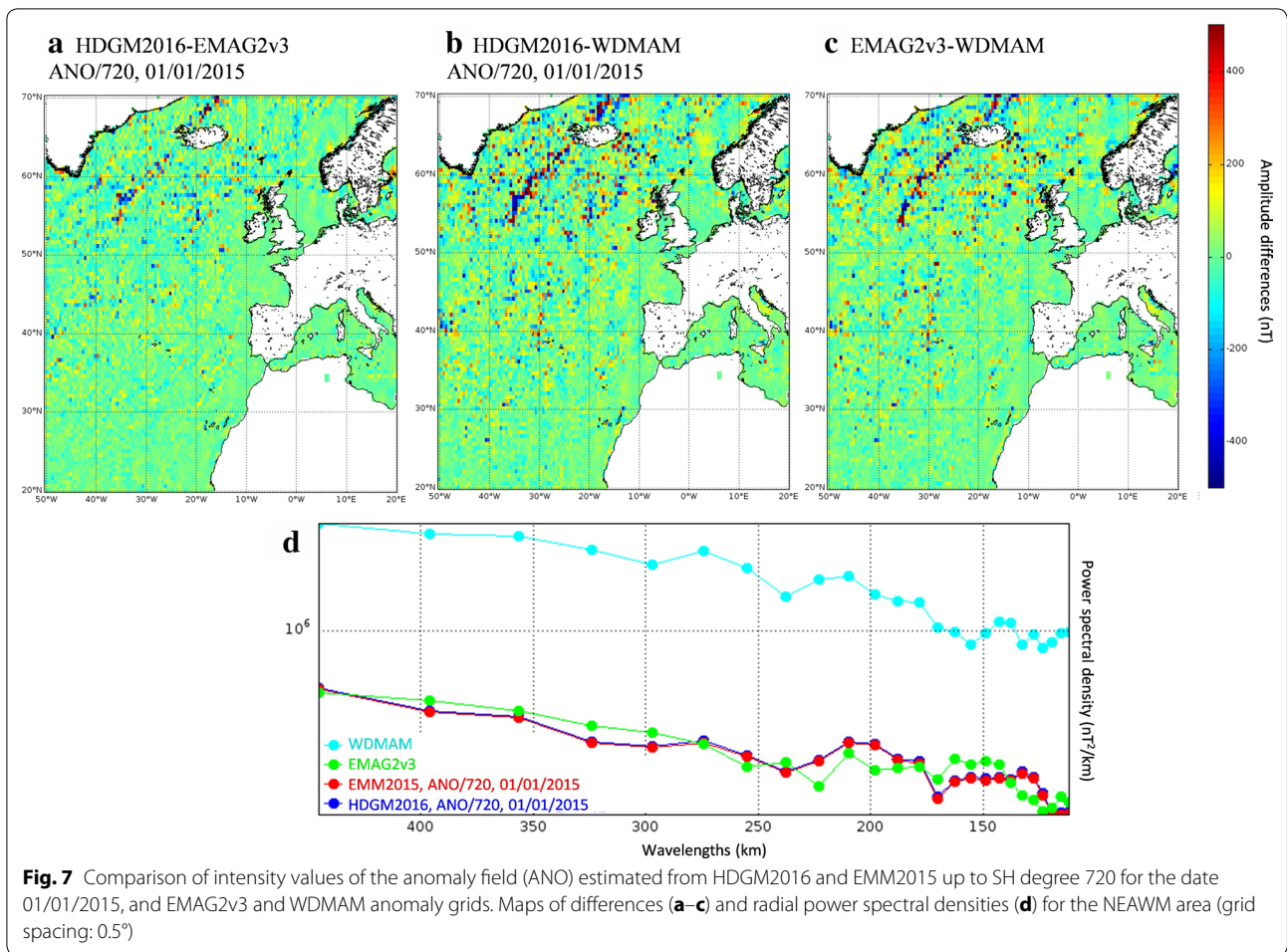


Table 3 Differences in intensity values of the anomaly field (ANO) in nT estimated from HDGM2016 up to SH degree 720, EMAG2v3 and WDMAM anomaly grids and marine datasets gathered by area of interest

Area of interest	Model					
	HDGM2016 ^a 01/01/2010 ANO/720 0.5°	HDGM2016 ^a 01/01/2015 ANO/720 0.5°	EMAG2v3 ^a 0.5°	WDMAM ^a 0.5°	EMAG2v3 ^b 2'	WDMAM ^b 3'
NEAWM area (i.e. full dataset)	-1.50 ± 65.87	-5.40 ± 65.71	-5.75 ± 67.33	1.01 ± 81.44	-5.48 ± 89.14	-0.58 ± 69.41
Mid-Atl. ridge 20–45°N	-5.09 ± 88.61	-9.11 ± 88.69	-13.12 ± 91.11	-8.27 ± 118.65	-8.74 ± 132.35	-2.59 ± 101.25
Canarian Isl. to offshore west Portugal	-12.99 ± 62.96	-15.73 ± 62.65	-13.34 ± 59.97	-5.67 ± 62.04	-13.24 ± 55.94	-7.66 ± 42.79
Bay of Biscay	-0.50 ± 37.81	-6.42 ± 37.87	0.72 ± 37.86	6.52 ± 43.02	2.14 ± 36.41	3.20 ± 34.32
English Channel to North Sea	18.17 ± 36.05	11.60 ± 36.05	8.65 ± 32.44	9.52 ± 35.09	2.73 ± 60.45	-1.37 ± 57.19
W. Mediterranean Sea	2.01 ± 42.48	-1.03 ± 42.39	1.00 ± 49.22	12.49 ± 50.51	-0.49 ± 49.47	7.03 ± 37.75

Marine data are processed and filtered^a or only processed^b to give spectral content comparable to that of the models

worth filter. The filtering is questionable, as it is at the origin of long-wave residual signals making it difficult to interpret the difference models. Extensive use

of the classically applied truncation method (see for example Barthelmes and Köhler 2016) would enable a more robust comparative analysis.

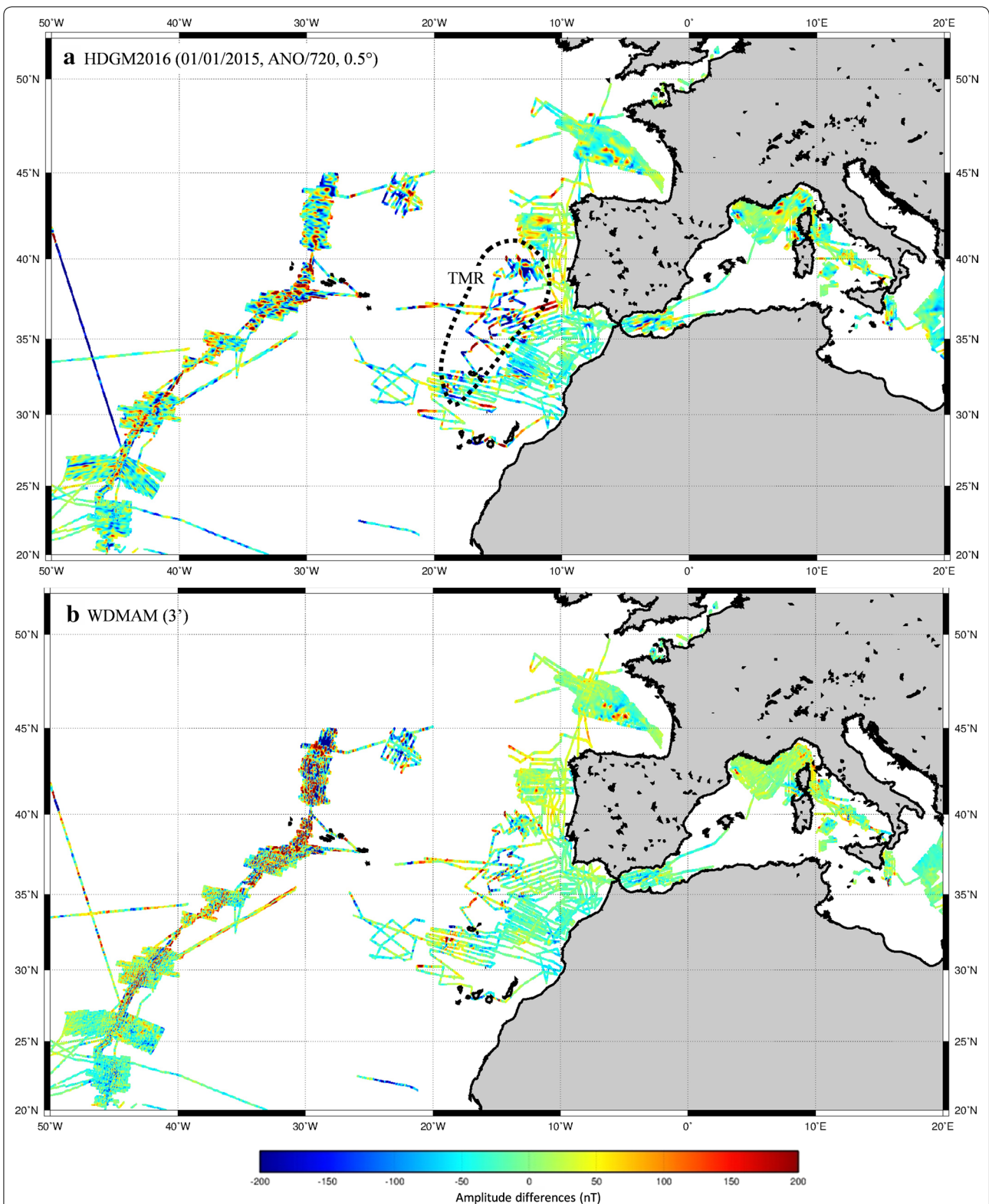


Fig. 8 Maps of differences between global anomaly models and marine data for the NEAWM area. **a** Intensity values of the anomaly field (ANO) estimated from HDGM2016 model up to SH degree 720 for the date 01/01/2015 (grid spacing: 0.5°) versus processed and filtered data. **b** WDMAM anomaly grid (grid spacing: 3 arc min.) versus unfiltered data. Images are derived from 2 min.-gridded models of differences computed between models and data. *TMR* Tore-Madeira Rise

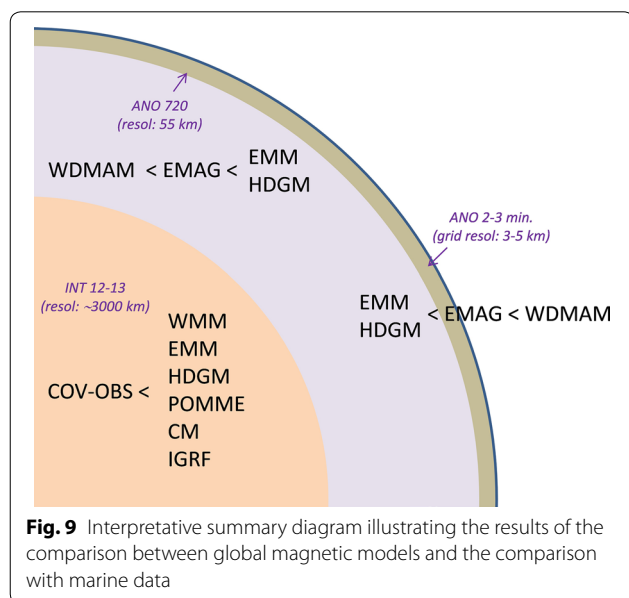
Conclusions

We have presented a comparison of nine global geomagnetic models and their evaluation using an external marine dataset processed according Shom's methodology. Results can be interpreted in the form of a summary diagram that provides a direct overview of the quality of the models (Fig. 9).

The main findings after comparing global magnetic models are:

- Up to SH degree 13:
 - The WMM2015, EMM2015, HDGM2016, POMME-9, CM4 and IGRF-12 models quite similarly reflect the internal component of the geomagnetic field with relative differences in intensity value of less than 10 nT (for an order of magnitude of 10^5 nT). Differences in inclination and declination values are estimated to be lower than 0.1° for WMM2015, HDGM2016core and IGRF-12 models.
 - The COV-OBS.x1 model is interpreted to be equivalent to others but solely for the date 01/01/2010. The computation for the date 01/01/2015 is provisional and consequently less robust.
 - According to the work of Thébault et al. (2015b), our results can be generalized to candidate models used to produce the reference model IGRF-12, and in particular to CHAOS5 model (Finlay et al. 2015).

These results demonstrate that any model can be used with insignificant errors to compute raw anomalies from total field measurements by removing the internal component of the Earth's magnetic field.



- Up to SH degree 720 or 0.5° equivalent grid spacing:
 - HDGM2016 and EMM2015 are similar with low differences of about a few nanoteslas, for all dates and extents, and consistent spectral content. Only long-wave variations are observed and are explained by the inclusion of new SWARM data in the 2016 revision of the HDGM model. HDGM2016 and EMM2015 are thus equivalent overall for both internal and lithospheric components. This result is not surprising because they are built according to the same methods and based on almost the same datasets (see Table 1).
 - The EMM2015 model is doubtful with respect to negative inclination and declination values. For the NEAWM area, the inclination grid is consistent and comparable with the grid derived from HDGM2016. Inclination and declination grids computed from the EMM2010 model are also consistent. EMM inconsistencies for both parameters seem to be observed only for the 2015 version.
 - Differences between HDGM2016 and EMM2015 comparatively to EMAG2v3 and WDMAM are significant but about one and a half times more for WDMAM (standard deviations of about 110 nT compared to 75 nT for EMAG2v3). Direct differences between EMAG2v3 and WDMAM are about 5 ± 100 nT with extrema higher than 1300 nT located in the mid-Atlantic ridge.

The evaluation of the global lithospheric HDGM2016, EMAG2v3 and WDMAM models by comparison with marine data for the NEAWM area gives the following information:

- Up to SH degree 720 or 0.5° equivalent grid spacing, mean differences between processed and filtered data and the HDGM2016 and EMAG2v3 models are the lowest and are estimated at about a few nanoteslas with standard deviations of about 65 nT.
- In contrast, at full grid spacing, the 3-arc-minute WDMAM model minimizes differences with processed unfiltered data. They slightly decrease as resolution increases (increase of 10 nT in standard deviation between 0.5° and 3 min.), while they significantly increase for EMAG2v3 (decrease of 20 nT between 0.5° and $2'$). These results suggest that the priority should be given to WDMAM for levelling and evaluating marine datasets and for computing enhanced high-resolution regional magnetic maps.

Additional files

Additional file 1. Comparative statistical analysis of differences in intensity values of the internal field (INT) estimated up to SH degrees 12 and 13 from global models (A) at a global scale reduced by 30° in latitude and 20° in longitude (grid spacing: 1°) and (B) for the NEAWM area (grid spacing: 0.5°).

Additional file 2. Comparative statistical analysis of differences in inclination and declination values estimated (A) at a global scale reduced by 30° in latitude and 20° in longitude (grid spacing: 1°) and (B) for the NEAWM area (grid spacing: 0.5°).

Additional file 3. Maps of differences in inclination and declination values estimated from EMM2015 (A) and EMM2010 (B) and IGRF-12 (reference) models at a global scale reduced by 30° in latitude and 20° in longitude (grid spacing: 1°). Probably due to digital coding, the EMM2015 lithospheric model is doubtful for negative values of inclination and declination. Tests did not identify any problems for the previous version of the product (EMM2010).

Additional file 4. Comparative statistical analysis of differences in intensity values of the anomaly field (ANO) estimated up to SH degree 720 from HDGM2016 and EMM2015 and derived from EMAG2v3 and WDMAM (A) at a global scale reduced by 30° in latitude and 20° in longitude (grid spacing: 1°) and (B) for the NEAWM area (grid spacing: 0.5°).

Abbreviations

ANO: anomaly field of the Earth's magnetic field; BGS: British Geological Survey; CEA: Commissariat à l'énergie atomique et aux énergies alternatives, France; CIRES: Cooperative Institute for Research in Environmental Sciences; CGMW: Commission for the Geological Map of the World; CM: comprehensive model of the geomagnetic field; DGA: Direction Générale de l'Armement (French Defence Procurement Agency); DTU: Danish Technical University; EMAG: Earth Magnetic Anomaly Grid; EMM: enhanced magnetic model; ESA: European Space Agency; GFZ: GeoForschungszentrum Potsdam; HDGM: High Definition Geomagnetic Model; IAGA: International Association of Geomagnetism and Aeronomy; IPGP: Institut de Physique du Globe de Paris, University of Sorbonne Paris Cité, France; IGRF: International Geomagnetic Reference Field; INT: internal component of the Earth's magnetic field; ISTERRE: Institute of Earth Sciences, University of Grenoble, France; LF: low frequency anomaly (only corrected from diurnal variations); LF + HF: low plus high frequency anomaly (corrected from diurnal and agitation variations); LPG: Laboratoire de Planétologie et Géodynamique, University of Nantes, France; MSL: mean sea level; NASA: National Aeronautics and Space Administration; NCEI: National Centers for Environmental Information; NEAWM: north-eastern Atlantic Ocean and western Mediterranean Sea (area of interest); NATO: North Atlantic Treaty Organization; NGA: US National Geospatial-intelligence Agency; NOAA: National Oceanic and Atmospheric Administration; PGL: Planetary Geodynamics Laboratory; POMME: Potsdam Magnetic Model of the Earth; SH: spherical harmonics; Shom: Service Hydrographique et Océanographique de la Marine (French Hydrographic and Oceanographic Service); SISMER: Systèmes d'Informations Scientifiques pour la MER (French National Oceanographic Data Centre); WMM: World Magnetic Model.

Authors' contributions

OJF is the main contributor to this study (processing, interpretation, summary/reporting). RD and LLMF worked as expert supervisors and project managers. All authors read and approved the final manuscript.

Authors' information

Shom's geophysical department specializes in marine geophysical data processing and interpretation. It focusses on potential methods (gravity and magnetism).

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The geomagnetic field models used in this study are publicly available from the following links: IGRF-12 (<https://www.ngdc.noaa.gov/1AGA/vmod/igrf.html>), WMM2015 (<https://www.ngdc.noaa.gov/geomag/WMM/DoDWM/M.shtml>), COV-OBS.x1 (<http://www.spacecenter.dk/files/magnetic-models/COV-OBSx1/>), CM4 (http://planetary-mag.net/earth_interface.html), POMME-9 (<http://www.geomag.org/models/pomme9.html>), EMM2015 (<https://www.ngdc.noaa.gov/geomag/EMM/>), EMAG2v3 (<https://www.ngdc.noaa.gov/geomag/emag2.html>), WDMAM (<http://wdmam.org/>). The HDGM2016 model is under licence (<https://www.ngdc.noaa.gov/geomag/HDGM/index.html>). External raw marine magnetic datasets are available from SISMER's web portal (<https://www.ifremer.fr/sismer>). Some external processed datasets are also available from NCEI's web portal (<https://maps.ngdc.noaa.gov/viewers/geophysics/>).

Consent for publication

Not applicable.

Ethics approval and consent to participate

Not applicable.

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References

- Alken P, Maus S, Chulliat A, Manoj C (2015) NOAA/NGDC candidate models for the 12th generation International Geomagnetic Reference Field. *Earth Planets Space* 67:68. <https://doi.org/10.1186/s40623-015-0215-1>
- Backus G, Parker R, Constable C (1996) Foundations of geomagnetism. Cambridge University Press, Cambridge
- Barthelmes F, Köhler W (2016) International Centre for Global Earth Models (ICGEM). In: Drewes H, Kuglitsch F, Adám J et al (eds) The Geodesists Handbook 2016. *J Geod* 90:907–1205. <https://doi.org/10.1007/s00190-016-0948-z>
- Burg JP (1975) Maximum entropy spectral analysis. Ph.D. thesis, Stanford University
- Chulliat A, Macmillan S, Alken P, Beggan C, Nair M, Hamilton B, Woods A, Ridley V, Maus S, Thomson A (2015) The US/UK World Magnetic Model for 2015–2020. <https://doi.org/10.7289/v5tb14v7>
- Defense Mapping Agency (1993) Military specification for World Magnetic Model (WMM). Document MIL-W-89500
- Dyment J, Choi Y, Hamoudi M, Lesur V, Thébault E (2015) Global equivalent magnetization of the oceanic lithosphere. *Earth Planet Sci Lett* 430:54–65. <https://doi.org/10.1016/j.epsl.2015.08.002>
- Finlay CC, Olsen N, Tøffner-Clausen L (2015) DTU candidate field models for IGRF-12 and the CHAOS-5 geomagnetic field model. *Earth Planets Space* 67:114. <https://doi.org/10.1186/s40623-015-0274-3>
- Fournier A, Aubert J, Thébault E (2015) A candidate secular variation model for IGRF-12 based on Swarm data and inverse geodynamo modelling. *Earth Planets Space* 67(1):81. <https://doi.org/10.1186/s40623-015-0245-8>

- Gillet N, Jault D, Finlay CC, Olsen N (2013) Stochastic modeling of the Earth's magnetic field: inversion for covariances over the observatory era. *Geochem Geophys Geosyst* 14:766–786. <https://doi.org/10.1002/ggge.20041>
- Gillet N, Barrois O, Finlay CC (2015) Stochastic forecasting of the geomagnetic field from the COV-OBS.x1 geomagnetic field model, and candidate models for IGRF-12. *Earth Planets Space* 67:71. <https://doi.org/10.1186/s40623-015-0225-z>
- Hamilton B, Ridley VA, Beggan CD, Macmillan S (2015) The BGS magnetic field candidate models for the 12th generation IGRF. *Earth Planets Space* 67(1):69. <https://doi.org/10.1186/s40623-015-0227-x>
- Langel RA (1987) The main field. In: Jacobs JA (ed) *Geomagnetism*, vol I. Academic Press, HBJ, New York
- Le Mouél JL (1970) Le levé aéromagnétique de la France. Calcul des composantes du champ à partir des mesures de l'intensité. *Ann Geophys* 26(2):229–258
- Lesur V, Rother M, Wardinski I, Schachtschneider R, Hamoudi M, Chambodut A (2015) Parent magnetic field models for the IGRF-12GFZ-candidates. *Earth Planets Space* 67(1):87. <https://doi.org/10.1186/s40623-015-0273-4>
- Lesur V, Hamoudi M, Choi Y, Dymont J, Thébaud E (2016) Building the second version of the World Digital Magnetic Anomaly Map (WDMAM). *Earth Planets Space* 68:1–13. <https://doi.org/10.1186/s40623-016-0404-6>
- Lowes FJ (2000) An estimate of the errors of the IGRF/DGRF fields 1945–2000. *Earth Planets Space* 52:1207–1211
- Maus S (2010) An ellipsoidal harmonic representation of Earth's lithospheric magnetic field to degree and order 720. *Geochem Geophys Geosyst* 11:Q06015. <https://doi.org/10.1029/2010GC003026>
- Maus S, Rother M, Stolle C, Mai W, Choi S, Lühr H, Cooke D, Roth C (2006) Third generation of the Potsdam Magnetic Model of the Earth (POMME). *Geochem Geophys Geosyst* 7:Q07008. <https://doi.org/10.1029/2006GC001269>
- Maus S, Sazonova T, Hemant K, Fairhead JD, Ravat D (2007) National Geophysical Data Center candidate for the World Digital Magnetic Anomaly Map. *Geochem Geophys Geosyst* 8:Q06017. <https://doi.org/10.1029/2007GC001643>
- Maus S et al (2009) EMAG2: a 2-arc min resolution Earth Magnetic Anomaly Grid compiled from satellite, airborne, and marine magnetic measurements. *Geochem Geophys Geosyst* 10:Q08005. <https://doi.org/10.1029/2009GC002471>
- Maus S, Manoj C, Rauberg J, Michaelis I, Lühr H (2010) NOAA/NGDC candidate models for the 11th generation International Geomagnetic Reference Field and the concurrent release of the 6th generation Pomme magnetic model. *Earth Planets Space* 62:729–735. <https://doi.org/10.5047/eps.2010.07.006>
- Meyer B, Saltus R, Chulliat A (2016) EMAG2: Earth Magnetic Anomaly Grid (2-arc-minute resolution) Version 3. Model, National Centers for Environmental Information, NOAA. <https://doi.org/10.7289/V5H70CVX>
- Meyer B, Chulliat A, Saltus R (2017) Derivation and error analysis of the Earth Magnetic Anomaly Grid at 2 arc min Resolution Version 3 (EMAG2v3). *Geochem Geophys Geosyst* 18:4522–4537. <https://doi.org/10.1002/2017GC007280>
- Quesnel Y, Catalan M, Ishihara T (2009) A new global marine magnetic anomaly data set. *J Geophys Res* 114:B04106. <https://doi.org/10.1029/2008JB006144>
- Sabaka TJ, Olsen N, Purucker ME (2004) Extending comprehensive models of the Earth's magnetic field with Ørsted and CHAMP data. *Geophys J Int* 159:521–547
- Sabaka TJ, Olsen N, Tyler RH, Kuvshinov A (2015) CM5, a pre-Swarm comprehensive geomagnetic field model derived from over 12 year of CHAMP, Ørsted, SAC-C and observatory data. *Geophys J Int* 200:1596–1626. <https://doi.org/10.1093/gji/ggu493>
- Saturnino D, Langlais B, Civet F, Thébaud E, Manda M (2015) Main field and secular variation candidate models for the 12th IGRF generation after 10 months of Swarm measurements. *Earth Planets Space* 67(1):96. <https://doi.org/10.1186/s40623-015-0262-7>
- Shom (2007) Acquisition et traitement des mesures magnétiques marines. Procédure spécifique PS2007-072. Shom's internal document
- Thébaud E, Purucker M, Whaler KA, Langlais B, Sabaka TJ (2010) The magnetic field of the Earth's lithosphere. *Space Sci Rev* 155:95–127
- Thébaud E et al (2015a) International Geomagnetic Reference Field: the 12th generation. *Earth Planets Space* 67:79. <https://doi.org/10.1186/s40623-015-0228-9>
- Thébaud E, Finlay CC, Alken P, Beggan CD, Canet E, Chulliat A, Langlais B, Lesur V, Lowes FJ, Manoj C, Rother M, Schachtschneider R (2015b) Evaluation of candidate geomagnetic field models for IGRF-12. *Earth Planets Space* 67:112. <https://doi.org/10.1186/s40623-015-0273-4>
- Vigneron P, Hulot G, Olsen N, Léger J-M, Jager T, Brocco L, Sirol O, Coisson P, Lalanne X, Chulliat A, Bertrand F, Boness A, Fratter I (2015) A 2015 International Geomagnetic Reference Field (IGRF) candidate model based on Swarm's experimental absolute magnetometer vector mode data. *Earth Planets Space* 67:95. <https://doi.org/10.1186/s40623-015-0265-4>

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