

Climatological models of non-polar geomagnetic daily variations using the DIFI methodology with Swarm and CHAMP satellite data

Arnaud Chulliat^{1,2,*} , Louis Chauvet³ , Gauthier Hulot³ , Robin Duchêne³, and Martin Fillion³ 

¹ Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, 216 UCB, Boulder, CO 80309, USA

² NOAA National Centers for Environmental Information, 325 Broadway, Boulder, CO 80305, USA

³ Université Paris Cité, Institut de physique du globe de Paris, CNRS, 1 Rue Jussieu, Paris 75005, France

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Abstract—Climatological models of non-polar geomagnetic daily variations are valuable tools for applications ranging from studying ionospheric current systems to correcting magnetic field survey data. Several such models have been developed as part of the Dedicated Ionospheric Field Inversion (DIFI) project during the Swarm satellite mission. Here, we present the latest version of the DIFI model, DIFI-8, derived from ten years of magnetic field measurements by the Swarm Alpha and Bravo satellites (2014–2023), supplemented with data from ground-based observatories. We also introduce an updated version of the extended DIFI model, xDIFI-2, constructed using data from Swarm, CHAMP, and ground-based observatories, and covering the period from 2001 to 2023. As with previous versions, these models provide estimates of both the primary and induced magnetic fields generated by mid-latitude solar quiet (Sq) currents and the Equatorial Electrojet (EEJ) within ± 55 degrees quasi-dipole (QD) latitudes, at both ground and Low-Earth Orbit (LEO) satellite altitudes. In addition, DIFI-8 incorporates corrections for toroidal magnetic fields based on a recently published climatological model. Both models have been extensively validated using independent ground-based observatory data. The equivalent current systems and total current intensities derived from DIFI-8 and xDIFI-2 are consistent over the two-decade period, suggesting that these models may be reliably applied even outside their formal domain of validity, with minimal additional error.

Keywords: Swarm / Geomagnetism / Ionosphere / Modelling / Space weather

1 Introduction

Non-polar geomagnetic daily variations are observed in all geomagnetic field recordings, both at the Earth's surface and in low-Earth orbit, and have long been a focus of scientific study (e.g., Yamazaki & Maute, 2017). These variations are primarily driven by electric currents in the ionospheric E-region (ionospheric wind dynamo) and by induced electric currents in the Earth's mantle. At mid-latitudes, they are often referred to as “solar quiet” (Sq) variations, as their amplitude and phase are strongly influenced by solar local time, and they are most prominent during geomagnetically quiet periods. Variations in ionospheric E-region conductivity, driven by changes in solar flux and seasonal insolation, strongly influence the amplitude and morphology of the Sq current system. These variations cause seasonal and longitudinal differences (e.g., Pedatella et al., 2011, and references therein) and can lead to total current

intensities that differ by more than a factor of three between solar maximum and minimum (Campbell & Matsushita, 1982; Takeda et al., 1986). At low latitudes, the variations are dominated by the Equatorial Electrojet (EEJ), a narrow band of current flowing along the geomagnetic dip equator during the daytime in the ionospheric E-region (see, e.g., Forbes, 1981; Alken et al., 2015). Both Sq and EEJ magnetic fields exhibit temporal variations influenced by season, solar cycle, and geomagnetic activity. They are also affected by the day-to-day variability of thermospheric winds and tides. As part of space weather, Sq and EEJ variations can perturb the geomagnetic environment, affecting navigation systems that rely on the geomagnetic field, including those using magnetic anomaly maps for alternative magnetic navigation in GPS-denied environments (e.g., Canciani & Raquet, 2016).

The production mechanisms of the Sq and EEJ are well understood (e.g., Richmond & Thayer, 2000; Yamazaki & Maute, 2017), and various physics-based models have been developed (e.g., Qian et al., 2014). However, these models

*Corresponding author: arnaud.chulliat@colorado.edu

typically focus on investigating the coupled electrodynamics of the ionosphere and thermosphere, rather than on accurately predicting geomagnetic variations for practical applications. There is also a long history of developing empirical equivalent current models based on geomagnetic field observations. When based solely on ground-based data, such models generally lack true global coverage (especially in longitude). An empirical modeling approach incorporating low-Earth orbit (LEO) satellite data was pioneered as part of the Comprehensive Model phase 3 (CM3, [Sabaka et al., 2002](#)). Although CM3 used a limited amount of satellite data with insufficient local time-longitude coverage, it represented a significant step forward by providing, for the first time, a global Sq and EEJ model that separated primary and induced fields and was thus capable of predicting daily geomagnetic variations both at the Earth's surface and at LEO altitudes. CM3 was soon extended to CM4 ([Sabaka et al., 2004](#)) and later to CM5 ([Sabaka et al., 2015](#)). These widely used models incorporated CHAMP and Ørsted satellite data, with CM5 additionally including SAC-C data, and provided improved local time-longitude coverage.

As part of the Swarm satellite mission ([Friis-Christensen et al., 2006](#)), launched in 2013, and for the purpose of producing Swarm Level 2 products ([Olsen et al., 2013](#)), two independent processing chains were developed for non-polar geomagnetic daily variations: the Comprehensive Inversion (CI, [Sabaka et al., 2013](#)) and the Dedicated Ionospheric Field Inversion (DIFI, [Chulliat et al., 2013](#)). The CI performs a single inversion for all sources simultaneously, while the term “dedicated” in DIFI refers to geomagnetic daily variations being inverted separately from magnetic fields generated by other sources, after these fields have been removed using different models or signal processing techniques. Dedicated modeling enables more flexible data correction methods and provides independent validation of the CI. CI and DIFI models provide global representations of the quiet-time, climatological, non-polar daily variations at both ground and LEO altitudes during the Swarm mission ([Chulliat et al., 2016](#); [Sabaka et al., 2018](#)). These models separate primary and induced fields. Several DIFI models have been released to date, and this paper focuses on two newly released models: DIFI-8 and xDIFI-2. While DIFI-8 is largely a continuation of previous Swarm-based DIFI models, incorporating more recent data (from 2014 to 2023), xDIFI-2 is a composite model that combines data from both Swarm and CHAMP satellites, covering the period from 2001 to 2023.

The paper is organized as follows. [Section 2](#) provides a brief overview of the DIFI methodology. In [Section 3](#), the DIFI-8 model is presented, including the data used, pre-processing methods, and an evaluation of model performance. [Section 4](#) presents the xDIFI-2 model. Both models are discussed in [Section 5](#), and conclusions and perspectives are provided in [Section 6](#).

2 DIFI methodology

The DIFI methodology is described in detail by [Chulliat et al. \(2013, 2016\)](#). DIFI models are computed using both LEO satellite vector data (e.g., Swarm data) and ground-based observatory data. The first step involves data pre-processing. For satellite data, this includes selecting geomagnetically quiet periods and applying corrections based on core, lithospheric,

and magnetospheric magnetic field models. Specific selection criteria and the models used for corrections will be detailed in the following sections. Additional empirical, track-by-track corrections and filtering are applied to remove unmodeled magnetospheric field variations and high-latitude ionospheric fields from the satellite data (see [Chulliat et al., 2016](#) for details). In DIFI-8, a new correction was introduced to account for toroidal magnetic fields in Swarm data, using a climatological model of F-region ionospheric currents developed by [Fillion et al. \(2023\)](#). This correction was not applied to the satellite data in xDIFI-2, as the toroidal field models are only valid at Swarm altitudes and cannot be straightforwardly applied to CHAMP data. Observatory data are selected using the same geomagnetically quiet period criteria as the satellite data and are corrected for core and magnetospheric fields. For each observatory, the average nighttime level over the entire data interval is determined using data from 21:00 to 03:00 local time and is then subtracted.

Satellite and observatory vector data are jointly inverted for two spherical harmonic models of degree 45 and order 5 in quasi-dipole coordinates ([Richmond, 1995](#)), modulated in time by two Fourier series. The first model represents the magnetic field generated by sources located at an altitude of 110 km (primary field), while the second model represents the magnetic field generated by sources beneath the Earth's surface (induced field). The first model is an internal field model at LEO satellite altitude, but an external field model at the Earth's surface; the second model is always an internal field model. The first Fourier time series describes the daily variations of wavenumbers $p = 0-4$, corresponding to oscillations with periods 24 h, 12 h, 8 h, 6 h, and a constant signal. The second Fourier series describes seasonal variations of wavenumbers $s = -2$ to 2, corresponding to oscillations with periods of 12 months, 6 months, and a constant signal. The coefficients of both models are linearly dependent on solar activity, represented by the solar radio flux index F10.7, through a global scaling factor of the form $(1 + N \times \text{F10.7})$. The factor N , known as the Wolf ratio, is the same for all coefficients and has a value of $N = 14.85 \times 10^{-3} \text{ SFU}^{-1}$ (expressed in solar flux units, or SFU, where $1 \text{ SFU} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$), as previously determined by [Sabaka et al. \(2002\)](#).

As in [Chulliat et al. \(2016\)](#), the primary and induced fields are related through a so-called Q matrix, which expresses the inductive effect of mantle conductivity across the various spatial and temporal scales that make up the primary field. Q is a block-diagonal matrix in which the blocks corresponding to non-zero s values are identical and consist of the same five different sub-matrices, one for each wavenumber p . The $s = 0$ block consists of the same four sub-matrices for $p > 0$ as for non-zero s block matrices, but a zero matrix for $p = 0$, since the time-independent component of the primary field produces no induced field. The Q matrices were computed by Alexei Kuvshinov from a laterally variable conductivity shell ([Manoj et al., 2006](#)) and a 1D conductivity profile beneath it ([Püthe et al., 2015](#)).

The DIFI inversion is carried out with two regularization terms. The first dampens all coefficients equally, while the second minimizes the horizontal gradient of the current density at all local times, with a geographical weighting to avoid over-damping of the narrow equatorial electrojet signal. Although the inversion is performed in quasi-dipole coordinates up to degree

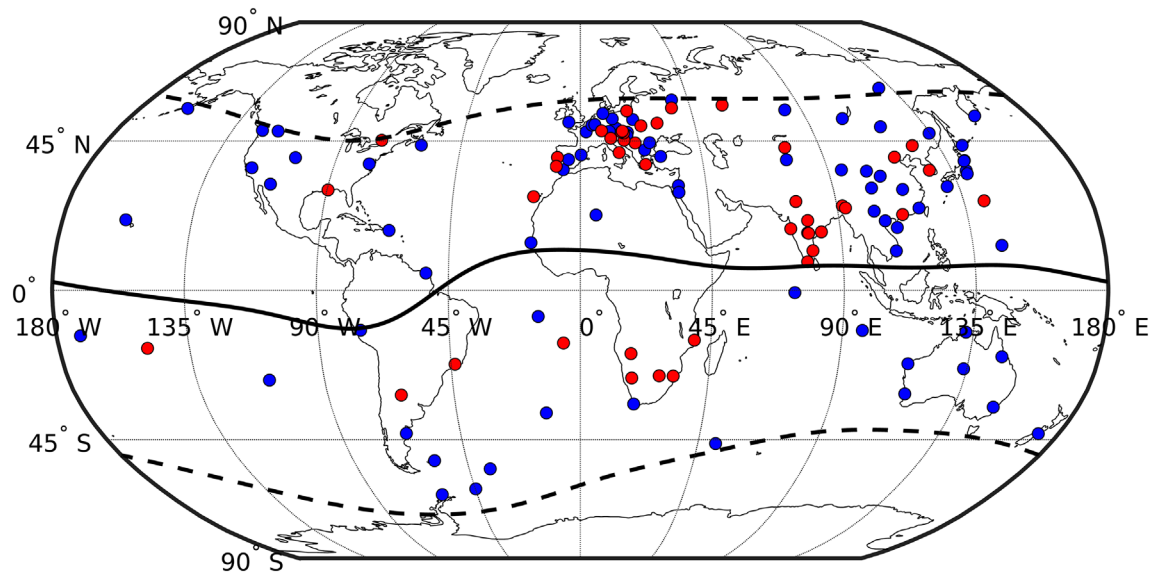


Figure 1. Map showing the locations of the observatories used for building (blue dots) and validating (red dots) the DIFI-8 model. Quasi-dipole latitudes of $\pm 55^\circ$ are indicated by black dashed lines, and the magnetic dip equator is shown as a thick black line. Quasi-dipole latitudes are calculated for the year 2018.

45 and order 5, the resulting model is subsequently transformed (and released, if applicable) into dipole coordinates, up to degree 60 and order 12. The final model in dipole coordinates contains 68,400 real coefficients, while the intermediate model in quasi-dipole coordinates comprises 11,875 coefficients. The format used to release the successive DIFI models developed to date has been kept consistent with the format described in Chulliat et al. (2013).

All models use the same input: location in geocentric dipole coordinates (r, θ_d, ϕ_d); time t , expressed in years from January 1 at 00:00 Universal Time (UT); Magnetic Universal Time (MUT), defined as $t_m = (180 - \phi_{d,s})/15$ and expressed in hours, where $\phi_{d,s}$ is the dipole longitude of the subsolar point (the point on the Earth's surface closest to the Sun), expressed in degrees, and the F10.7 index. From the model coefficients, the primary and induced magnetic field potentials can be calculated using formulas (2) and (3) in Chulliat et al. (2016). The corresponding primary and induced magnetic fields are then obtained by taking the gradient of these potentials in the desired coordinate system.

3 DIFI-8 model

Following the release of DIFI-2015b (Chulliat et al., 2016), several new versions, DIFI-2 to DIFI-7 (released between 2016 and 2022), were developed as additional Swarm data became available. These versions employed the same methodology and algorithms as DIFI-2015b, with no significant changes other than the longer time span of Swarm and observatory data included. Each successive model superseded its predecessor. All models are available online (see Data Availability section) from the University of Colorado and the European Space Agency (ESA), where they are listed as ESA products SW_OPER_MIO_SHA_2D, versions 0201 to 0801. The model

presented in this section, DIFI-8 (ESA product SW_OPER_MIO_SHA_2D, version 0901), is the most recent iteration and introduces a correction for toroidal fields. It is available on the same websites.

DIFI-8 was constructed from the following data:

- Swarm Alpha and Bravo satellite vector data: Level 1b MAGx_LR (1 Hz) data, baseline 0602/0603, covering the period from January 1, 2014, to December 31, 2023. These data are available from ESA (see the Data Availability section).
- Magnetic observatory data: Definitive and quasi-definitive (Peltier & Chulliat, 2010) hourly mean magnetic field measurements, collected at selected magnetic field observatories from January 1, 2014, to December 31, 2023. These data were quality-controlled, pre-processed, and distributed by the British Geological Survey as the “SW_OPER_AUX_OBS” Swarm data product (Macmillan & Olsen, 2013).

A map showing the locations of the observatories used in DIFI-8 is provided in Figure 1. The map also indicates quasi-dipole latitudes of $\pm 55^\circ$, which represent the model's domain of validity, and the dip equator. The domain of validity is primarily determined by the structure of the Sq and EEJ fields and the preprocessing of satellite data. Note that the selection criterion for observatories was $\pm 55^\circ$ geomagnetic dipole latitude, not $\pm 55^\circ$ quasi-dipole latitude, which led to omitting two Northern Hemisphere observatories (St. John's, Canada, and Eskdalemuir, United Kingdom) and including one observatory slightly outside the domain of validity (Yakutsk, Russia). These differences are not expected to significantly impact the model's performance.

Satellite data were decimated at a rate of 1 in 10, and both satellite and observatory data were selected during

Table 1. Mean (μ) and root-mean-square (σ) residuals, and number of data points (N), for Alpha and Bravo satellite data (within quasi-dipole latitudes of $\pm 55^\circ$), observatory data used in the inversion, and observatory data used in the validation. Results are shown for models DIFI-8a (with toroidal field corrections, TFC) and DIFI-8b (without corrections, no TFC). Residuals are provided for the radial (r), polar (θ), and azimuthal (ϕ) components of the magnetic field. For satellite data, residuals are computed only within the domain of validity, defined by quasi-dipole latitudes within $\pm 55^\circ$.

	N	μ_r (nT)	σ_r (nT)	μ_θ (nT)	σ_θ (nT)	μ_ϕ (nT)	σ_ϕ (nT)
(a) DIFI-8a (TFC)							
Alpha & Bravo	716,597	−0.03	3.51	−0.16	4.30	−0.17	7.01
Alpha	365,211	0.02	3.57	−0.20	4.39	−0.20	7.13
Bravo	351,386	−0.07	3.44	−0.13	4.21	−0.14	6.88
Obs. Inversion	846,978	−0.14	4.53	0.20	6.34	−0.08	5.86
Obs. Validation	1,095,895	−0.53	4.78	−0.69	7.42	−0.03	6.57
(b) DIFI-8b (no TFC)							
Alpha & Bravo	718,824	−0.03	3.49	0.42	4.66	−0.20	8.79
Alpha	366,363	0.01	3.55	0.39	4.71	−0.22	8.90
Bravo	352,461	−0.08	3.43	0.44	4.61	−0.18	8.68
Obs. Inversion	846,978	−0.15	4.53	0.28	6.34	−0.07	5.85
Obs. Validation	1,095,895	−0.53	4.79	−0.48	7.41	0.03	6.56

geomagnetically quiet periods using the following criteria: $Kp < 2$, $|Dst| < 20$ nT, $|IMF By| < 8$ nT, -2 nT $< IMF Bz < 6$ nT. The Kp index (Matzka et al., 2021) measures the average level of geomagnetic disturbance at 13 subauroral observatories. The disturbance storm-time (Dst) index, produced by Kyoto University (see the link in the [Data Availability section](#)), tracks the strength of the magnetic field generated by the magnetospheric ring current. $IMF By$ is the dusk-dawn component of the interplanetary magnetic field (IMF), perpendicular to the Sun–Earth line and in the ecliptic plane, while $IMF Bz$ is the north–south component of the IMF, perpendicular to the ecliptic plane. Both components are measured by NASA’s Advanced Composition Explorer (ACE) satellite and affect the level of geomagnetic activity within the magnetosphere. IMF data are extracted from NASA/GSFC’s OMNI data set through OMNIWEB (Papitashvili & King, 2020).

The data were then corrected for core and magnetospheric fields using the CHAOS-7 model (Finlay et al., 2020), with version 7.17 applied to satellite data and version 7.16 to observatory data. For satellite data, the core field and its secular variation were truncated at spherical harmonic degree and order 15; for observatory data, they were truncated at degree and order 20. Satellite data were further corrected for the lithospheric field (starting from degree and order 16) using the MF7 model (Maus et al., 2008; see the model and related information at the link in the [Data Availability section](#)). The remaining static magnetic field at observatories was empirically removed by calculating mean values from data collected during nighttime, defined as 21:00–03:00 local time, over the entire data interval. Additional track-by-track corrections and filtering were applied to the satellite data following Chulliat et al. (2016), as stated in [Section 2](#).

Two models were calculated as part of the DIFI-8 preparation: DIFI-8a, which includes additional toroidal field corrections applied to satellite data using the model of Fillion et al. (2023), and DIFI-8b, which does not include these corrections. The toroidal field corrections were applied during the same pre-processing step as the corrections for other non-ionospheric magnetic fields, and before the additional empirical corrections. As a result, the number of data points included in the inversion differs slightly between DIFI-8a and DIFI-8b.

The differences between the modeled and observed magnetic fields at the observation points and times (residuals) for both models, within quasi-dipole latitudes of $\pm 55^\circ$, are shown in [Table 1](#). This table also includes residuals from a separate set of ground-based observatories used exclusively for validation. Locations of these observatories are also shown in [Figure 1](#). The satellite mean and root-mean-square (RMS) data residuals are generally lower for the model with toroidal field corrections than for the model without them, supporting the assumption that such corrections remove non-potential magnetic fields, which are not modeled in the DIFI inversion. The effect on both types of residuals is small, primarily affecting the polar and azimuthal field components, and is consistent with expectations based on the amplitudes of the modeled toroidal fields. Toroidal field corrections have virtually no effect on residuals from observatory data, whether from observatories used in the inversion or from those used for validation. This indicates that toroidal fields do not influence model performance at ground level, as expected, since they are confined to the ionospheric F-region. Based on these findings, DIFI-8a was adopted as the final version of the DIFI-8 model.

RMS data residuals for the validation dataset are larger than those for the inversion dataset by 6%, 17% and 12% for the radial, polar, and azimuthal components, respectively. Mean residuals are also higher for the radial and polar components. As shown in [Figure 2](#), most of the increase in RMS residuals can be attributed to a small number of validation observatories located at low QD latitudes, particularly for the polar component. This may partly be due to the stronger daily variations associated with the equatorial electrojet (EEJ), which flows along the magnetic dip equator. More accurately modeling the EEJ would require a higher spatial resolution parameterization in DIFI. At mid-latitudes, residuals are smaller, with similar mean and RMS values for both the inversion and validation datasets. Another likely contributor to the larger residuals at some validation observatories is lower data quality. The four validation observatories with the largest RMS residuals in the polar component are PPT (Pamatai), TIR (Tirunelveli), PND (Pondicherry), and NGP (Nagpur). All four also exhibit large mean residuals, suggesting possible baseline issues. A closer

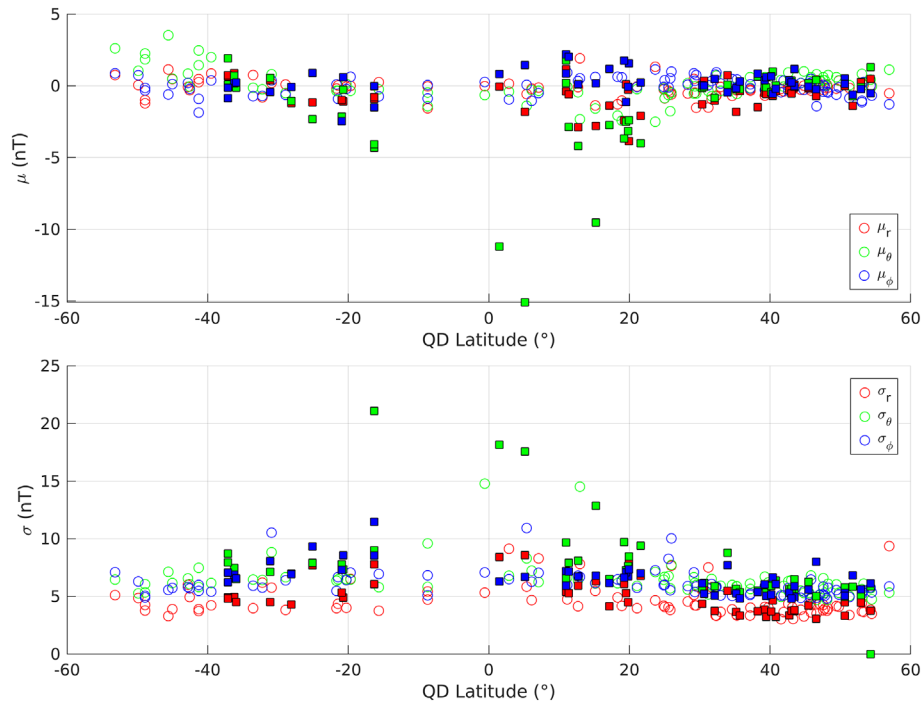


Figure 2. Mean (top) and root-mean-square (bottom) residuals for observatories used in building (circles) and validating (filled squares) the DIFI-8 model, shown as a function of quasi-dipole latitude. Residuals are provided for the radial (red), polar (green), and azimuthal (blue) magnetic field components at each observatory.

inspection of data and logs from PPT reveals gradual baseline shifts, likely caused by nearby construction activities beginning around 2017. The pre-processing applied to the validation observatory data (identical to that used for the inversion observatory data) cannot correct for such baseline discontinuities, since it removes a baseline calculated over the entire data period. This explains the observed increase in mean residuals. Excluding these four observatories from the validation dataset reduces the mean and RMS residuals for the polar component to -0.49 nT and 6.70 nT, respectively.

The stream function for the equivalent ionospheric sheet current density, defined on a sphere of radius $r = a + h$, where $a = 6371.2$ km is the reference Earth radius and $h = 110$ km, can be directly derived from the DIFI model coefficients (Sabaka et al., 2002; Chulliat et al., 2016). Here, sheet current density refers to the electric current per unit area in a thin ionospheric layer; since the layer is assumed to be infinitely thin, it is effectively the electric current per unit length. The stream function is a scalar field whose contours represent the flow of horizontal currents, and the sheet current density is obtained as the perpendicular gradient of this stream function. The stream function is expressed in amperes (A) or kiloamperes (kA).

Figure 3 shows the stream function for the DIFI-8 model on April 1 at four different UTs. Additional maps for all seasons (January 1, April 1, July 1, and October 1) are provided in the Supplementary Material (Figs. S1–S4). The stream functions from DIFI-8 closely resemble those from DIFI-2015b (Chulliat et al., 2016) and subsequent versions of the DIFI model (see maps at the University of Colorado website listed in the Data Availability section). A small but noticeable difference is that the nightside stream function, which is generally weak, shows

positive values (“yellow”) over larger areas compared to DIFI-2015b. However, the overall consistency between these models indicates that the inclusion of additional Swarm data has not led to major changes in the model.

The total current intensity flowing between the Sq foci, the locations of maximum and minimum horizontal ionospheric currents in the Northern and Southern Hemispheres, is calculated as the total current (in amperes) between these points, obtained from the difference between the maximum and minimum stream function values at the foci. As shown in Figure 4, where the F10.7 index is arbitrarily fixed at 100 SFU, this intensity varies significantly with UT and season. Here, UT can be seen as a proxy for the geographic longitude where the largest current densities occur. While the magnitudes and UT variations of the total current intensity are roughly similar at the spring (April 1) and fall (October 1) equinoxes, they differ markedly during northern summer (July 1) and northern winter (January 1). In both summer and winter, the total current is consistently lower than in spring and fall, reaching much lower values at UT = 22:00 over the Pacific Ocean and at UT = 07:00 over the Asia/Indian Ocean region, respectively. During winter, however, the total current increases sharply around UT = 18:00 in the American sector, exceeding the peak values observed in summer at UT = 12:00 over Europe and Africa. This wintertime surge is a consistent feature across different versions of the DIFI-8 model (as well as the xDIFI-2 model; see next section) and occurs predominantly in the Northern Hemisphere (see Figs. S1 and S9, and Chulliat et al., 2016). It coincides with a pronounced southward bend of the dip equator in the American sector. The toroidal field corrections applied to the satellite data in the DIFI-8a (DIFI-8) model result in slightly lower current

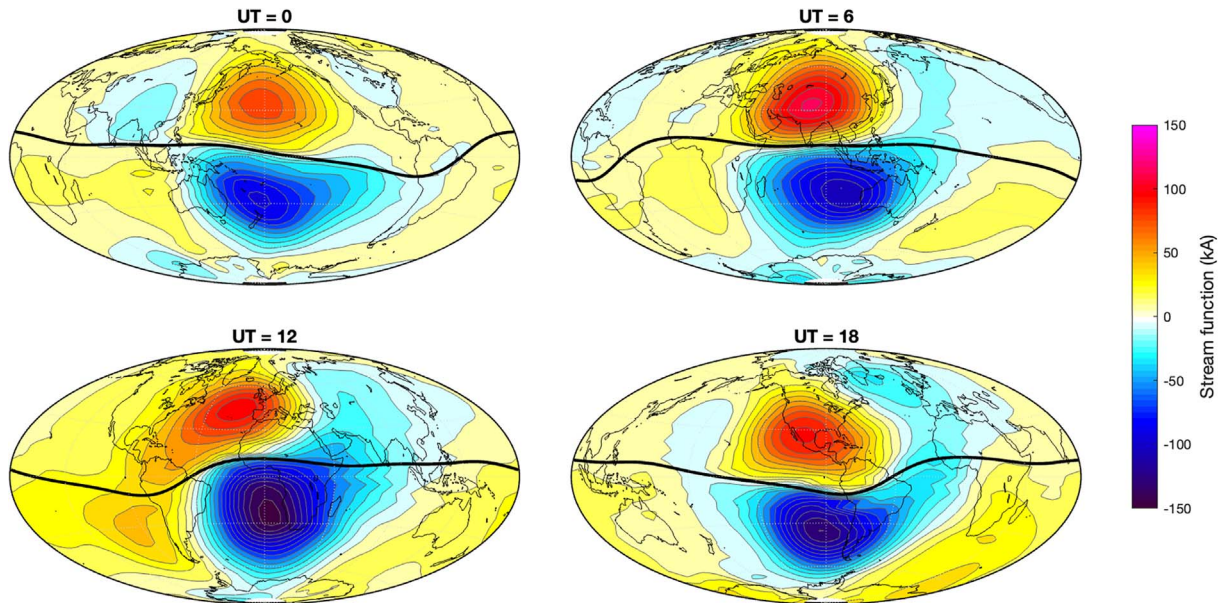


Figure 3. Stream function representing the equivalent sheet current density associated with the primary magnetic field from the DIFI-8 model on April 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 solar flux units (SFU).

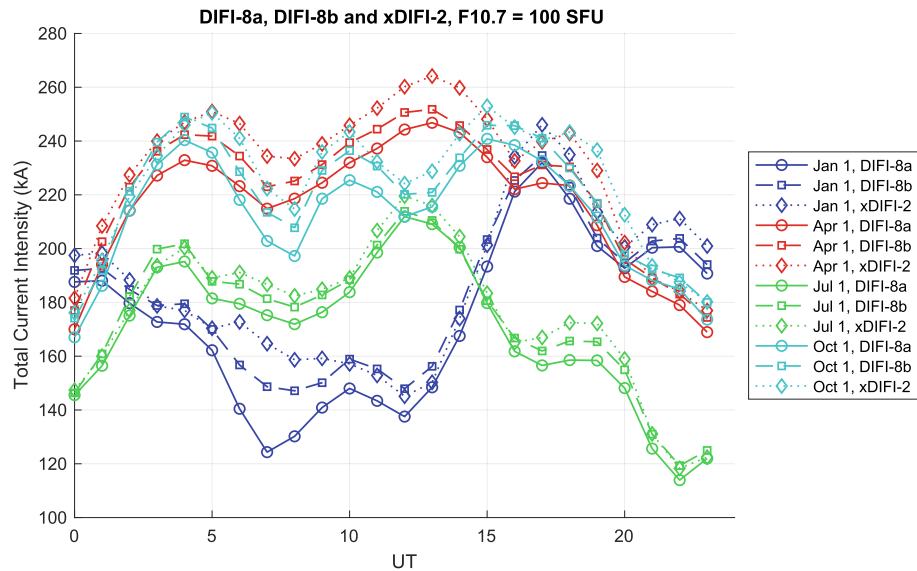


Figure 4. Total current intensity (in kA) flowing between the Sq foci in the Northern and Southern Hemispheres as a function of UT and season, based on the DIFI-8 (also referred to as DIFI-8a), DIFI-8b, and xDIFI-2 models. The F10.7 is fixed at 100 SFU.

intensities (by approximately 5–10% on average) at all UTs and seasons compared to DIFI-8b.

4 xDIFI-2 Model

Starting in 2022, the DIFI methodology was used to create models that extend the time interval of the Swarm mission using non-Swarm satellite data. These models are referred to as “Extended DIFI” or “xDIFI” models. The first such model,

xDIFI-1 (ESA product SW_OPER_MIO_SHA_2D, version 0702), was based on a combination of Swarm, CHAMP, and observatory data from January 1, 2001, to June 30, 2021. In this section, we introduce a new iteration incorporating more recent Swarm data: xDIFI-2 (ESA product SW_OPER_MIO_SHA_2D, version 0902). xDIFI models are available from the same websites as the standard DIFI models (see [Data Availability section](#)).

xDIFI-2 was constructed using the following extended dataset:

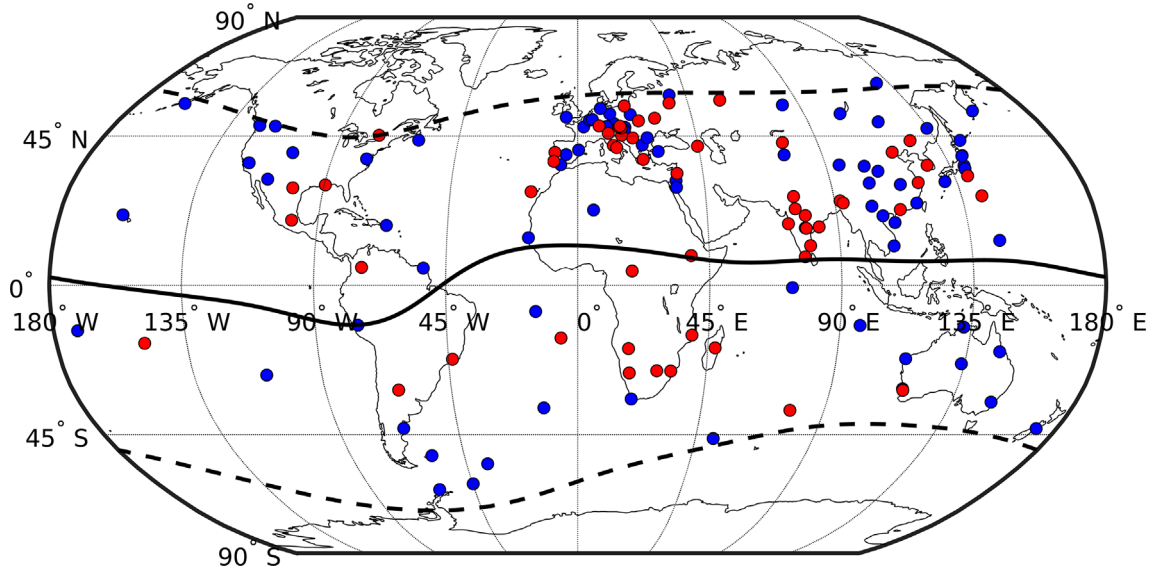


Figure 5. Map showing the locations of the observatories used for building (blue dots) and validating (red dots) the xDIFI-2 model. Quasi-dipole latitudes of $\pm 55^\circ$ are indicated by black dashed lines, and the magnetic dip equator is shown as a thick black line. Quasi-dipole latitudes are calculated for the year 2012.

- Swarm Alpha and Bravo satellite vector data: Level 1b MAGx_LR (1 Hz) data, baseline 0602/0603, covering the period from January 1, 2014, to December 31, 2023 (the same data used for DIFI-8).
- CHAMP satellite vector data: L3 baseline data (Rother et al., 2019), spanning January 1, 2001, to December 31, 2009.
- Magnetic observatory data: Definitive and quasi-definitive hourly mean magnetic field measurements from selected observatories, covering the period from January 1, 2001, to December 31, 2023. This includes the same observatory data used for DIFI-8 between January 1, 2014, and December 31, 2023. The data were quality-controlled, pre-processed, and distributed by the British Geological Survey as part of the same “SW_OPER_AUX_OBS” Swarm data product used for DIFI-8.

The locations of the observatories used in xDIFI-2 are shown in Figure 5.

Swarm satellite data used in xDIFI-2 were selected and corrected using the same criteria and models as those applied in DIFI-8 (cf. Section 3). CHAMP satellite data (identical to those used in the production of the previously released xDIFI-1 version) were selected using the same geomagnetically quiet period criteria as the Swarm data and were corrected for core and magnetospheric fields using version 7.8 of the CHAOS-7 model. The core field and its secular variation were truncated at spherical harmonic degree and order 15. The MF7 model was used (starting from degree and order 16) to correct for the lithospheric field. No toroidal field corrections were applied to either the Swarm or CHAMP data in order to maintain consistency in pre-processing throughout the model’s period, as the model of Fillion et al. (2023) cannot be straightforwardly applied to CHAMP data. Additional track-by-track corrections and filtering were applied following Chulliat et al. (2016).

Observatory data were pre-processed in the same manner as for DIFI-8.

Table 2 presents the xDIFI-2 data residuals (within quasi-dipole latitudes of $\pm 55^\circ$) for all categories of data used in the inversion, as well as for a validation dataset comprising observatory data that were not included in the inversion. The mean and RMS residuals for Swarm Alpha and Bravo are nearly identical to those for the DIFI-8b model (which excludes toroidal field corrections; see Table 1), suggesting that the inclusion of nine additional years of satellite data and thirteen additional years of observatory data did not significantly affect model quality during the Swarm era. (The small differences in the number of Swarm data points between DIFI-8 and xDIFI-2 are due to the inadvertent removal of one day of Swarm data from the xDIFI-2 dataset, as well as subtle differences in the implementation of the decimation process.) However, the mean and RMS residuals for CHAMP are somewhat systematically larger than those for Swarm. This difference, despite identical preprocessing, corrections, and nearly identical magnetometer data quality, is likely due in part to the greater weighting of Swarm data in the model, as it includes two Swarm satellites (with nearly four times more data in total) compared to the single CHAMP satellite. Another contributing factor may be the less homogeneous local time coverage of the CHAMP mission, resulting from its slower drift in local time and the presence of only one satellite. Finally, temporal changes in the ionospheric field over the two decades covered by the xDIFI-2 dataset may also play a role in this difference.

The RMS observatory residuals in xDIFI-2 (Table 2) are larger than those in DIFI-8a and DIFI-8b (Table 1) for all components. While mean observatory residuals differ slightly, they are not noticeably larger or smaller, except perhaps for the polar component in the validation dataset. This likely reflects the greater heterogeneity in the quality of observatory datasets compared to satellite datasets, especially in the validation

Table 2. xDIFI-2 model mean (μ) and root-mean-square (σ) residuals, and number of data points (N), for Swarm Alpha, Swarm Bravo, and CHAMP satellite data (within quasi-dipole latitudes of $\pm 55^\circ$), as well as observatory data used in the inversion and validation. Residuals are provided for the radial (r), polar (θ), and azimuthal (ϕ) components of the magnetic field. For satellite data, residuals are computed only in the domain of validity, defined by quasi-dipole latitudes within $\pm 55^\circ$.

	N	μ_r (nT)	σ_r (nT)	μ_θ (nT)	σ_θ (nT)	μ_ϕ (nT)	σ_ϕ (nT)
xDIFI-2							
All Satellites	907,837	0.05	3.83	0.57	5.06	-0.09	9.07
Alpha	366,274	0.01	3.58	0.45	4.75	-0.22	8.92
Bravo	352,430	-0.08	3.44	0.49	4.64	-0.17	8.70
CHAMP	189,133	0.35	4.83	0.99	6.26	0.30	9.98
Obs. Inversion	1,989,266	-0.08	5.99	0.12	6.87	-0.07	6.60
Obs. Validation	2,831,118	-0.39	6.72	-1.32	9.75	0.03	8.53

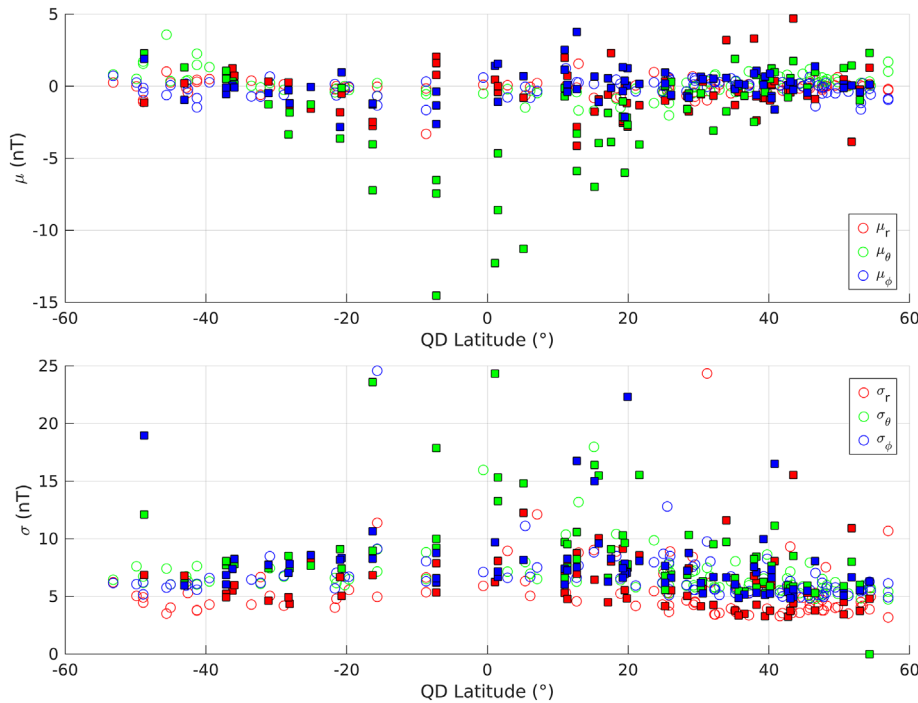


Figure 6. Mean (top) and root-mean-square (bottom) residuals for observatories used in building (circles) and validating (filled squares) the xDIFI-2 model, shown as a function of quasi-dipole latitude. Residuals are provided for the radial (red), polar (green), and azimuthal (blue) magnetic field components at each observatory.

dataset, where less stringent observatory selection criteria were applied. The quality of observatory data is generally believed to have improved in the years leading up to the Swarm mission (e.g., Chulliat et al., 2017), which may explain the larger RMS residuals when including observatories from the early 2000s. The limited impact of older observatory data on mean residuals may be attributed to the consistent removal of static magnetic fields from all observatory data using the same method.

The differences between RMS residuals of the inversion and validation observatory datasets are larger for xDIFI-2 (Table 2) than for DIFI-8 (a or b; see Table 1). As shown in Figure 6, most of these differences are driven by a small number of validation observatories located at low QD latitudes. As in Figure 2, this effect is most pronounced for the polar component. As with DIFI-8, unmodeled EEJ contributions and lower

data quality at certain observatories are likely the main causes. The latter may be further amplified by the lower quality of some observatory data in the early 2000s.

As with DIFI-8, the stream function for the equivalent current density can be directly computed from the xDIFI-2 model coefficients. It is shown in Figure 7 at the same four UTs and season (April 1) as the DIFI-8 stream function in Figure 3. Additional maps for all seasons (January 1, April 1, July 1, and October 1) are provided in the Supplementary Material (Figs. S5–S8). These maps generally do not reveal any significant differences between the stream functions of DIFI-8 and xDIFI-2. The largest difference occurs in the Southern hemisphere on January 1 at UT = 06:00 (Figs. S1 and S5), where the currents are visibly more intense in xDIFI-2 than in DIFI-8. This observation is confirmed by Figures S9 and S11, which

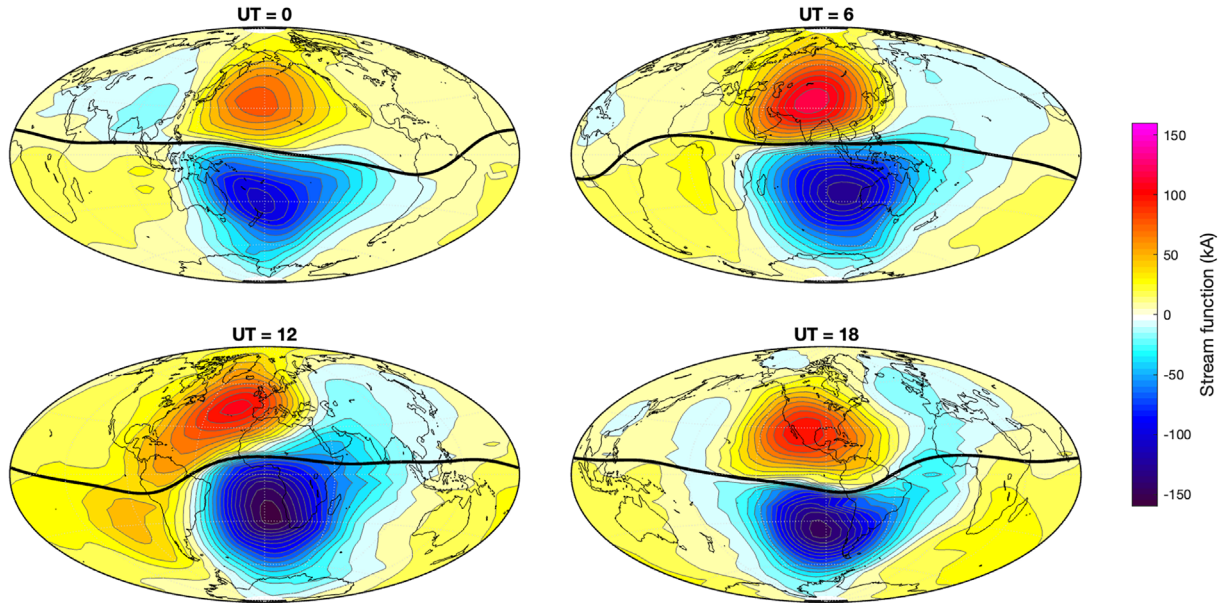


Figure 7. Stream function representing the equivalent sheet current density associated with the primary magnetic field from the xDIFI-2 model on April 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Table 3. Mean (μ) and root-mean-square (σ) residuals of the DIFI-8 model, and number of data points (N), for Swarm Alpha, Swarm Bravo, and CHAMP satellite data used in the inversion of xDIFI-2 (within quasi-dipole latitudes of $\pm 55^\circ$), as well as observatory data used in the inversion and validation of xDIFI-2. Residuals are provided for the radial (r), polar (θ), and azimuthal (ϕ) components of the magnetic field. For satellite data, residuals are computed only in the domain of validity, defined by quasi-dipole latitudes within $\pm 55^\circ$.

	N	μ_r (nT)	σ_r (nT)	μ_θ (nT)	σ_θ (nT)	μ_ϕ (nT)	σ_ϕ (nT)
DIFI-8							
All Satellites (xDIFI-2)	907,837	0.05	3.83	0.61	5.12	-0.10	9.07
Alpha (xDIFI-2)	366,274	0.02	3.56	0.48	4.80	-0.22	8.93
Bravo (xDIFI-2)	352,430	-0.08	3.43	0.52	4.70	-0.18	8.70
CHAMP (xDIFI-2)	189,133	0.36	4.88	1.01	6.32	0.30	9.98
Obs. Inversion (xDIFI-2)	1,989,266	-0.14	6.06	0.14	7.00	-0.10	6.69
Obs. Validation (xDIFI-2)	2,831,118	-0.42	6.66	-1.66	9.87	-0.03	8.58

show maximum primary stream functions in each hemisphere as a function of UT. Overall, the two models are in close agreement.

It is therefore unsurprising that the overall characteristics of the total current intensity as a function of UT and season in xDIFI-2 closely resemble those in DIFI-8 (see Fig. 4). In particular, the wintertime surge of total current when the American sector is sunlit remains consistent with that observed in DIFI-8 (and DIFI-8b). The primary difference is a 5–10% increase in total current intensity in xDIFI-2 compared to DIFI-8, mostly during equinoxes. This increase is likely due, at least in part, to the absence of toroidal field corrections in xDIFI-2, similar to DIFI-8b, which also shows larger current intensities than DIFI-8. Slightly larger differences between DIFI-8 and xDIFI-2 than between DIFI-8 and DIFI-8b are observed for certain UTs and seasons, especially in spring (April 1); the reason for these differences remains unknown.

5 Discussion

The two models presented in this study, DIFI-8 and xDIFI-2, are quite similar, despite xDIFI-2 incorporating an additional thirteen years of satellite and ground-based observatory data. DIFI-8 covers a 10-year period, slightly shorter than a full 11-year solar cycle, whereas xDIFI-2 spans 23 years, covering approximately two full solar cycles. The close agreement between the models indicates that the DIFI parameterization is robust across multiple solar cycles, even when those cycles vary significantly in solar activity. For example, the sunspot number exceeded 200 early in the xDIFI-2 interval, while it barely exceeded 150 during the DIFI-8 interval (Clette & Lefèvre, 2015). This consistency suggests that both models may be reliably applied beyond their respective temporal domains, potentially extending their applicability to one solar cycle before and after the original time intervals.

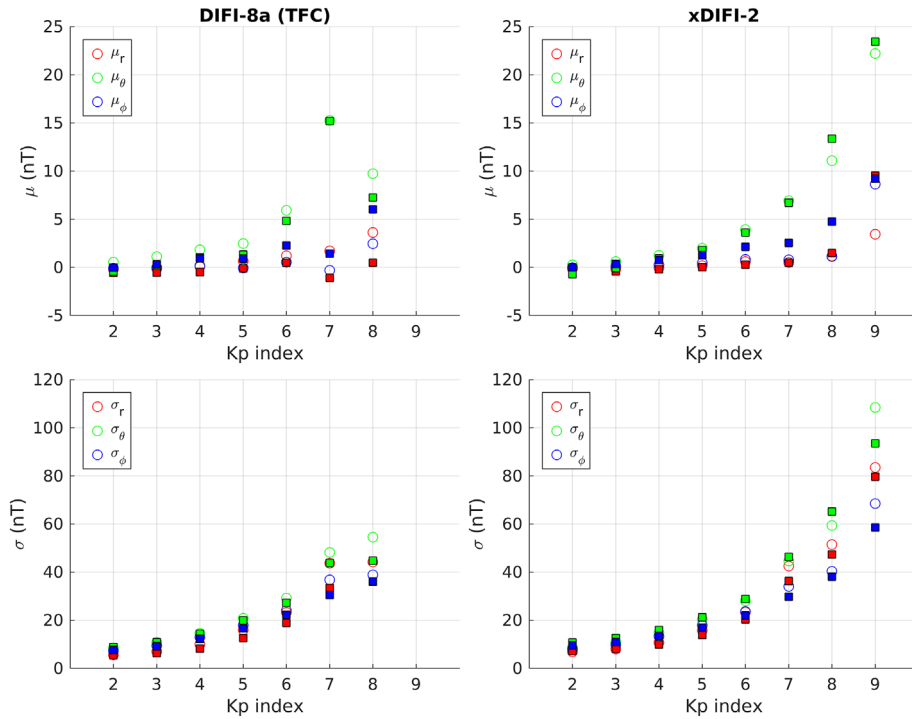


Figure 8. Mean (μ) and root-mean-square (σ) residuals (in nT) of the DIFI-8 and xDIFI-2 models as a function of the Kp index, for observatories used in building (circles) and validating (filled squares) each model. Residuals are shown for the radial (red), polar (green), and azimuthal (blue) magnetic field components.

To further test this idea, residual statistics for the DIFI-8 model were calculated using the same datasets used in the xDIFI-2 inversion and validation (within quasi-dipole latitudes of $\pm 55^\circ$), including the CHAMP data and observatory data outside the DIFI-8 domain of validity (2014–2023). As shown in Table 3, the DIFI-8 residuals with respect to the xDIFI-2 Swarm dataset are nearly identical to those of xDIFI-2 itself (Table 2), as well as to the DIFI-8b Swarm residuals (Table 1). This is expected, as Swarm data in the xDIFI-2 dataset are not corrected for toroidal fields. Surprisingly, the DIFI-8 residuals relative to the xDIFI-2 CHAMP dataset are also very close to the original xDIFI-2 CHAMP residuals. Differences remain below 1% for the RMS and 2% for the mean. Similarly, differences remain small for the xDIFI-2 inversion and validation observatory datasets, exceeding 2% for the polar component only. These results confirm that DIFI-8 can be applied with minimal error over the 13 years preceding its nominal domain of validity.

The results presented in Sections 3 and 4, as well as in the Supplementary Material, also confirm several findings from earlier versions of the DIFI models, including DIFI-2015b as described by Chulliat et al. (2016). These findings include:

- A local time shift between summer and winter current systems, observed in both hemispheres (Figs. S10 and S12).
- A seasonal asymmetry between spring and fall, particularly pronounced in the Southern Hemisphere (Figs. S9 and S11).
- Stronger Sq currents in the Southern Hemisphere during spring compared to the southern summer (which corresponds to northern winter) (Fig. S9).

- A significant influence of the main geomagnetic field, especially the bent dip equator in the American sector, on the strength and morphology of the Sq current system. A pronounced surge in total current intensity occurs over the American sector during northern winter, and this surge is entirely confined to the Northern Hemisphere (Figs. S9 and S11).
- A wave-4 structure in the longitudinal variation of total Sq current in the Southern Hemisphere (Figs. S9 and S11).

While the DIFI and xDIFI models are constructed using magnetic field measurements collected during geomagnetically quiet periods, they nevertheless incorporate a linear dependence on solar activity through the F10.7 index. This raises the question of whether these models can also be used during periods of moderate or even high geomagnetic activity. To investigate this, observatory residuals were calculated for DIFI-8 and xDIFI-2 during periods of elevated geomagnetic activity, defined by Kp indices ranging from 2 (including 2–, 2o, and 2+) to 9.

For each model, the same observatories as those described in Sections 3 and 4 were used, again divided into an inversion observatory set (used for model computation) and a validation observatory set (used for model validation only). However, in this case, the datasets were defined differently. Although the same model and empirical corrections were applied to the observatory data prior to residual calculation, no selection based on *Dst*, *IMF By*, or *IMF Bz* was applied, and no decimation was applied to the data from the inversion observatory set. Instead, all available data from all observatories were used. As a result, this analysis includes a significantly larger number of data

points from the inversion observatory set (2,578,407 for DIFI-8 and 6,051,517 for xDIFI-2) compared to the validation set (1,070,954 for DIFI-8 and 2,875,932 for xDIFI-2). As expected, the number of data points at each activity level decreases with increasing geomagnetic activity (see, e.g., the statistics provided by the NOAA Space Weather Prediction Center¹). For example, for DIFI-8, there are 1,849,964 data points for $Kp = 2$ and 3,105 for $Kp = 8$. (There was no data point for $Kp = 9$ during the DIFI-8 period of validity.) For xDIFI-2, the corresponding numbers are 4,307, 475 for $Kp = 2$ and 4,415 for $Kp = 9$.

The results show that the mean and RMS residuals for both observatory datasets and both models increase with the Kp index, as shown in Figure 8. The increases are relatively modest for moderate activity ($Kp = 3$ –4): mean residuals remain below 3 nT in absolute value, and RMS residuals remain below 20 nT, compared with the typical amplitude of the Sq magnetic field, which is 20–50 nT at mid-latitudes. However, residuals become substantially larger during periods of high geomagnetic activity. This is likely due to a combination of factors: the low temporal resolution of the F10.7 index (daily), which limits its ability to capture rapid variations during geomagnetic storms; increased errors in the magnetospheric field model used to correct the observatory data; and increased intrinsic modeling error in DIFI-8 and xDIFI-2 due to rapid changes in the morphology and amplitude of the Sq and EEJ current systems. The latter could be related to the leakage of high-latitude DP2 electric fields into lower latitudes, which is known to have a significant impact on mid- and low-latitude ionospheric currents (Yamazaki et al., 2016). At some observatories, especially those near the coasts, local induction effects (e.g., Olsen & Kuvshinov, 2004) not captured by the laterally variable conductivity model used in DIFI-8 and xDIFI-2 may also contribute to the error. The results for the DIFI-8 and xDIFI-2 models are generally in good agreement, with differences becoming more noticeable for larger Kp values. This is likely due to the much smaller data samples for higher Kp values (approximately two orders of magnitude smaller between $Kp = 4$ and 8), which magnifies the effects of observatories with lower quality data during geomagnetic storms. This also leads to larger discrepancies between residuals for inversion and validation observatories.

6 Conclusion and perspectives

This paper presents two new models of non-polar geomagnetic daily variations developed using the DIFI methodology. The first model, DIFI-8, is based on ten years of Swarm satellite data (2014–2023) and selected ground-based observatory data from the same period. Unlike previous versions of DIFI, the Swarm data used in constructing DIFI-8 were corrected for toroidal magnetic fields using the model of Fillion et al. (2023). The second model, xDIFI-2, includes the same datasets, supplemented with CHAMP satellite data from 2001 to 2009 and additional ground-based observatory data from 2001 to 2013; however, it does not incorporate any toroidal magnetic field correction. Both models were thoroughly tested and validated using extensive, independent ground-based observatory datasets. The largest errors were observed at low latitudes,

likely due to unmodeled, higher-resolution spatial variations associated with the Equatorial Electrojet.

Despite differences in their construction, the main features of the DIFI-8 and xDIFI-2 models remain consistent with those of previous DIFI and xDIFI versions. In particular, the surge in total current intensity over the American sector during northern winter, coinciding with the bent dip equator, and the wave-4 structure in the longitudinal variation of the total Sq current in the Southern hemisphere are robust features observed across all DIFI and xDIFI models. This consistency, spanning over two solar cycles, suggests that the DIFI and xDIFI models may be applicable beyond their nominal periods of validity, potentially extending to one solar cycle before and after their defined timeframes. Although DIFI and xDIFI are based on quiet-time magnetometer measurements, they have demonstrated reasonable performance, with only modest increases in error, during periods of moderate geomagnetic activity ($Kp \leq 4$). However, during periods of high geomagnetic activity, errors are expected to be significantly larger, though some of these may be attributable to inaccuracies in other models (e.g., magnetospheric models) used in the data correction process.

DIFI and xDIFI models can be used to correct for external magnetic field variations in a wide range of applications, including satellite data processing, geomagnetic field modeling, marine and aeromagnetic survey data analysis, and magnetic field-based navigation (MagNav). As such, they are valuable tools alongside other geomagnetic field models. Future research could focus on enhancing model performance at low latitudes by increasing spatial resolution to better capture small-scale variations associated with the EEJ. Another promising direction involves integrating DIFI and xDIFI with models of high-latitude geomagnetic variations, enabling the development of more comprehensive global models of external field variations.

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Data availability statement

The data used in this research are available from the following sources: Swarm and observatory data from <https://swarm-diss.esa.int>; F10.7 data from <ftp://swarm-diss.esa.int> (account required); CHAMP data from <ftp://isdftp.gfz-potsdam.de/champ/ME/Level3/MAG/>;

¹ <https://www.swpc.noaa.gov/noaa-scales-explanation>.

the Kp index from <https://kp.gfz.de/en/data>; the Dst index from <https://wdc.kugi.kyoto-u.ac.jp/dstdir/>; and IMF data from https://spdf.gsfc.nasa.gov/pub/data/omni/omni_cdaweb/hourly/. The MF7 model is available at <https://geomag.colorado.edu/magnetic-field-model-mf7> and the CHAOS-7 model at <https://www.spacecenter.dk/files/magnetic-models/CHAOS-7/>. The DIFI and xDIFI models are available at <https://geomag.colorado.edu/geomagnetic-and-electric-field-models> and <https://swarm-diss.esa.int>.

Supplementary material

Figure S1: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the DIFI-8 model on January 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 solar flux units (SFU).

Figure S2: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the DIFI-8 model on April 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S3: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the DIFI-8 model on July 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S4: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the DIFI-8 model on October 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S5: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the xDIFI-2 model on January 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S6: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the xDIFI-2 model on April 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S7: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the xDIFI-2 model on July 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S8: Stream function representing the equivalent sheet current density associated with the primary magnetic field from the xDIFI-2 model on October 1 at UT = 00:00, 06:00, 12:00, and 18:00. A current of 10 kA flows between adjacent contours. The dip equator is indicated by a thick black line. Each map is centered on

the subsolar point at the corresponding UT. The F10.7 is arbitrarily fixed at 100 SFU.

Figure S9: Evolution with Universal Time (UT) and season of the maximum absolute value of the DIFI-8 primary stream function in the Northern (N) and Southern (S) hemispheres. These maxima represent the total currents (in kA) flowing in the dayside vortex for each hemisphere. The F10.7 solar flux is arbitrarily fixed at 100 SFU.

Figure S10: Evolution with Universal Time (UT) and season of the difference between the local time (LT) of the DIFI-8 current system focus (defined as the point where the stream function reaches its maximum absolute value) and local noon in each hemisphere. A positive value indicates that the current system trails the noon meridian, while a negative value indicates it leads. The F10.7 solar flux is arbitrarily fixed at 100 SFU.

Figure S11: Evolution with Universal Time (UT) and season of the maximum absolute value of the xDIFI-2 primary stream function in the Northern (N) and Southern (S) hemispheres. These maxima represent the total currents (in kA) flowing in the dayside vortex for each hemisphere. The F10.7 solar flux is arbitrarily fixed at 100 SFU.

Figure S12: Evolution with Universal Time (UT) and season of the difference between the local time (LT) of the xDIFI-2 current system focus (defined as the point where the stream function reaches its maximum absolute value) and local noon in each hemisphere. A positive value indicates that the current system trails the noon meridian, while a negative value indicates it leads. The F10.7 solar flux is arbitrarily fixed at 100 SFU.

The supplementary materials of this article are available at <https://www.swsc-journal.org/10.1051/swsc/2025041/olm>.

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