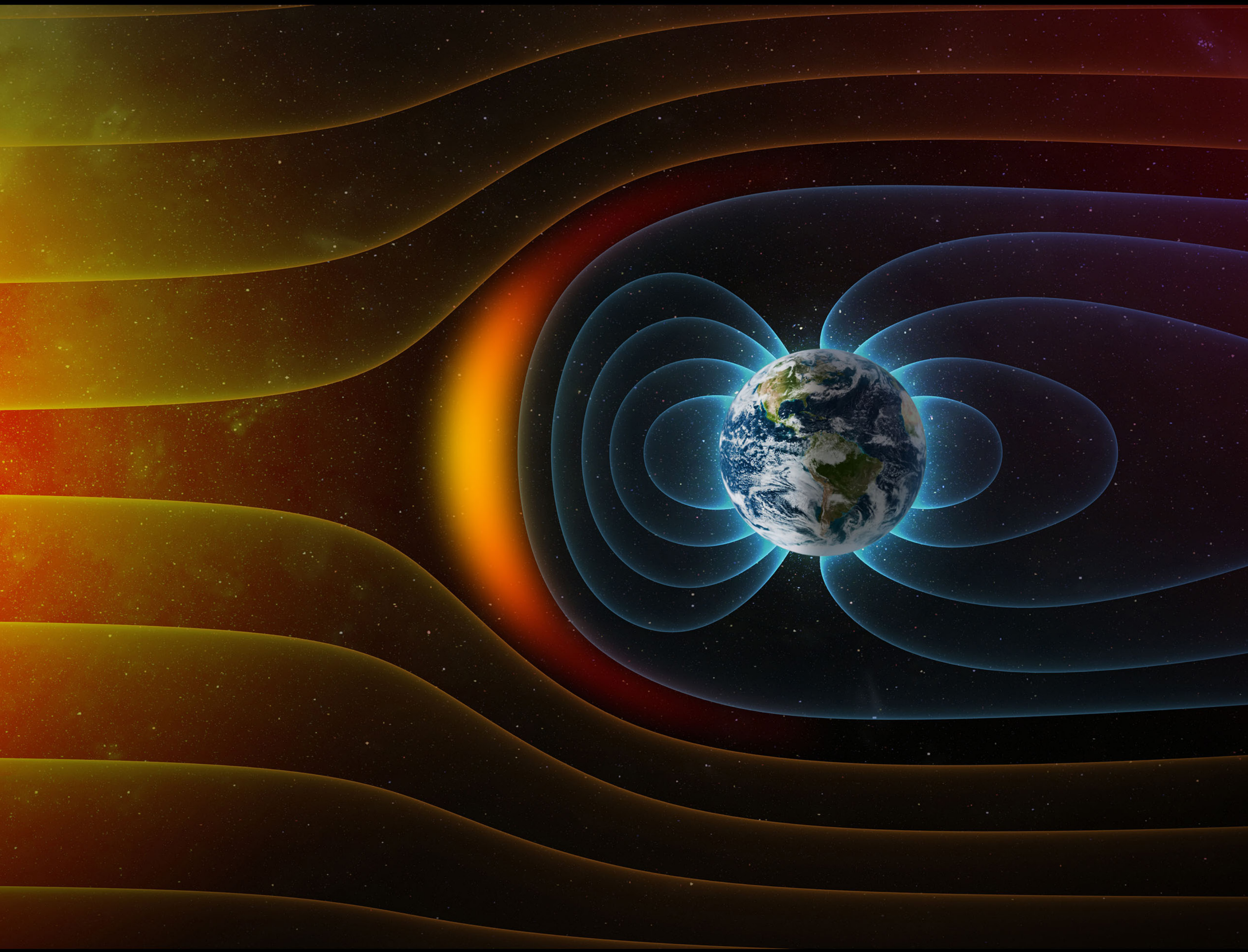
December
2022

STATE OF THE GEOMAGNETIC FIELD



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CONTENTS

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Summary

The performance of the World Magnetic Model 2020 (WMM2020) was assessed by comparing its predictions on January 1, 2023 with that of a more recent model inferred from data collected by the European Space Agency (ESA) Swarm satellites from November 2013 until September 2022. For all magnetic field components, the WMM2020 global root-mean-square error increased by less than 5% over the past three years and remained well below the maximum error allowed by the U.S. Department of Defense WMM specification. In addition, the WMM2020 secular variation was again deemed an accurate approximation of the actual secular variation observed at ground-based observatories and Swarm-based geomagnetic virtual observatories in 2021 and 2022. This suggests that nonlinear changes in the Earth's magnetic field have remained small over the past three years. Since 2020, the north magnetic dip pole has moved at an average speed of 43 km/yr, and the south magnetic dip pole at 9 km/yr. Neither underwent any noticeable change in direction. These movements led to minor changes in the shape and location of the WMM blackout zones, where compass accuracy is reduced. The South Atlantic Anomaly, where the geomagnetic field intensity is smallest, continued to deepen (by about 80 nT at sea level) and move westwards (its center moved by about 70 km at sea level). Over the past year, three strong to severe geomagnetic storms occurred; these storms led to significant but temporary effects on WMM performance, mostly at high geomagnetic latitudes.

Introduction

The World Magnetic Model (WMM) is a spherical harmonic model of the Earth's main magnetic field and its slow temporal change. It is jointly developed by the National Centers for Environmental Information (NCEI) and the British Geological Survey (BGS) and is a joint product of the United States' National Geospatial-Intelligence Agency (NGA) and the United Kingdom's Defence Geographic Centre (DGC). The WMM is the standard model used by the U.S. and U.K. governments as well as international organizations (e.g., the North Atlantic Treaty Organization and the International Hydrographic Organization) for navigation, attitude and heading referencing systems that make use of the geomagnetic field. It is also used widely in navigation and heading systems unaffiliated with the government.

The main geomagnetic field is constantly changing due to convection flows and waves in the Earth's core. As this change cannot entirely be predicted, the accuracy of the WMM slowly decreases over time, necessitating that it be regularly updated (typically every five years). This report reviews the performance of the latest WMM (released in December 2019 and referred to as WMM2020), verifies that it still meets specification MIL-PRF-89500B (U.S. Department of Defense, 2019) on January 1, 2023 (2023.0 hereafter), and provides an assessment of its secular variation after three years. The previous assessment was undertaken in December 2021 (Chulliat *et al.*, 2021). This report also includes a description of noteworthy changes in the Earth's main magnetic field since WMM2020's release, including continued magnetic pole drifts and the further deepening of the South Atlantic anomaly in the geomagnetic field intensity. A new section in this report summarizes solar cycle progression and estimates effects on WMM performance during magnetic storms.

WMM Performance: Model Errors at 2023.0

The performance of WMM2020 was assessed at epoch 2023.0 by comparing it with a more recent model derived from satellite magnetometer data. This data was collected by the ESA Swarm tri-satellite constellation from November 2013 until September 2022. (See the Appendix for more information on the Swarm model). The WMM global root-mean-square error (RMSE) for each component was obtained by adding in quadrature the omission error, associated with magnetic fields not included in the WMM (e.g., crustal and disturbance magnetic fields), and the commission error, which includes both the modeling error and the secular variation forecasting error. A full description of the WMM RMSE estimation methodology can be found in the WMM2020 technical report (Chulliat *et al.*, 2020; WMM2020-TR hereafter). Areas where the horizontal component is smaller than 2000 nT (Blackout Zones) were excluded from the declination and grid variation error calculations.

Table 1 is an update of Table 15 in WMM2020-TR, where the global RMSE for each magnetic field component was calculated at epoch 2023.0 using the Swarm-based model described above (row 3). For all components, the errors at 2023.0 are well below the maximum errors allowed by the WMM military specification (row 1). These errors are also much closer to those at the beginning (row 2) of the WMM2020 five-year cycle than to the forecast errors at the end (row 4) of that cycle, suggesting that the differences between the WMM2020-predicted and the actual secular variations were small over the past three years. Errors at 2023.0 are also in broad agreement with the WMM error model (row 5), which was built from estimated average errors over the five-year cycle and considers geometrical relationships between the components and the fact that the declination error goes to infinity at the magnetic poles.

Row		H (nT)	F (nT)	I (°)	D (°)	GVN (°)	GVS (°)
1	Military Specification MIL-W-89500B	200	280	1.00	1.00	1.00	1.00
2	Global RMSE at 2020.0	126	129	0.20	0.37	0.67	0.67
3	Global RMSE at 2023.0	128	132	0.21	0.38	0.68	0.67
4	Global RMSE at 2025.0 (forecast)	134	144	0.23	0.42	0.83	0.70
5	Error Model	128	145	0.21	$\delta D = \sqrt{(0.26)^2 + (5625/H)^2}$		

Table 1: *Estimated WMM2020 global RMSEs at 2020.0, 2023.0 and 2025.0, vs. the maximum global RMSEs allowed by the WMM military specification. H is the horizontal intensity, F the total intensity, I the inclination angle, D the declination angle, GV_N the grid variation north, and GV_S the grid variation south. The error at 2025.0 is a forecast error based on the error during previous WMM five-year cycles. WMM error model values are provided in the last row. Full descriptions of the components, the WMM uncertainty estimation methodology, and the WMM error model are available in the WMM2020-TR.*

As can be seen in **Table 1**, grid variation north (GV_N) is the component with the largest relative increase of its RMSE over the WMM cycle. GV_N is defined as the difference between magnetic declination and longitude above 55°N latitude, and its error is the same as that of declination above 55°N. GV_N has the largest error because (a) the declination omission error at high latitudes is larger than at lower latitudes due to more intense disturbance magnetic fields, and (b) the geomagnetic secular variation is largest for the declination in the northern polar cap due to the fast north magnetic pole drift (see "Magnetic Poles" section below). **Figure 1** shows how the GVN RMSE evolved over the current and past four WMM cycles. The error was minimal at the beginning of each cycle and increased until a new model was released, reflecting the increase in secular variation forecasting error as time advances (hence the "sawtooth" shape of this diagram). Compared to errors three years into previous cycles, the error at 2023.0 is the smallest. This suggests that the GVN error is unlikely to exceed the specification before the end of the current five-year cycle.

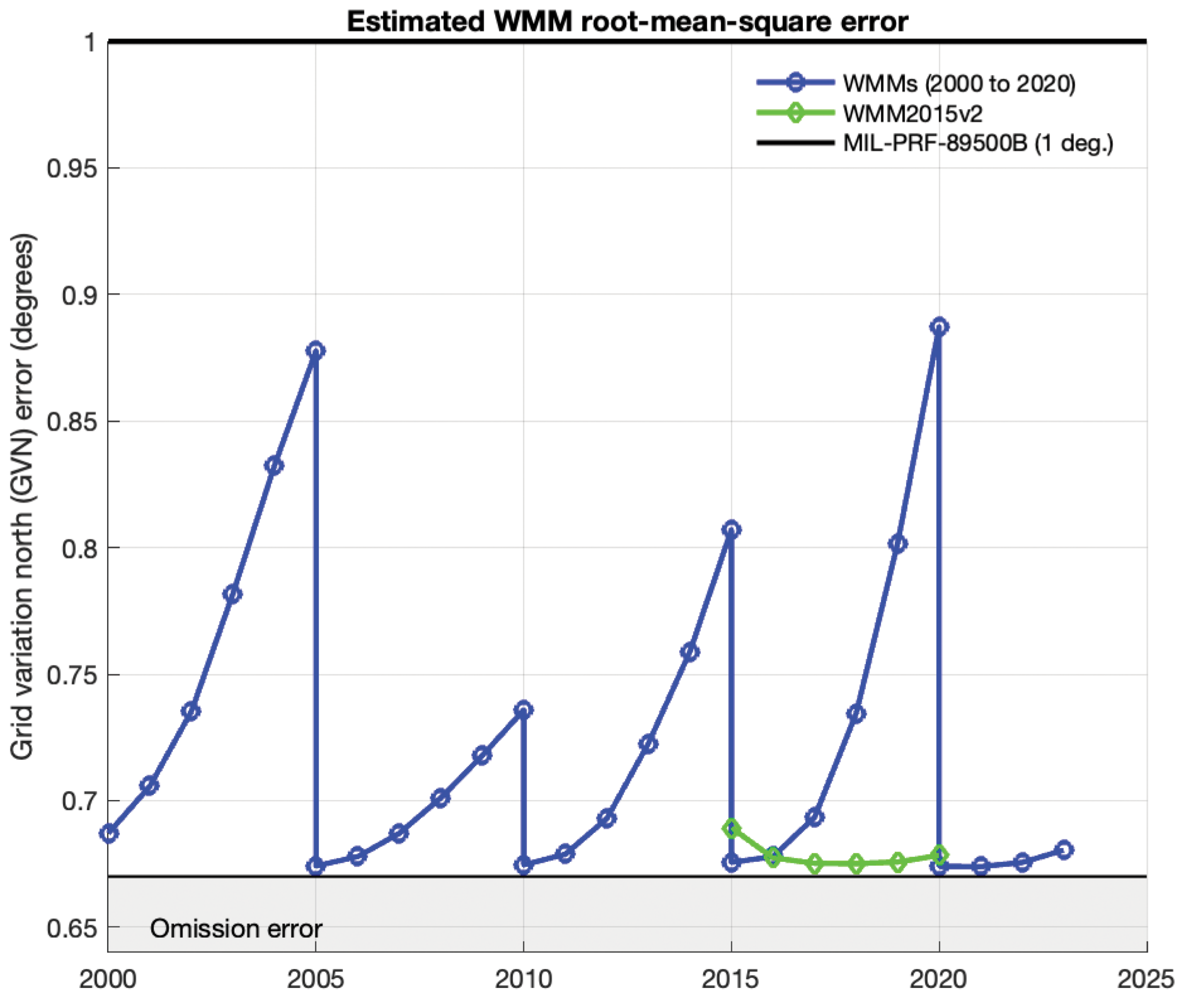

Figure 1: *WMM global RMSE for the grid variation north (GVN) component from 2000 to 2023. Errors for six successive WMMs are shown: WMM2000, WMM2005, WMM2010, WMM2015, WMM2015v2, and WMM2020. WMM2015v2 was an out-of-cycle WMM released in late 2018 in case WMM2015 were to breach the specification before the end of the cycle. (The specification was revised in 2019 with the introduction of so-called blackout zones, see below; blackout zones are no longer considered in WMM error calculations.)*

WMM Performance: Secular Variation Assessment

The WMM2020 secular variation (SV) was assessed by comparing it to independent SV estimates for 2020, 2021, and 2022 provided by (a) ground magnetic observatories (at Earth's surface) and (b) geomagnetic virtual observatories (at 490 km altitude). The methods for processing each type of data and calculating RMSEs between observed and WMM2020-predicted SV are described in the Appendix.

Geomagnetic virtual observatories (GVO) are produced from observations collected by low-Earth-orbit satellites, in this case those from the ESA Swarm mission. Data are collected over one month in 700 km diameter cylindrical bins that extend vertically to satellite altitude. The binned data are used to estimate a local cubic potential field for each bin, which is then used to estimate the field at the bin center. A time series of such point estimates can be built up month-by-month, across a grid of 300 equally spaced bins which cover the Earth's surface. GVO datasets are updated every four months by BGS, in collaboration with the Technical University of Denmark (DTU) for the ESA Swarm mission, as described in Hammer *et al.* (2021).

RMSEs between the predicted SV of WMM2020 and the observed SV (**Table 2**) are small and placed at the low end of expected values given the past 20 years of observations. There is an increase in RMSE from 2020 to 2022, which was expected given the divergence of the SV prediction from reality over the lifespan of the WMM. This behavior is seen when comparing WMM2020 to both ground and satellite observations of secular variation.

Ground observatories (at Earth's surface)						
Year	**dH (nT/yr)**	**dF (nT/yr)**	**dI (min/yr)**	**dD (min/yr)**	**dGV_N (min/yr)**	**dGV_S (min/yr)**
2020	7	7	1	1	2	1
2021	9	10	1	2	2	2
2022	11	13	1	2	2	1
Geomagnetic Virtual Observatories (at 490 km)						
2020	3	4	1	1	5	1
2021	5	6	1	1	5	1
2022	7	7	1	3	11	1

Table 2: *RMSEs between WMM2020 predictions of secular variation and annual differences of monthly mean ground observatory and monthly geomagnetic virtual observatory data. Values are given for all observations in a calendar year.*

It should be noted that RMSE values for 2022 are based on data available at the time of reporting, and that calculating secular variation backdates observations by half a year. Ground observatory data from a limited number of observatories with a limited geographic distribution were available, providing observed SV up to May 2022 at the latest. (Note that the 2021 values have been updated since the last report and now include data from the entire 2021 calendar year.) Geomagnetic virtual observatory data were available globally, providing observed SV up to February 2022. Also, due to the dependence of the magnetic field on distance from the field source, values at the Earth's surface are larger than at satellite altitudes.

RMSE at high northern latitudes (shown by GVN) are typically larger than those at high southern latitudes (shown by GVS), and larger than the changes seen in the global RMSE of other magnetic elements. This indicates the continuing change of the field at high northern latitudes, as observed by WMM2015 and WMM2015v2.

The mapped RMSE values for observatories generally show consistently greater values over time at high latitudes, where external field signals contaminate the data to a greater extent. The same can be said for more remote locations where observatory operation is often challenging. For ground observatories, the lowest values are typically seen in Europe and North America where dense coverage helps to constrain our models. For time periods when a wide geographic distribution of observations is available, larger RMSE values are seen in regions where the magnetic field is changing most rapidly, particularly where acceleration of the field is observed. Such rapid changes – accelerations in particular – are not captured by WMM2020 by design.

The mapped RMSE for geomagnetic virtual observatories (**Figure 2**) show a clearer spatial pattern than those of observatories, due to the former's greater density and regular geographic distribution. Higher RMSE values are seen over regions where the field is changing most rapidly, highlighting accelerations of the field over the South Atlantic Anomaly (SAA) and over central Asia, for example. Overall, these RMSE are small and accumulating slowly such that they do not cause concern for the accuracy of WMM2020 in its lifespan.

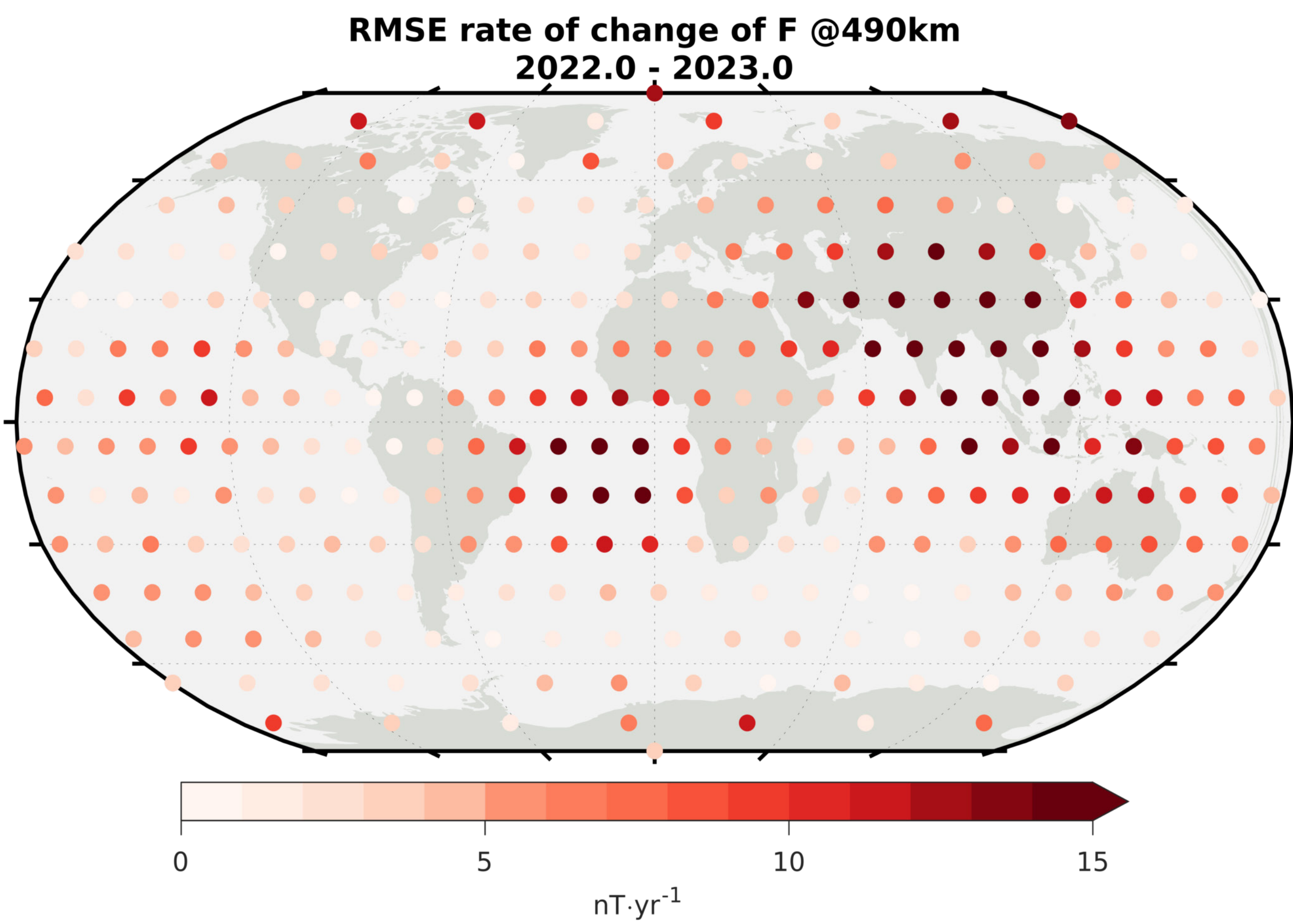

***Figure 2**: RMSE between prediction of WMM2020 SV of total intensity (F) and geomagnetic virtual observatory data in 2022.*

Examples of observations compared to WMM versions from 2000 to present highlight both the common occurrence and impact of field accelerations. At Honolulu (**Figure 3a**) we see evidence of jerks (the sharp changes in SV) in 2007, 2014, 2017, and likely in 2020 (Pavón-Carrasco *et al.*, 2021). While current RMSE at Honolulu is small, we may expect to see it grow in subsequent years if the recent trend of SV there continues. At Ascension Island in the South Atlantic where high RMSE in rate of change of F is seen in the satellite data (see **Figure 2**) we observed the continual deceleration of the field's intensity from approximately 2014 to 2022 (**Figure 3b**). The divergence seen from WMM2020 may continue, or may decrease if there are further occurrences of geomagnetic jerks. At Hyderabad, India (**Figure 3c**) we see an example of a region with some of the largest RMSE values in 2022 (see **Figure 2**). We see that the trend of SV since the 2017 jerk there has continued and is diverging from the WMM2020 SV prediction. As at Ascension, we cannot predict if this current diverging trend will continue through the lifespan of WMM2020. These trends were noted by Chulliat *et al.*, (2021) and have not altered in 2022.

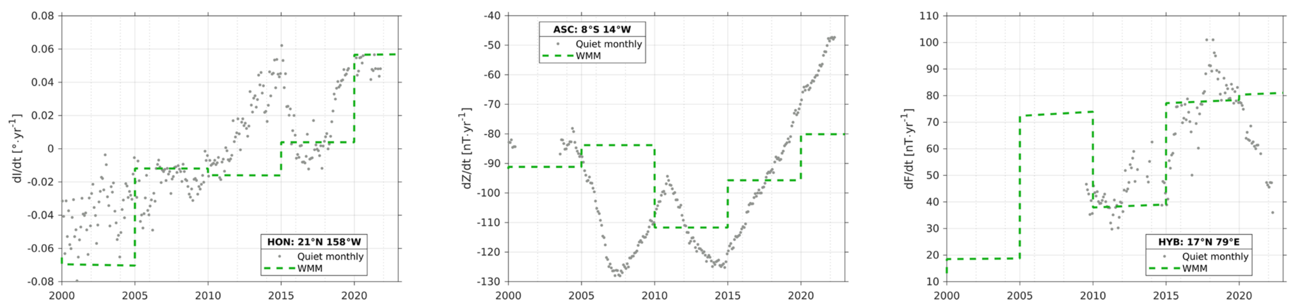

Figure 3: *Observed rate of change of (a) inclination angle in degrees (I) at Honolulu, Hawai'i, United States (HON), (b) vertical field (Z) in nT/year at Ascension Island, South Atlantic (ASC) and (c) field intensity (F) in nT/year at Hyderabad, India (HYB). Quiet-dark monthly mean data are shown as gray circles, WMM predictions (WMM2000, WMM2005, WMM2010, WMM2015v2, WMM2020) are shown by the green dashed line.*

We do not see significant enough deviation between the WMM2020 SV predictions and observed SV in 2020, 2021, and 2022 to merit further assessment.

Magnetic Dip Poles and Blackout Zones

Magnetic dip poles, defined as the points where the geomagnetic field is exactly vertical (i.e., perpendicular to the ellipsoid), drift in time as the main magnetic field slowly changes. The fastest moving pole over 2020-2023 was the one located in the northern hemisphere, with an average drift speed of 43 km/year compared to 9 km/year for the south magnetic pole. WMM2020 pole locations are available at https://www.ncei.noaa.gov/products/wandering-geomagnetic-poles and https://geomag.bgs.ac.uk/education/poles.html. **Figures 4 and 5** show the pole locations at 2023.0 and at the beginning (2020.0) and end (2025.0, predicted) of the WMM2020 cycle.

As dip poles drift, WMM2020 Blackout Zones and Caution Zones slowly change in time (**Figures 4 and 5**). Blackout Zones are defined as regions of the World Geodetic System 1984 (WGS84) ellipsoid where the horizontal component is less than 2000 nT. In Blackout Zones, WMM declination values are not accurate and compass accuracy is degraded. Caution Zones are regions where the horizontal intensity is less than 6000 nT and greater than 2000 nT. Blackout and Caution Zones are automatically updated in NGA products and NCEI online calculators.

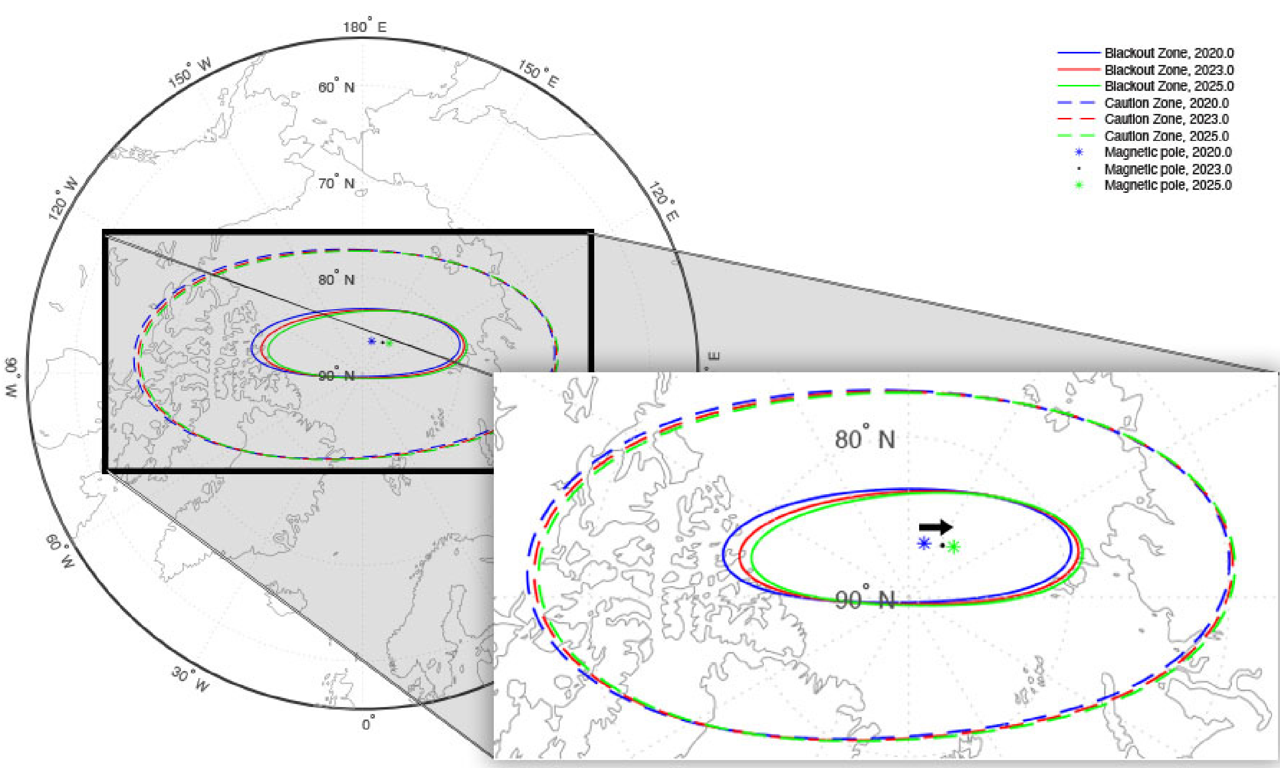

Figure 4: *Successive locations of the magnetic dip pole, Blackout Zone, and Caution Zone in the northern hemisphere throughout the WMM2020 five-year cycle.*

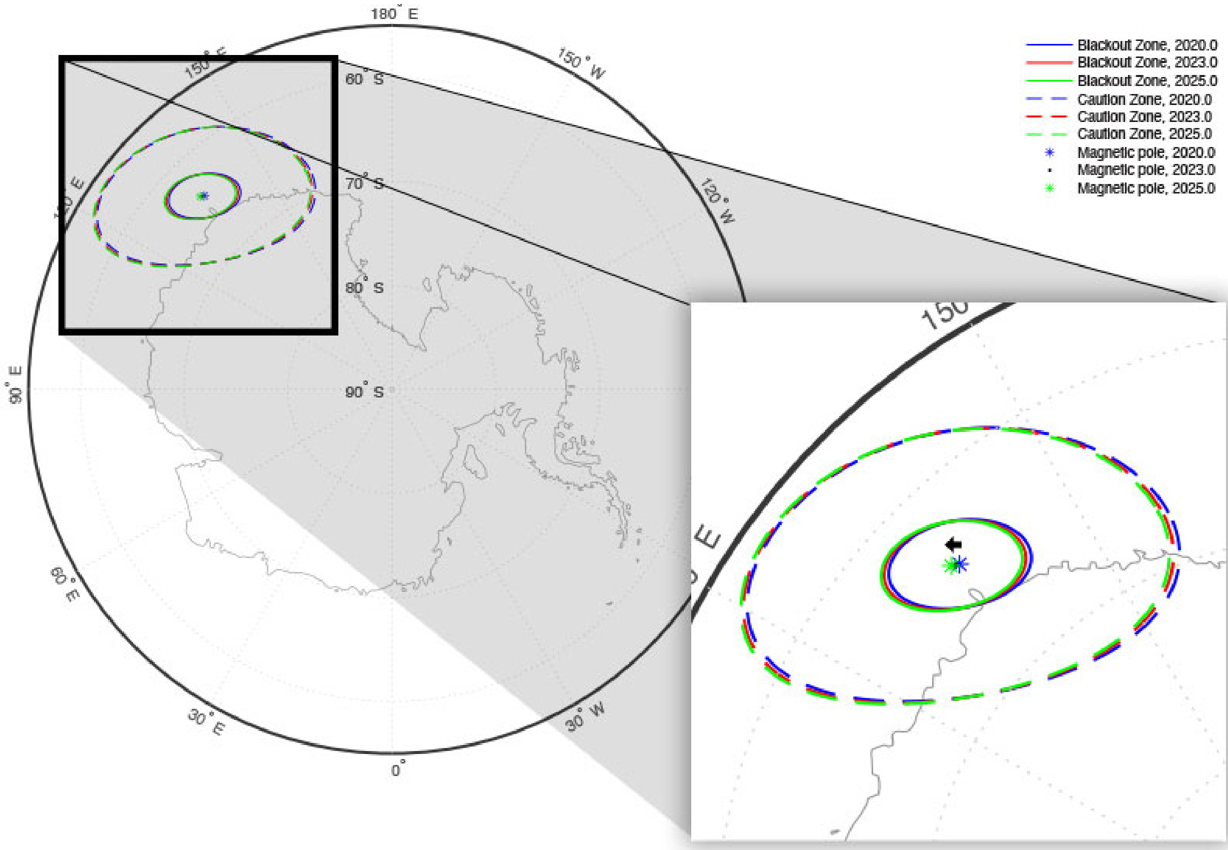

Figure 5: *Successive locations of the magnetic dip pole, Blackout Zone, and Caution Zone in the southern hemisphere throughout the WMM2020 five-year cycle.*

South Atlantic Anomaly

The South Atlantic Anomaly (SAA) is a region spanning the southern Atlantic and South America where the Earth's magnetic field is at its weakest. In the SAA the intensity of the field is about one-third of that near the magnetic poles. The SAA affects how closely energetic charged particles can reach the Earth, which impacts satellite radiation damage and radio propagation. Polar regions are also strongly affected by energetic charged particles, but the impacts there are less dependent on field intensity.

The SAA is deepening and moving westwards. **Table 3** shows the change in the SAA from 2020.0 to 2023.0 as estimated at Earth's surface and at 500 km by WMM2020. The area affected, as judged by the area inside the 25,000 nT contour at the Earth's surface, has increased by about 5% over this time. This contour approximates the region where radiation damage to satellites is most likely to occur.

	Altitude (km)	Minimum F (nT)	Latitude (°S)	Longitude (°W)
2020.0	0	22,232	26.2	59.1
2023.0	0	22,152	26.1	59.8
2020.0	500	18,428	22.4	58.2
2023.0	500	18,369	22.3	59.1

Table 3: *Monitoring the SAA intensity and location 2020.0 - 2023.0.*

Solar Cycle Progression and Magnetic Storms

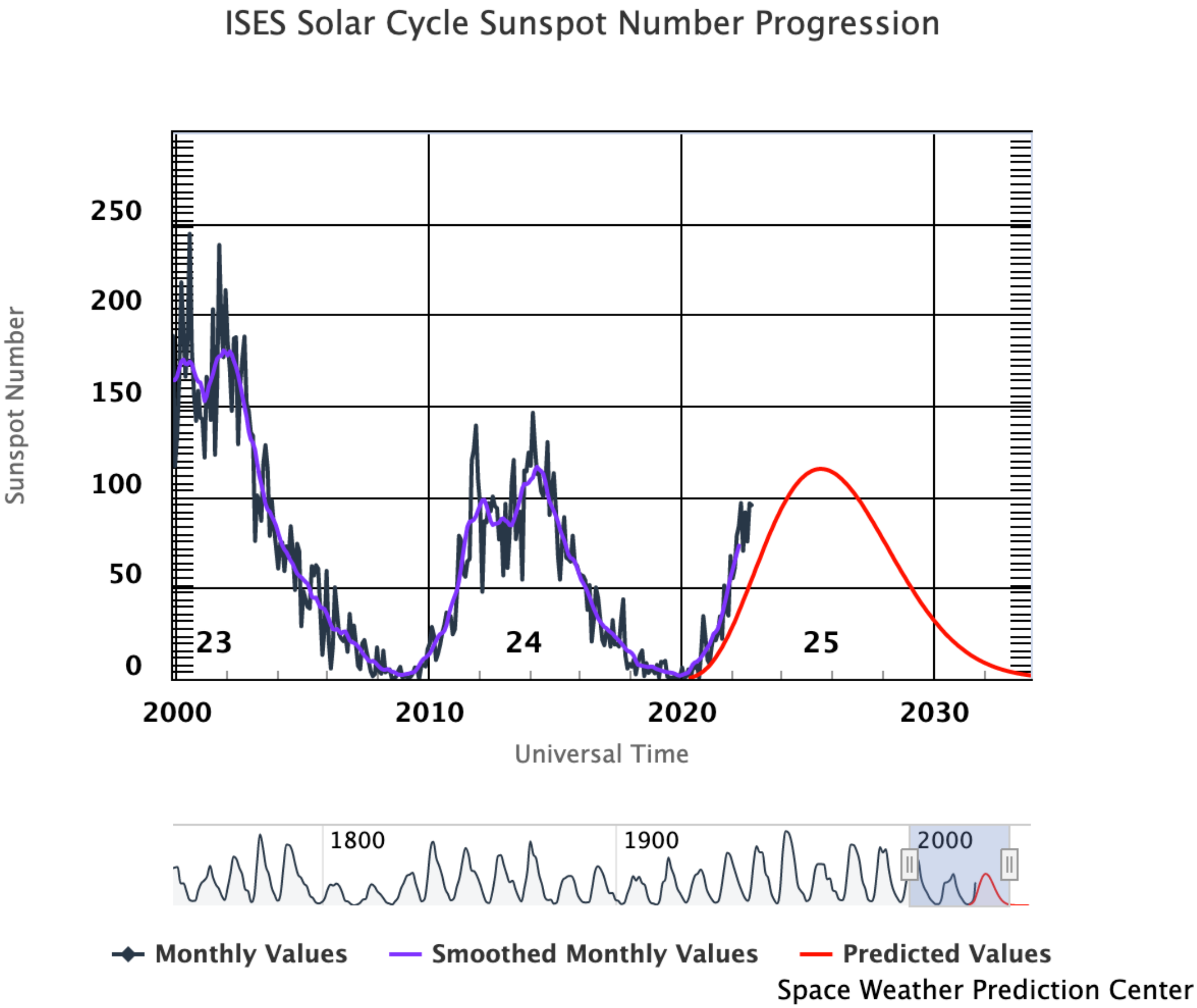

Figure 6: *Observed and predicted solar cycle since 2000. The black line represents the monthly average sunspot number, and the purple line represents a 13-month weighted, smoothed version of the monthly averaged data. The forecast for the current solar cycle is represented by the red line. This forecast comes from the Solar Cycle Prediction Panel representing NOAA, NASA, and the International Space Environmental Services (ISES). (Image provided by the NOAA Space Weather Prediction Center, https://www.swpc.noaa.gov/products/solar-cycle-progression).*

Although the Sun goes through an approximate 11-year cycle in activity (**Figure 6**), space weather impacts can occur at any point during the cycle. Space weather impacts relevant for the WMM user community are many and varied and include power outages, radio communications, satellite operations, etc. Space weather's impact on navigation is given particular consideration here due to differences between the WMM declination estimates and the actual declination during a space weather event. The magnetic field variations resulting from sources outside the Earth are considered in WMM error estimates in a root-mean-square sense. However, it is of interest to list extreme events over the past year and map the maximum declination deviations during these events as recorded on the ground by the network of observatories.

Using the NOAA Space Weather Prediction Center method of reclassifying magnetic storms by magnetic activity index Kp into the G(eomagnetic) storm scale G1-G5, a list of the largest storms, namely G3-G5 storms, during the period of November 1, 2021 to October 31, 2022 is presented in **Table 4**.

Date	Max Kp	NOAA storm classification
4 Nov 2021	8-	G4
10 Apr 2022	7-	G3
17 Aug 2022	7-	G3

Table 4: *List of G3-G5 magnetic storms from November 1, 2021 to October 31, 2022.*

For each storm date listed, we obtain seven days centered on the storm day of global observatory minute mean values from INTERMAGNET. Using the best quality data available, viz definitive in preference to quasi-definitive in preference to provisional in preference to variation, seven-day means are computed in declination. If the data are not already in declination (D) angular units, easterly intensity (Y) and northerly intensity (X), both in nT units, are converted to D in angular units. For each storm and each observatory, a maximum absolute D deviation from the mean is then computed. Plots are made for each storm depicting the maximum absolute D deviation (**Figure 7, 8 and 9**). The purpose of these figures is to illustrate an indicative worst case and global pattern rather than a real WMM error. It is "indicative" because local crustal fields are excluded, and it is “worst case” because standard errors arising from external sources are already included in the WMM error estimates. As expected, high latitude regions experience the largest maximum D deviations during magnetic storms: over 8° during the G4 storm on November 4, 2021 and over 4° during the G3 storms on April 10, 2022 and August 17, 2022.

For detailed space weather services, the WMM user is referred to NOAA Space Weather Prediction Center (https://www.swpc.noaa.gov/) and ESA Space Weather Service Network (https://swe.ssa.esa.int/current-space-weather).

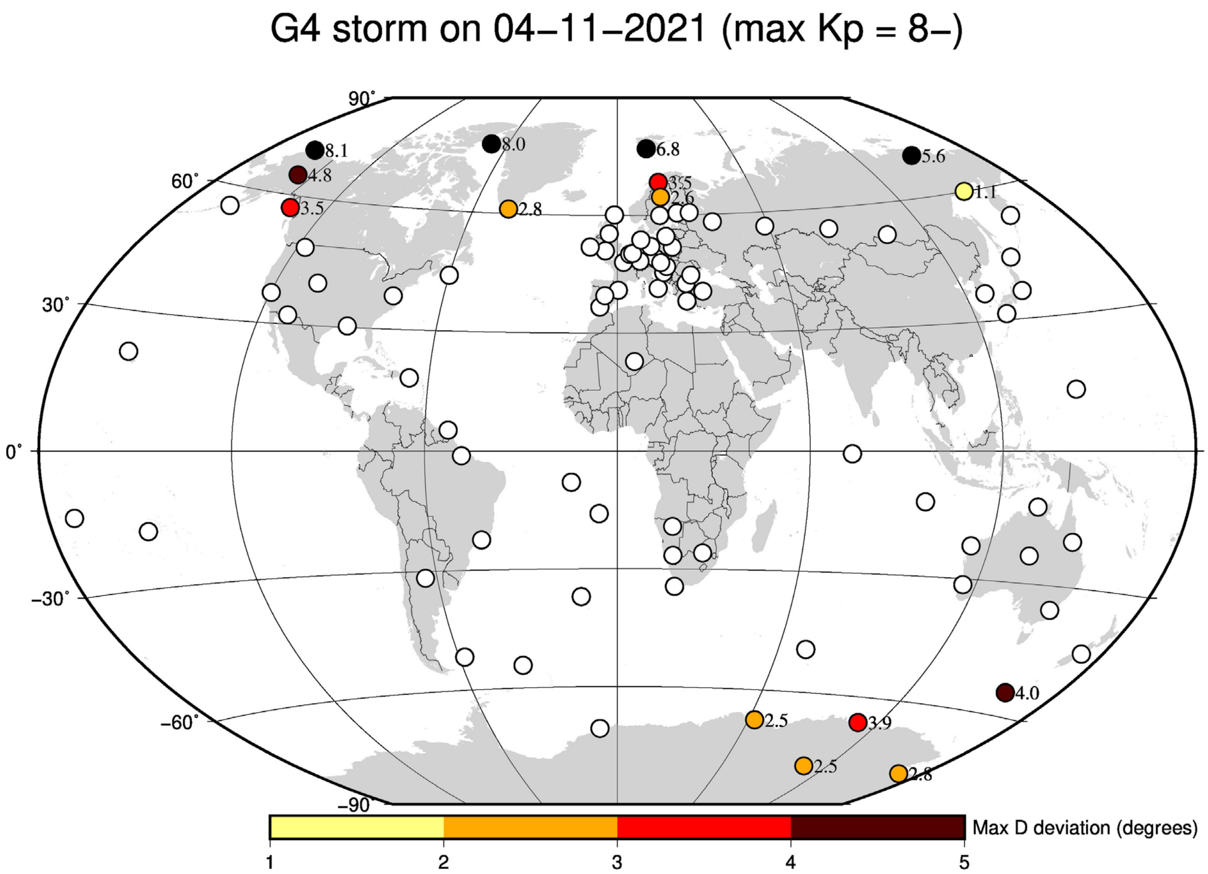

Figure 7: *Indicative maximum declination deviations during G4 storm on 4 November 2021. The white circles are observatories where the maximum deviation is less than the military specification of 1°.*

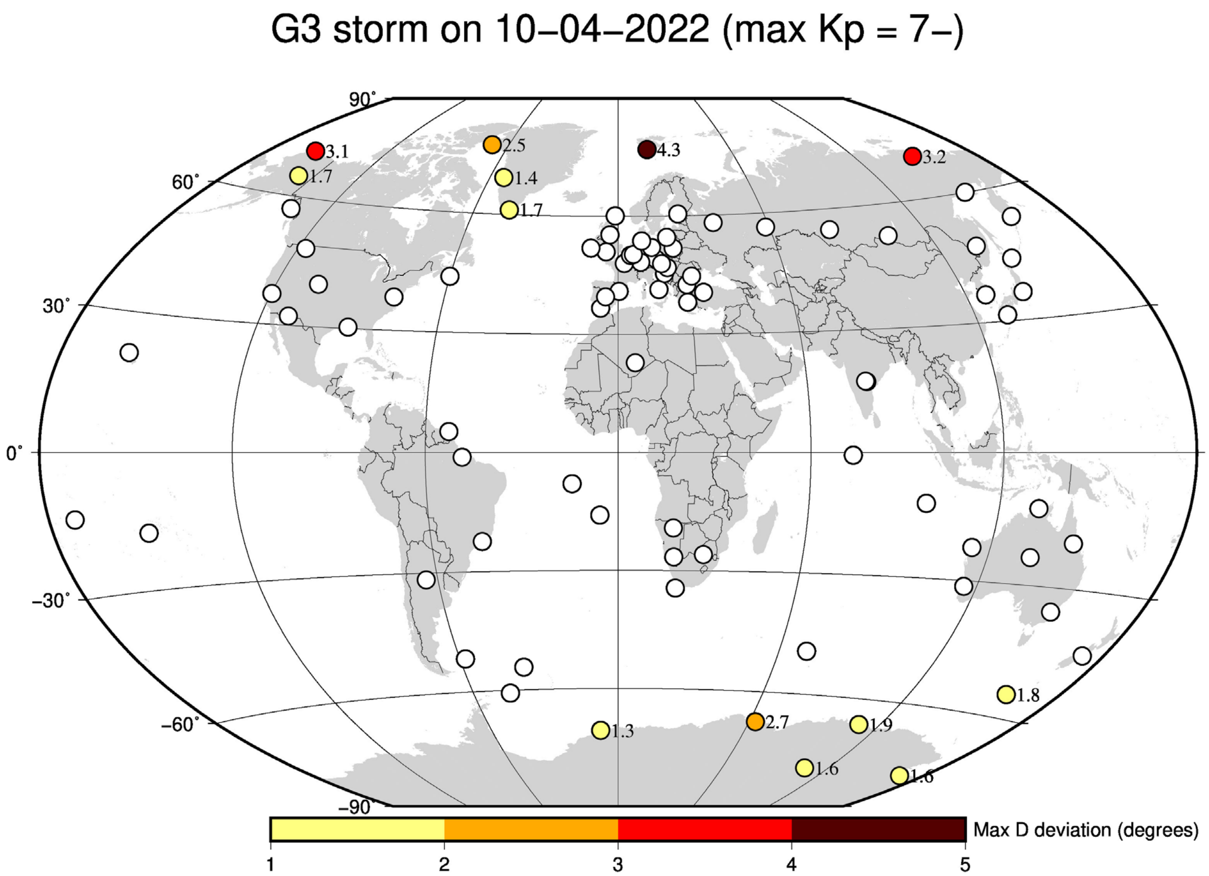

Figure 8: *Indicative maximum declination deviations during G3 storm on 10 April 2022. The white circles are observatories where the maximum deviation is less than the military specification of 1°.*

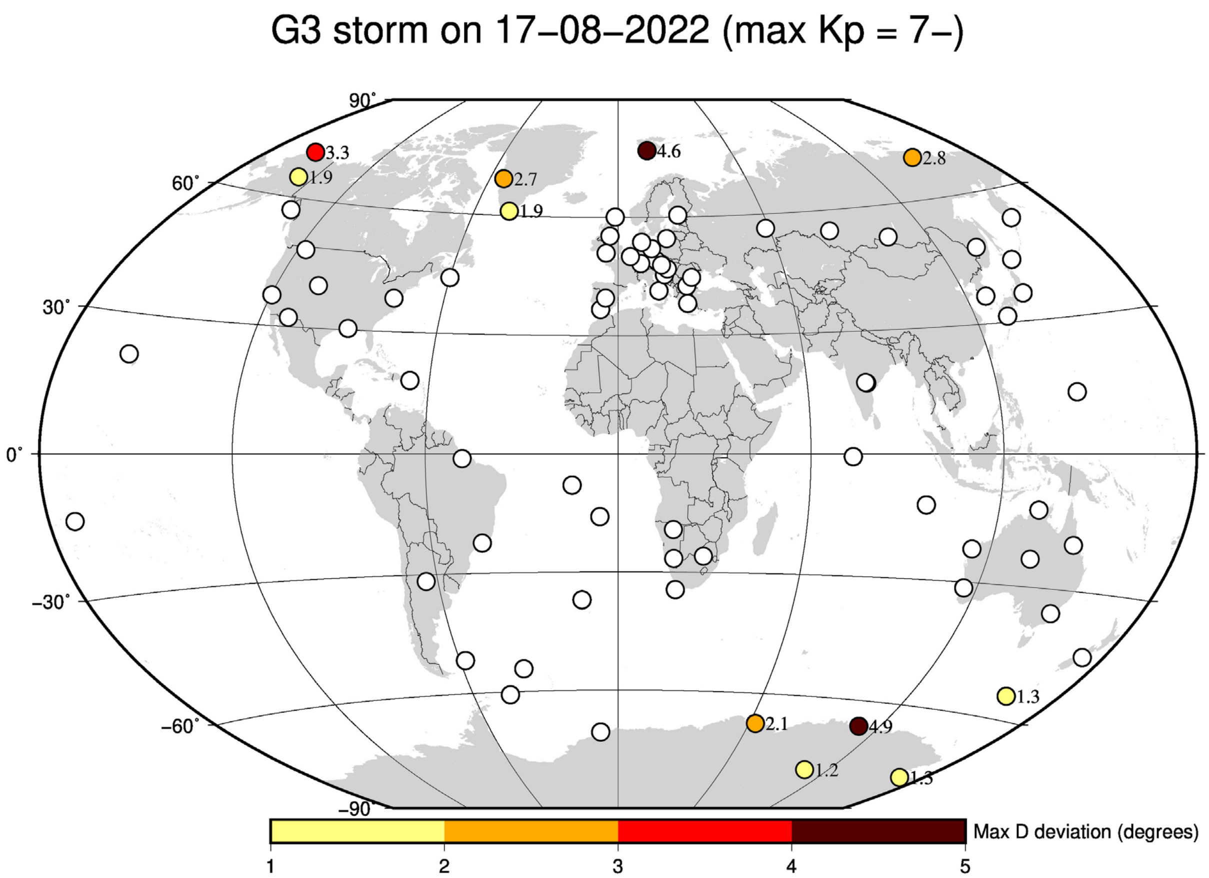

Figure 9: *Indicative maximum declination deviations during G3 storm on 17 August 2022. The white circles are observatories where the maximum deviation is less than the military specification of 1°.*

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Appendix

Swarm Reference Model

In October 2022, we developed a reference geomagnetic core field model from recent Swarm satellite data to serve as a truth reference for evaluating the performance of WMM2020. We used Swarm A and B satellite data from the mission start (November 2013) until the end of September 2022. The Swarm data were preprocessed to select data during geomagnetically quiet periods, using the selection criteria detailed in the WMM2020 Technical Report. We additionally selected data at low- and mid-latitudes between midnight and 5 a.m. local time in order to exclude regions of strong ionospheric current flow that would have introduced undesired signals into core field measurements. At high latitudes, we selected data when the satellite was in darkness using the solar zenith angle. The MF7 (Maus *et al.*, 2008) lithospheric field model was removed from the Swarm data to exclude the static crustal field for spherical harmonic degrees 16 to 133 from the data. Then, an internal core field model to spherical harmonic degree 15 was fitted to the nearly nine-year Swarm dataset, using order 6 splines with six-month knot spacing to represent the time variation of the Gauss coefficients. We simultaneously co-estimated an external spherical harmonic degree 2 field to account for the strong magnetospheric sources, primarily the ring current and tail currents. The external field was parameterized using the CHAOS methodology (Olsen *et al.*, 2014). Finally, we co-estimated a set of time varying alignment parameters to rotate vector fluxgate magnetic measurements from the instrument frame onboard the satellite into a geographic frame co-rotating with Earth. An iterative reweighted least squares method was used to fit the model to the Swarm dataset, using Huber weights to reduce the effect of outliers in the data.

Ground Observatory Data Processing

Root-mean-square-errors (RMSEs) between the WMM2020 predicted secular variation (SV) and ground observatory data were calculated as follows. We took version 0133 (November 2022) of the auxiliary observatory data product (AUX_OBS_2) for 2020 to 2022 produced for the ESA Swarm mission. This contained selected definitive hourly means from the World Data Centre for Geomagnetism (Edinburgh) and hourly means provided as quasi-definitive (delivered soon after collection with manually checked baselines applied). Any steps due to observatory changes were applied. These data were provided by 107 observatories in 2020, 89 observatories in 2021 and 58 observatories in 2022. We selected this data further for geomagnetically quiet times when the Kp index was less than or equal to 2+, the rate of change of the Dst index was less than or equal to 5 nT/year, and the Bz component of Interplanetary Magnetic Field (IMF) was greater than or equal to -2 nT. We then selected only data from the hours of 1 a.m. to 2 a.m. local time. These conditions minimized contamination of the observations by external field sources to better reflect the background core field level that the WMM represents. The hourly data were converted to monthly mean values, and then annual differences were taken to give SV values at the midpoint in time between a pair of samples. Predictions of WMM2020 SV were made at each time and location of an observation, and the RMSEs were calculated for each calendar year at each observatory, and for each calendar year globally.

Geomagnetic Virtual Observatory Data Processing

Root-mean-square-errors (RMSEs) between the WMM2020 predicted secular variation (SV) and satellite virtual observatory data were calculated as follows. We took the monthly internal field SV estimates of the ESA Swarm Level 2 Geomagnetic Virtual Observatory data set version 0101 (September 2022), and calculated RMSEs relative to WMM2020 using the same method as the one used for the ground observatories.