December

2023

STATE OF THE GEOMAGNETIC FIELD

CIRES

NATO
OTAN

Defence
Geographic
Centre

BGS
British
Geological
Survey

CONTENTS

DOI: 10.25923/cww1-sc35

SUMMARY

The performance of the World Magnetic Model 2020 (WMM2020) was assessed by comparing its predictions on January 1, 2024 with that of a more recent model inferred from data collected by the European Space Agency (ESA) Swarm satellites until September 2023. For all magnetic field components, the global root-mean-square error of WMM2020 increased by less than 10% of its previous value over the past four 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 up to 2023. 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 41 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 highly degraded. The South Atlantic Anomaly, where the geomagnetic field intensity is lowest, has continued to deepen (by about 25 nT at surface level) and move westward (its center moved by about 20 km at surface level) in the past year. Over the past year, three strong to severe geomagnetic storms occurred, leading to significant (e.g., declination deviations over 9 degrees) but temporary effects on WMM performance, mostly at high geomagnetic latitudes. As WMM2025 is anticipated for release in December 2024, this marks the final report on WMM2020.

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 developed by other bodies unaffiliated with national governments.

The main geomagnetic field is constantly changing due to convective flow of and waves in the Earth's liquid outer core. As the system is essentially chaotic on longer timescales, this change cannot be entirely predicted, and so 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, 2024 (2024.0 hereafter), and provides an assessment of its secular variation after three years. The previous assessment was undertaken in December 2022 (National Centers for Environmental Information (U.S.) & British Geological Survey, 2022). This report also includes a description of noteworthy changes in the Earth's main magnetic field since WMM2020's release, including continued magnetic pole drift and the further deepening of the South Atlantic anomaly in the geomagnetic field intensity component. A section in this report summarizes solar cycle progression and estimates the effects on WMM performance during magnetic storms. This is the last report on WMM2020; WMM2025 is anticipated for release in December 2024.

WMM PERFORMANCE: MODEL ERRORS AT 2024.0

The performance of WMM2020 was assessed at epoch 2024.0 by comparing it with a more recent model derived from satellite magnetometer data. The data were collected by the ESA Swarm tri-satellite constellation from November 2013 until September 2023. (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 (i) the omission error, associated with magnetic fields not included in the WMM (e.g., crustal and disturbance magnetic fields), and (ii) 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 2024.0 using the Swarm-based model described above. For all components, the errors at 2024.0 (row 3) are well below the maximum errors allowed by the WMM military specification (row 1). These errors are also lower (especially for declination and grid variation) than the predicted values at the end of the WMM2020 five-year cycle, suggesting that the differences between the WMM2020-predicted and the actual secular variations were small over the past four years. Errors at 2024.0 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 (°)	GV_N (°)	GV_S (°)
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 2024.0	131	135	0.22	0.38	0.69	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, 2024.0, 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 average error accumulated 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 shown in **Table 1**, grid variation north (GVN) exhibits the largest expected relative increase in its RMSE over the WMM cycle. GVN is defined as the difference between magnetic declination and longitude above 55°N latitude, and its error is the same as the declination error above 55°N. GVN 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 2024.0 is the smallest. This suggests that the GVN error is unlikely to exceed the specification before the end of the current five-year cycle.

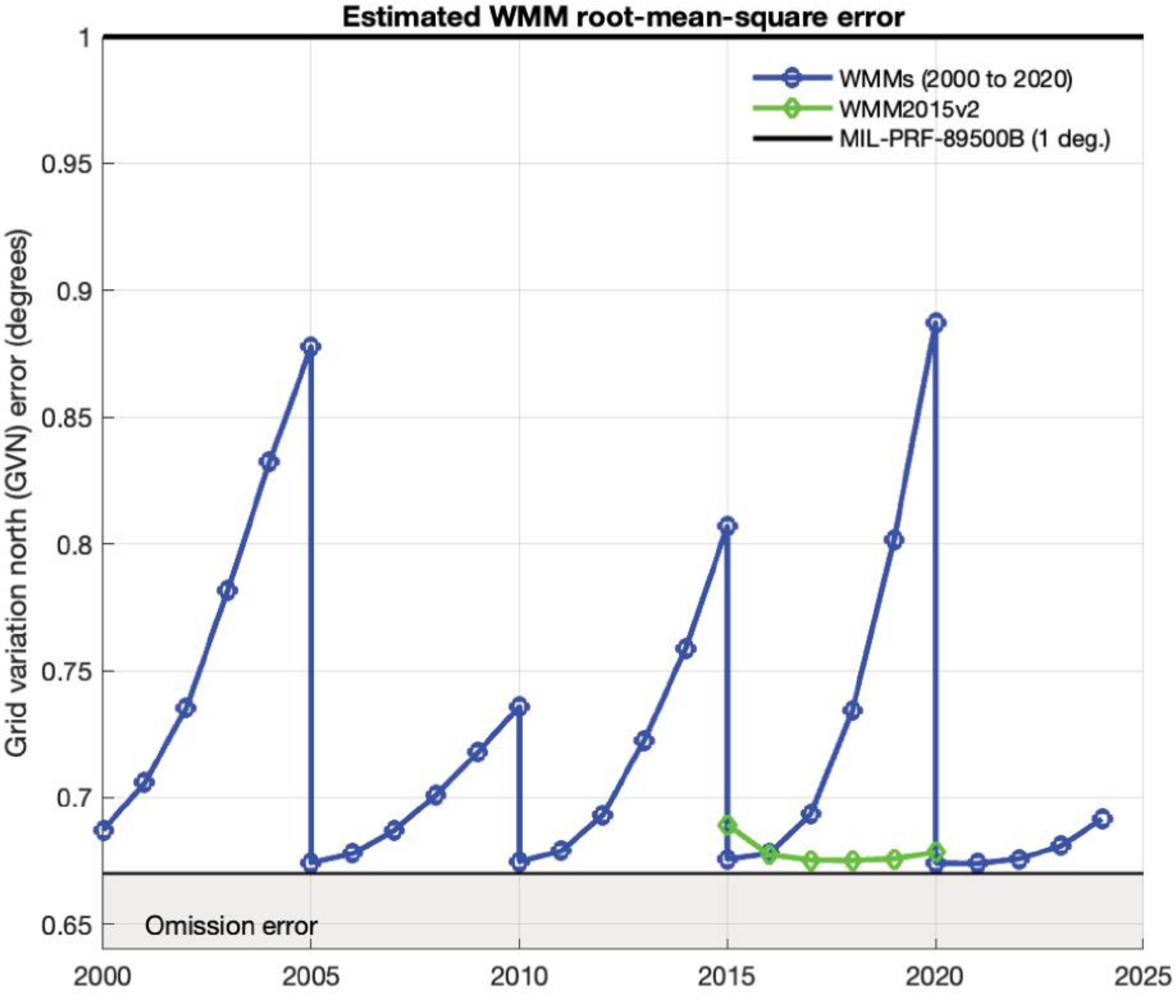

Figure 1: *WMM global RMSE for the grid variation north (GVN) component from 2000 to 2024. Errors for six successive WMMs are shown: WMM2000, WMM2005, WMM2010, WMM2015, WMM2015v2, and WMM2020. WMM2015v2 was an out-of-cycle WMM released in late 2018 in case WMM2015 were to breach the specification before the end of the cycle. (The specification was revised in 2019 with the introduction of so-called blackout zones (see below). These blackout zones are no longer considered in WMM error calculations, and past points were recalculated without them.)*

WMM PERFORMANCE: SECULAR VARIATION ASSESSMENT

The WMM2020 secular variation (SV) was assessed by comparing it to independent SV estimates for 2020, 2021, 2022, and 2023 provided by (a) ground magnetic observatories (at Earth's surface) and (b) geomagnetic virtual observatories (at 490 km altitude) derived from Swarm data. 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 that 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 generally an increase in RMSE from 2020 to 2023, 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)**	**dGVN (min/yr)**	**dGVS (min/yr)**
2020	7	7	1	2	3	1
2021	10	10	1	2	3	2
2022	12	12	1	3	4	2
2023	13	14	1	3	3	4
Geomagnetic Virtual Observatories (at 490 km)						
2020	3	4	1	2	6	1
2021	5	6	1	2	5	1
2022	7	8	1	2	6	2
2023	9	11	2	2	5	2

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 available observations in a calendar year.*

It should be noted that RMSE values for 2023 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 April 2023 at the latest. (Note that values for all years have been updated since the last report as more data becomes available.) Geomagnetic virtual observatory data were available globally, providing observed SV up to April 2023. Note, 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 (not shown) generally show consistently higher values at high latitudes, where unmodelled external field signals are present in the data to a greater extent. The RMSE of GVS from ground observatory data suggest a notable increase between 2022 and 2023 not seen in the GVO data; however, this may be an effect of the limited amount of ground data available for 2023 at the time of reporting and the higher level of variability found in preliminary, non-definitive observatory data. The same issue can occur at remote locations where observatory operation is often challenging. For ground observatories, the lowest values are typically seen in Europe and North America where dense spatial 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 as the South Atlantic and Northern Australasia/South-East Asia. Such rapid changes—accelerations in particular—are, by design, not captured by WMM2020.

The mapped RMSE for geomagnetic virtual observatories (**Figure 2**) show a clearer spatial pattern than those of observatories, due to the uniform global coverage. 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 from central Asia, South-East through to Australasia, for example. In 2023, a region of higher RMSE developed in the Eastern Pacific. Although it is a robust feature, it cannot be observed on the ground due to a lack of ground observatories in the Pacific. Overall, the RMSEs are small and accumulating slowly and as such are not a cause for concern with regard to the accuracy of WMM2020 over its lifespan.

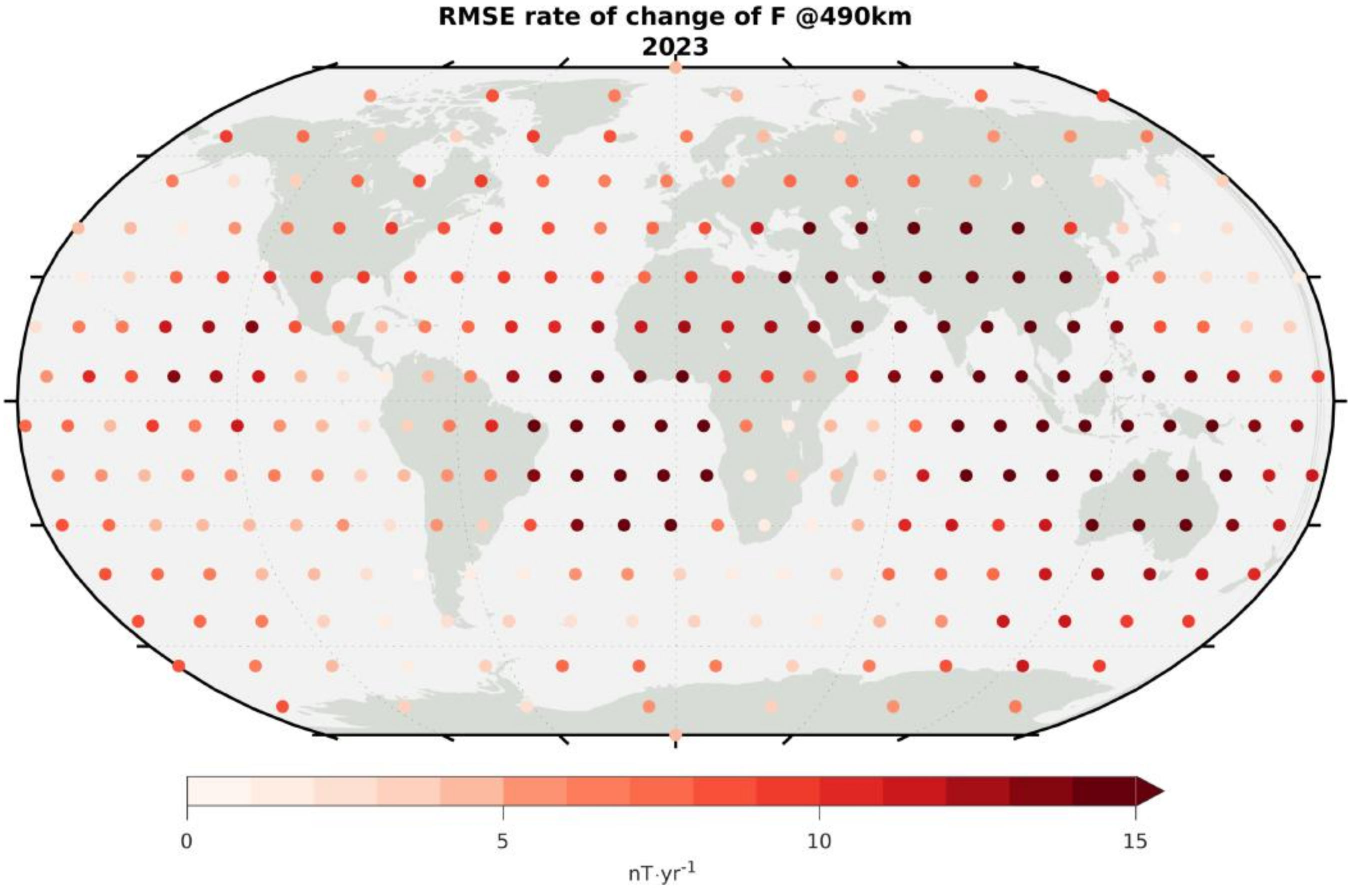

Figure 2: *RMSE between prediction of WMM2020 SV of total intensity (F) and geomagnetic virtual observatory data in 2023.*

Three examples of magnetic observations compared to WMM (from 2000 to present) highlight the occurrence and impact of occasional field accelerations (known as 'jerks'). There is evidence of several jerks (the sharp changes in SV) in Honolulu (**Figure 3a**), most recently in 2020 (Pavón-Carrasco *et al*., 2021). The 2020 particular acceleration led to a divergence from the WMM prediction. While the present RMSE in Honolulu is small, we expect to see it grow further during the WMM2020 lifespan until 2025.The Hermanus Observatory in South Africa is on the edge of a region with high RMSE. Here, we observe the continual increase of the magnitude of the rate of change of declination between approximately 2017 to 2022 (**Figure 3b**). The divergence from WMM2020 then began to decrease due to a recent geomagnetic jerk in the South Atlantic. In Kakadu, Australia (**Figure 3c**) we see an example from the region with the largest RMSE values in 2023 (see **Figure 2**). Kakadu is at the edge of an expanding region of larger RMSE, the growth of which has been noted by previous annual reports. In Kakadu, we see jerks in the vertical component in 2017 and 2020 that have characterized this region in the past and led to a divergence from WMM2020. We do not know if this presently diverging trend in Honolulu and Kakadu will continue through the lifespan of WMM2020.

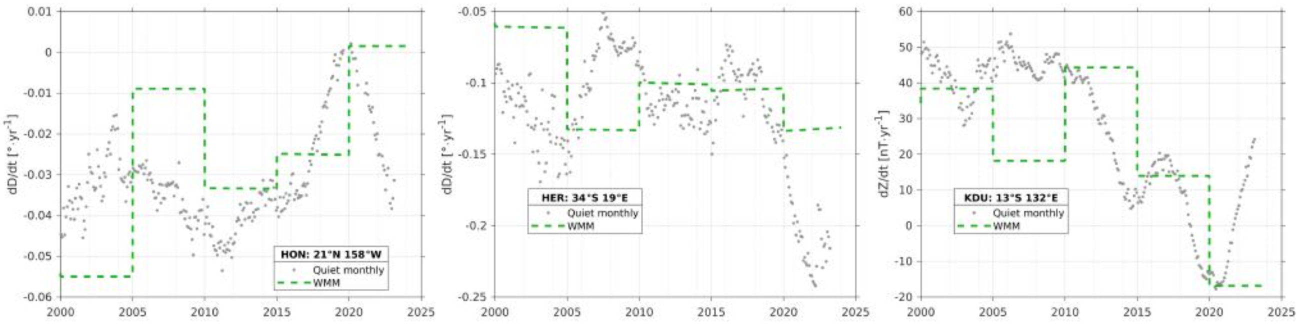

Figure 3: *Observed rate of change of (a) declination angle (D) in degrees/year in Honolulu, Hawai'i, United States (HON), (b) declination in Hermanus, South Africa (HER), and (c) vertical field (Z) in nT/year in Kakadu, Australia (KDU). Quiet-dark monthly mean data are shown as gray circles, WMM predictions (WMM2000, WMM2005, WMM2010, WMM2015v2, WMM2020) are shown by the green dashed line.*

However, we would like to point out that the magnitude of changes is small and that we also do not see significant enough deviation between the WMM2020 SV predictions and observed SV from 2020 to 2023 to merit further concern about the model's performance.

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. 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 2024.0 and at the beginning (2020.0) and end (2025.0, predicted) of the WMM2020 cycle.

Actual pole locations from 2020.0 to 2024.0 were determined using the same model derived from satellite magnetometer data that was used to assess the WMM2020's performance (see above). We found that the distances between WMM2020 and actual pole locations remained small compared to the distances covered every year by each pole (**Table 3**). This shows that the WMM2020 has remained very accurate in both polar regions since its release. (As WMM2020 and actual pole locations are so close to each other, only the WMM2020 locations are shown in **Figures 4 and 5**.)

The fastest moving pole between 2020–2024 was the one located in the northern hemisphere, with an average drift speed of 41 km/year compared to 9 km/year for the southern magnetic pole. The actual drift speed has remained close to the drift speed forecast by WMM2020 (**Figure 6**). This is unlike in the previous WMM cycle (2015–2020), when a sudden acceleration of the north magnetic pole just after the release of WMM2015 led to differences as large as 10 km/yr between the forecast and actual north magnetic pole drift speeds. The release of WMM2015v2, an out of cycle update, corrected for this. Interestingly, recent satellite data seem to suggest that the northern magnetic pole drift speed has slightly increased between 2022.5 and 2023.5.

As dip poles drift, WMM2020 Blackout Zones and Caution Zones slowly change over time (**Figures 4 and 5**). Blackout Zones are defined as regions of the World Geodetic System 1984 (WGS84) ellipsoid where the horizontal component of the magnetic field 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.

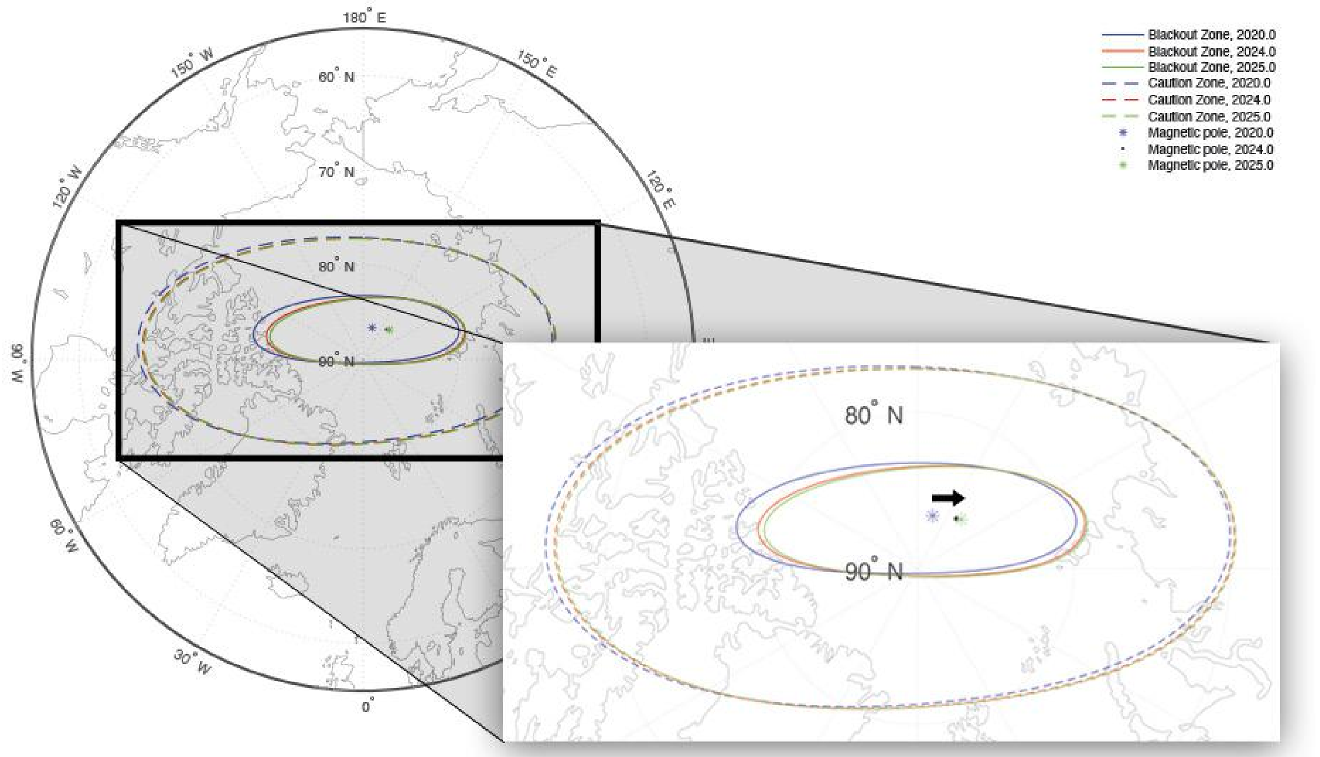

Figure 4: *Successive locations of the magnetic dip pole, Blackout Zone, and Caution Zone in the northern hemisphere throughout the WMM2020 five-year cycle.*

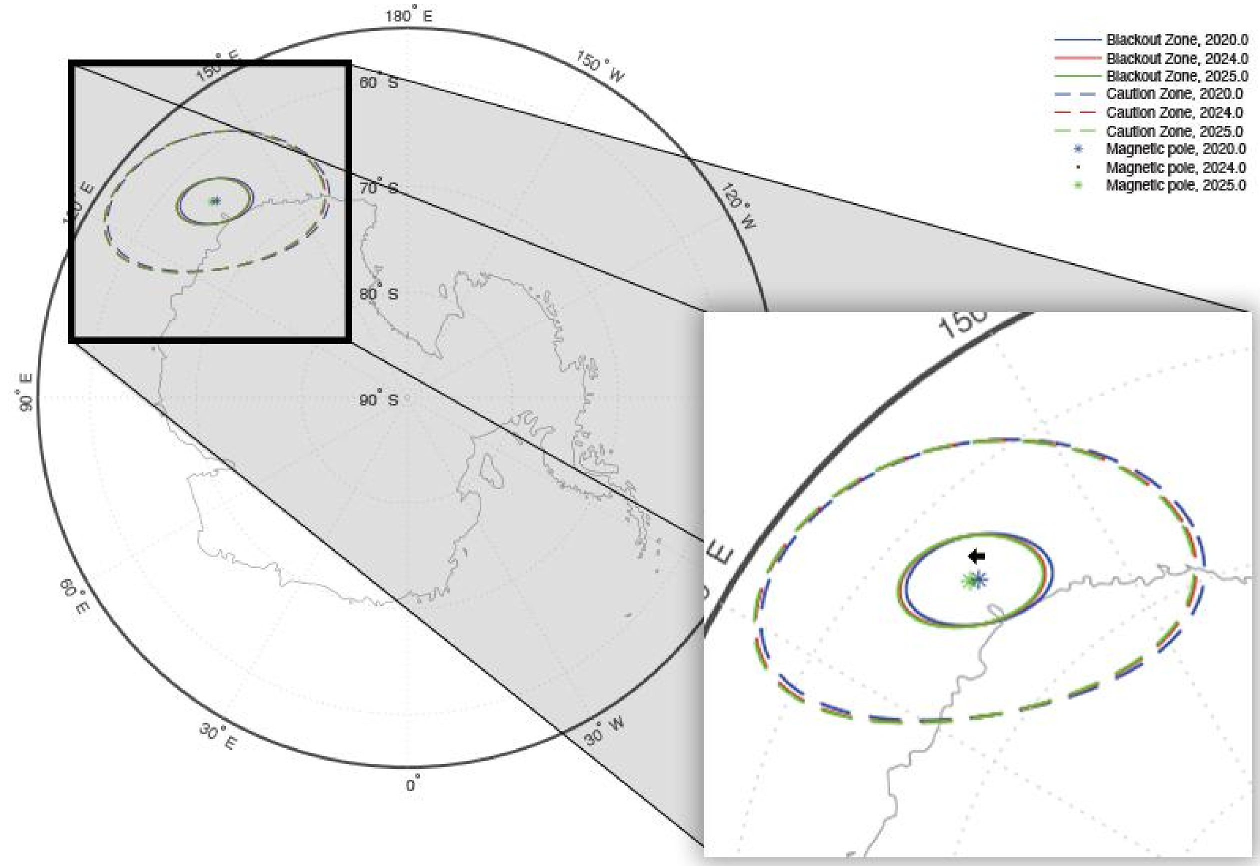

Figure 5: *Successive locations of the magnetic dip pole, Blackout Zone, and Caution Zone in the southern hemisphere throughout the WMM2020 five-year cycle.*

Epoch	WMM2020 vs. actual north magnetic pole locations (km)	WMM2020 vs. actual south magnetic pole locations (km)
2020.0	0.4	1.0
2021.0	3.6	1.3
2022.0	6.4	1.7
2023.0	8.9	2.1
2024.0	8.6	2.4

Table 3: *Distances between annual WMM2020 predicted magnetic pole locations and the actual magnetic pole locations in the northern and southern hemispheres.*

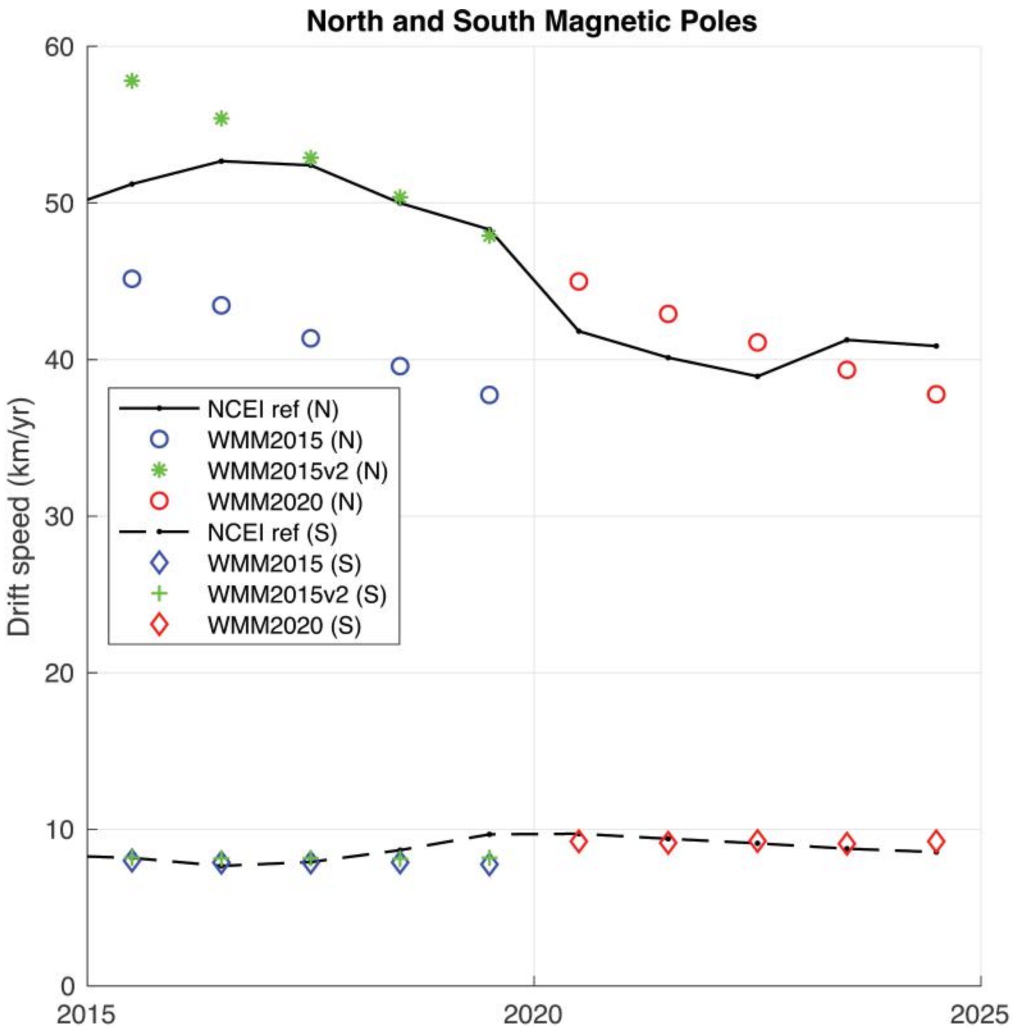

Figure 6: *Drift speed of the north and south magnetic poles, as predicted by a recent model derived from satellite magnetometer data (black solid and dashed lines), WMM2015 (blue circles and diamonds), WMM2015v2 (green stars and crosses), and WMM2020 (red circles and diamonds).*

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 4** shows the change in the SAA from 2020.0 to 2024.0 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 7% 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
2024.0	0	22,126	26.1	60.0
2020.0	500	18,428	22.4	58.2
2024.0	500	18,349	22.3	59.3

Table 4: *Monitoring the SAA intensity and location 2020.0–2024.0.*

SOLAR CYCLE PROGRESSION AND MAGNETIC STORMS

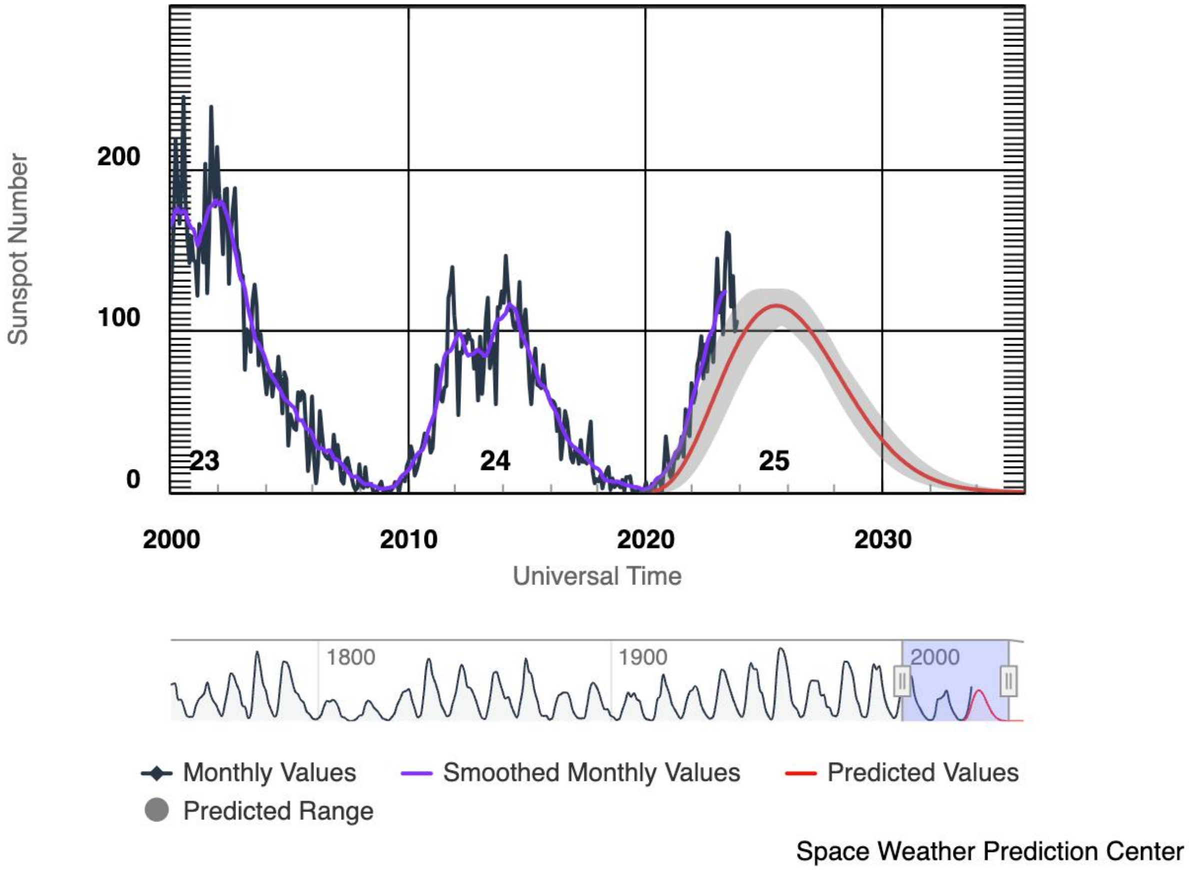

Figure 7: *Observed and predicted solar cycle since 2000. The black line represents the monthly average sunspot number, and the purple line represents a 13-month weighted, smoothed version of the monthly averaged data. The forecast for the current solar cycle is represented by the red line. This forecast 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 based on the 2019 expert panel prediction,* ***https://www.swpc.noaa.gov/products/solar-cycle-progression****.)*

Although the Sun goes through an approximate 11-year cycle in activity (**Figure 7**), 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, 2022 to October 31, 2023 is presented in **Table 5**.

	Max Kp	NOAA storm classification
27 Feb 2023	7-	G3
24 Mar 2023	8	G4
23 Apr 2023	8+	G4

***Table 5:** List of G3-G5 magnetic storms from November 1, 2022 to October 31, 2023.*

Plots are made for each storm depicting the maximum absolute D deviation (**Figures 8, 9, and 10**; see methods in the Appendix). 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 9° during the G4 storm on April 23, 2023, and over 6° during the G3 and G4 storms on February 27, 2023 and March 24, 2023, respectively. These three storms originated from a period of activity on the Sun that spanned three consecutive 27-day solar rotations.

Figure 7 shows that the Sun is in its ascending phase, approaching the peak of the current solar cycle. Observed sunspot numbers suggest that solar cycle 25 will be higher (more active) than the previous cycle as well as what the initial prediction from 2019 suggested. Newer cycle predictions from October 2023 call for the cycle to peak between January and October of 2024 with a maximum sunspot number between 137 and 173. Solar cycle 24 was one of the lower cycles in modern times and a potential minima of a centennial scale cycle. We may expect to observe storms of greater quantity and intensity in the remainder of the WMM2020 lifespan, along with a peak in geomagnetic activity that typically occurs two to three years after the peak of a sunspot number cycle.

For detailed space weather services, WMM users should visit the websites of the NOAA Space Weather Prediction Center (**https://www.swpc.noaa.gov/**) and ESA Space Weather Service Network (**https://swe.ssa.esa.int/current-space-weather**).

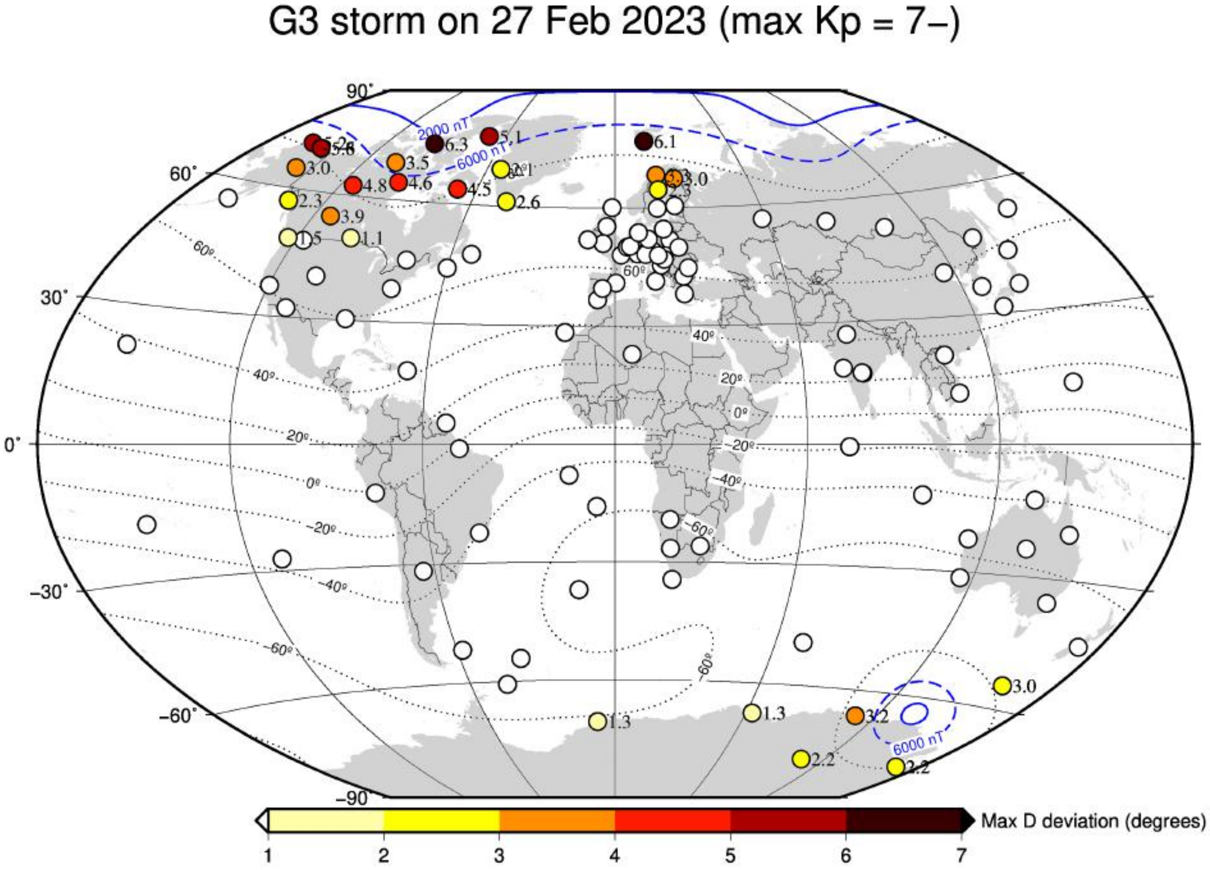
G3 storm on 27 Feb 2023 (max Kp = 7–)

Figure 8: *Indicative maximum declination deviations during the G3 storm on February 27, 2023. The white circles represent observatories where the maximum deviation is less than the military specification of 1°, and the black circles represent those where it is over 7°. The blue solid contour indicates the horizontal field value used to mark the WMM blackout zone (2000 nT), and the blue dashed contour the caution zone (6000 nT). The black dotted contours show the inclination of the magnetic field vector.*

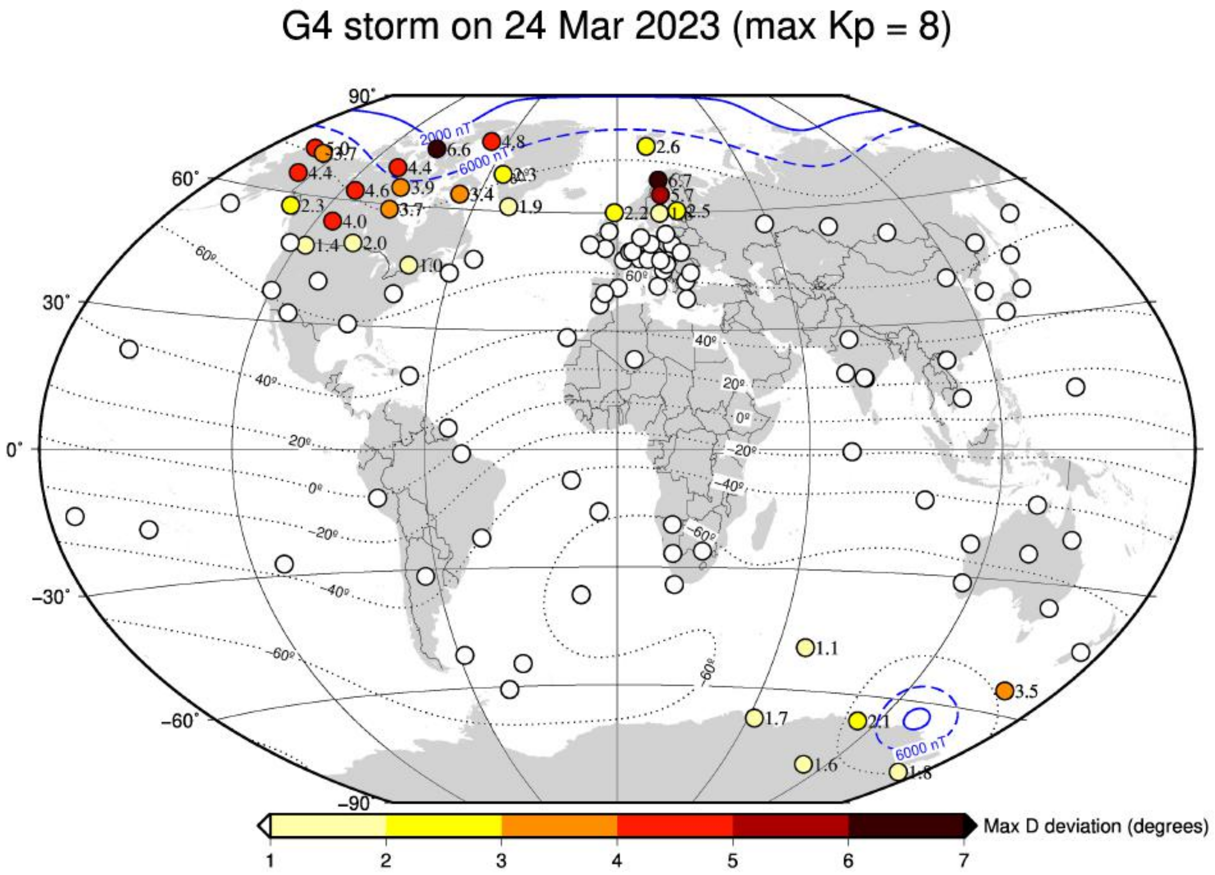

Figure 9: *Indicative maximum declination deviations during the G4 storm on March 24, 2023. Plot as described in* ***Figure 8*** *caption.*

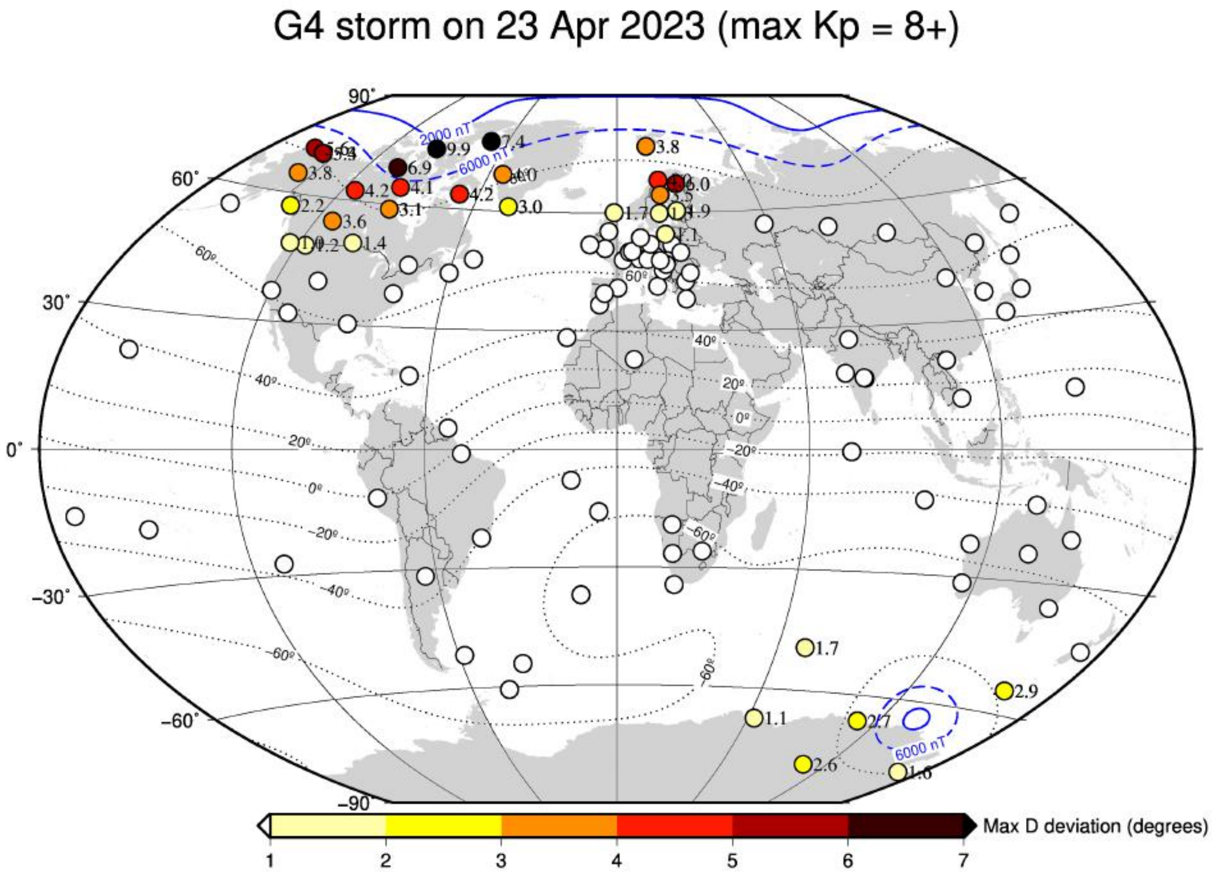

Figure 10: *Indicative maximum declination deviations during the G4 storm on April 23, 2023. Plot as described in Figure 8 caption.*

REFERENCES

Chulliat, A., Brown, W., Alken, P., Beggan, C., Nair, M., Cox, G., Woods, A., Macmillan, S., Meyer, B., & Paniccia, M. (2020). *The US/UK World Magnetic Model for 2020-2025: Technical Report*. National Centers for Environmental Information, NOAA. https://doi.org/10.25923/ytk1-yx35

National Centers for Environmental Information (U.S.) & British Geological Survey (2022). *State of the Geomagnetic Field 2022*. https://doi.org/10.25923/8r5d-fj70

U.S. Department of Defense (2019). *Performance specification—World Magnetic Model (WMM)* (Doc. MIL-PRF-89500B). http://everyspec.com/MIL-PRF/MIL-PRF-080000-99999/MIL-PRF-89500B_56010

Hammer, M. D., Cox, G. A., Brown, W. J., Beggan, C. D., & Finlay, C. C. (2021). Geomagnetic Virtual Observatories: monitoring geomagnetic secular variation with the Swarm satellites. *Earth, Planets and Space, 73*(1). https://doi.org/10.1186/s40623-021-01357-9

Maus, S., Yin, F., Lühr, H., Manoj, C., Rother, M., Rauberg, J., Michaelis, I., Stolle, C., & Müller, R. D. (2008). Resolution of direction of oceanic magnetic lineations by the sixth-generation lithospheric magnetic field model from CHAMP satellite magnetic measurements. *Geochemistry, Geophysics, Geosystems, 9*(7). https://doi.org/10.1029/2008gc001949

Olsen, N., Lühr, H., Finlay, C. C., Sabaka, T. J., Michaelis, I., Rauberg, J., & Tøffner-Clausen, L. (2014). The CHAOS-4 geomagnetic field model. *Geophysical Journal International, 197*(2), 815-827. https://doi.org/10.1093/gji/ggu033

Pavón-Carrasco, F. J., Marsal, S., Campuzano, S. A., & Torta, J. M. (2021). Signs of a new geomagnetic jerk between 2019 and 2020 from Swarm and observatory data. *Earth, Planets and Space, 73*(1). https://doi.org/10.1186/s40623-021-01504-2

APPENDIX

Swarm Reference Model

In October 2023, we developed a reference geomagnetic core field model from recent Swarm satellite data to serve as a 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 2023. 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 10-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 0138 (November 2023) of the auxiliary observatory data product (AUX_OBS_2) for 2020 to 2023 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) by INTERMAGNET, or the observatory operator. Any steps due to observatory changes were applied. These data were provided by 115 observatories in 2020, 105 observatories in 2021, 84 observatories in 2022, and 63 observatories in 2023. 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/hour, 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 selected hourly data were averaged to monthly mean values, and then annual differences were taken to give SV values at the midpoint in time between a pair of samples at each observatory. 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.

The results presented in this report rely on data collected at magnetic observatories. We thank the WDC for Geomagnetism (Edinburgh) (**https://wdc.bgs.ac.uk**), the national institutes that support observatories, and INTERMAGNET for promoting high standards of magnetic observatory practice (**https://intermagnet.org**).

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 (October 2023), and calculated RMSEs relative to WMM2020 using the same method as the one used for the ground observatories.

Magnetic Storms Data Processing

For each storm date listed in Table 5, we obtained seven days of minute mean values centered on the storm day from global observatories on the INTERMAGNET website. Using the best quality data available, viz definitive in preference to quasi-definitive in preference to provisional in preference to variation, seven-day means were computed in declination. If the data were not already in declination (D) angular units, easterly intensity (Y) and northerly intensity (X), both in nT units, were converted to D in angular units. For each storm and each observatory, a maximum absolute D deviation from the mean was then computed.