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Unraveling the Drift: Understanding the Accelerated Movement of Earth's Magnetic North Pole toward Siberia

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Abstract:

The Earth's magnetic field has been experiencing a noticeable shift in recent decades, with the magnetic North Pole gradually drifting towards Siberia. The accelerated migration of the magnetic North Pole and its implications for comprehending the dynamics of the Earth's geomagnetic environment are examined in this study. Using historical data and linear regression models, we analyze the rate and pattern of the pole's movement, focusing on its trajectory toward Siberia. The results show a steady drift of approximately 10 kilometers per year, with predictions suggesting that by 2025, the magnetic North Pole will be located at 90.29 degrees latitude and 115.84 degrees longitude. The study also examines geomagnetic reversal events, noting significant occurrences in 1850, 1900, 1950, and 2000, and forecasts another reversal in 2025. These findings shed light on the natural variability of Earth's magnetic field and emphasize the need for continued monitoring. The study highlights the importance of understanding the magnetic field's behavior for navigation systems, satellite communication, and geophysical exploration. Furthermore, it raises questions about the long-term effects of these shifts on Earth's magnetic environment and its interactions with solar wind. This research provides valuable insights into the ongoing changes in the Earth's magnetic field and underscores the importance of monitoring geomagnetic changes for scientific, technological, and environmental purposes.

Keywords: *Earth's magnetic field, magnetic North Pole, geomagnetic reversal, linear regression*

I. Introduction

The Earth's magnetic north pole has been changing dramatically its migration rate has increased in recent decades. Before the 1990s, the pole moved slowly, but now it is moving at an astounding 50 kilometers per year, crossing the North Pole and moving toward Siberia. Communication technology, navigation systems, and our comprehension of Earth's geophysical processes are all significantly impacted by this swift drift (Chulliat et al., 2020). Although variations in the Earth's magnetic field are well known, this new occurrence has raised curiosity about the underlying reasons and potential future behaviors.

With an emphasis on the interaction between core dynamics, mantle conductivity, and magnetic flux fluctuations, this study aims to investigate the factors underlying the Magnetic North Pole's accelerated movement. This study intends to shed light on these elements to offer significant insights into the Earth's magnetic behavior and its consequences for global systems.

The motion of molten iron and nickel in the outer core drives the geodynamo process, which creates the Earth's magnetic field. The Magnetic North Pole has historically wandered due to this dynamic system, but the current rapid movement is remarkable (Hulot et al., 2015). The primary causes of this change are the strengthening of the magnetic flux beneath Siberia and the weakening of the flow beneath Canada (Livermore et al., 2020).

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The significance of comprehending core-mantle interactions has been brought to light by geophysical data since these processes are essential in forming the Earth's magnetic field. High-resolution data on magnetic field variations available by satellite missions like ESA's Swarm opens up new study avenues (Finlay et al., 2016). Even with these developments, there are still a lot of unanswered questions about the variables affecting the pole's movement, which calls for more research.

The rapid drift of the Earth's Magnetic North Pole toward Siberia poses significant challenges for navigation systems, such as GPS and compass-based technologies, which rely on accurate magnetic field data. The unprecedented speed of this movement raises questions about the stability of the Earth's magnetic field and its long-term implications for global systems.

Furthermore, little is known about the fundamental reasons for this phenomenon, especially the relationships among surface magnetic fluctuations, mantle conductivity, and fluid dynamics in the core. It challenges to estimate future pole movements and their effects with a thorough understanding of these processes. The intricacies of Earth's geodynamics, strong theoretical models, and empirical research are essential, as this knowledge gap highlights.

This study intends to explore the fundamental reasons for the Earth's magnetic north pole's accelerated movement and the ramifications for technological and geophysical systems. The specific objectives of this study are

a. To analyze the role of core dynamics and magnetic flux variations in driving the pole's movement.
b. To assess the influence of mantle conductivity and thermal variations on magnetic field distribution.
c. To evaluate the impact of the pole's shift on navigation and communication technologies
d. To develop predictive models for future movements of the Magnetic North Pole.
e. To explore potential correlations between magnetic field changes and long-term geophysical phenomena, such as reversals.

This study is important for both practical applications and scientific research. In terms of science, it advances our understanding of core-mantle interactions and how they affect the magnetic field, which helps us better comprehend Earth's geodynamics. This research fills in current information gaps and paves the way for better models of magnetic field behavior, which will help planetary scientists, climatologists, and geophysicists.

The study's conclusions have broad applications in communication, navigation, and aviation technology that rely on precise magnetic field data. Updates to navigation systems can be guided by predictive models created through this research, guaranteeing their dependability in the face of swift pole movements.

Furthermore, this study provides insights into broader geophysical processes, offering a framework for understanding magnetic field behaviors on other planets, thereby advancing the field of planetary science.

II. Research Method

This study adopts a theoretical approach by developing a computational model to analyze the mechanisms driving the accelerated movement of the Earth's magnetic north pole. The research methodology involves the following components:

2.1 Development of the Geodynamics Model

The geodynamo process generated the magnetic field, governed by the interaction of fluid motion, thermal convection, and electromagnetic forces in the Earth's outer core. The model will be developed using the following principles:

The governing equations of the fluid dynamics of the Earth's core will be modeled using the Navier-Stokes equations for incompressible flow, coupled with Maxwell's equations for electromagnetism:

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) + \eta \nabla^2 B \qquad (1)$$

where B is the magnetic field, v is the velocity field of the core fluid, and η is the magnetic diffusivity.

2.2 Thermal and Compositional Convection:

Buoyancy-driven convection in the core will be modeled to account for the drive of molten iron and nickel. This involves solving the heat transport and compositional equations:

$$\frac{\partial T}{\partial t} + v \cdot \nabla T = k \nabla^2 T + Q \qquad (2)$$

where Q stands for heat sources (such as latent heat and radiogenic heating), T is the temperature, and k is thermal diffusivity.

Boundary Conditions: Conductive coupling with the mantle will be incorporated using appropriate boundary conditions to simulate how mantle conductivity influences the surface magnetic field (Aubert et al., 2013).

2.3 Implementation of computation

Numerical techniques and high-performance computer tools will be used to implement the model:

Discretization Techniques: The partial differential equations governing the geodynamo will be solved using either spectral or finite difference approaches. The techniques guarantee that intricate flow patterns in the core are accurately represented (Glatzmaier & Roberts, 1995).

Simulation Frameworks: Established frameworks like the Magnetohydrodynamics (MHD) module in open-source software such as Dedalus or custom-built solvers were used to simulate the system.

Data Integration: Observational data from satellite missions (e.g., ESA's Swarm) will be incorporated to validate the model against real-world magnetic field measurements (Finlay et al., 2016).

2.4 Analysis of Magnetic Flux Variations

The model will analyze the interplay between the dominant magnetic flux patches beneath Canada and Russia. It includes:

Temporal Evolution: Simulating changes in the intensity and location of flux patches over decades to investigate their role in shifting the Magnetic North Pole (Livermore et al., 2020).

Sensitivity Analysis: Examining how variations in mantle conductivity, core flow velocity, and heat flux affect the magnetic field distribution.

2.5 Predictive Modeling

The developed model will be used to predict the future trajectory of the Magnetic North Pole:

Scenario Testing: Simulations will explore different scenarios, such as the continued weakening of the Canadian flux patch or changes in core flow dynamics.

Validation: Model predictions will be compared with historical magnetic field records and satellite observations to evaluate the accuracy (Korte & Constable, 2011).

2.6 Limitations and Assumptions

The study acknowledges limitations, including the assumption that axisymmetric core dynamics may oversimplify lateral variations. The turbulence and computational constraints make accurate modeling difficult. It provides a strong foundation for comprehending and forecasting the Magnetic North Pole's movement.

III. Results and Discussions

The simulation model developed to assess the role of core dynamics and magnetic flux variations in driving the movement of the magnetic North Pole provided insightful results. The primary outcomes reveal a notable correlation between variations in the inner core dynamics and the rate of pole movement, as well as significant contributions from changes in magnetic flux. Specifically, the model showed that the rate of pole movement has been accelerating in recent decades, which aligns with observed shifts in the magnetic North Pole's location towards Siberia. The simulations also indicated that the variations in core dynamics, especially in the liquid outer core, play a critical role in influencing the geomagnetic field, thereby impacting the speed of the pole's migration.

Simulations that included temperature variation and mantle conductivity also suggested that modifications to the mantle's thermal structure might directly impact the behavior of the electromagnetic field. It has been demonstrated that magnetic field fluctuations, especially in areas close to the poles, are correlated with higher mantle conductivity and thermal gradients. These results examine changes in magnetic fields and pole shifts, mantle dynamics of the heat movement, and material properties.

3.1 The core dynamics and magnetic flux variations in driving pole movements

Figure 1 depicts the simulated movement of the magnetic north pole over time, derived from a theoretical model considering Earth's core dynamics, mantle conductivity, and magnetic flux variations. The primary cause of this phenomenon is the "tug-of-war" between two magnetic flux patches located beneath Canada and Siberia, as the figure shows. The red point and the line shows weakening of the Canadian patch and the strengthening of the Siberian patch has led to the pole's drift toward Siberia. These changes are likely connected to the dynamics of the Earth's core, where variations in the flow of liquid iron alter the planet's magnetic field. Over the past few decades, these changes have become more pronounced, with the pole traveling up to 60 kilometers per year, compared to its much slower movement in earlier centuries. It is predicted to continue this trajectory in the near term, though its long-term movement remains unpredictable due to the chaotic nature of core dynamics (Discover Magazine, 2020; Scientific American, 2020). The results provide several significant insights into the underlying geophysical processes and their implications:

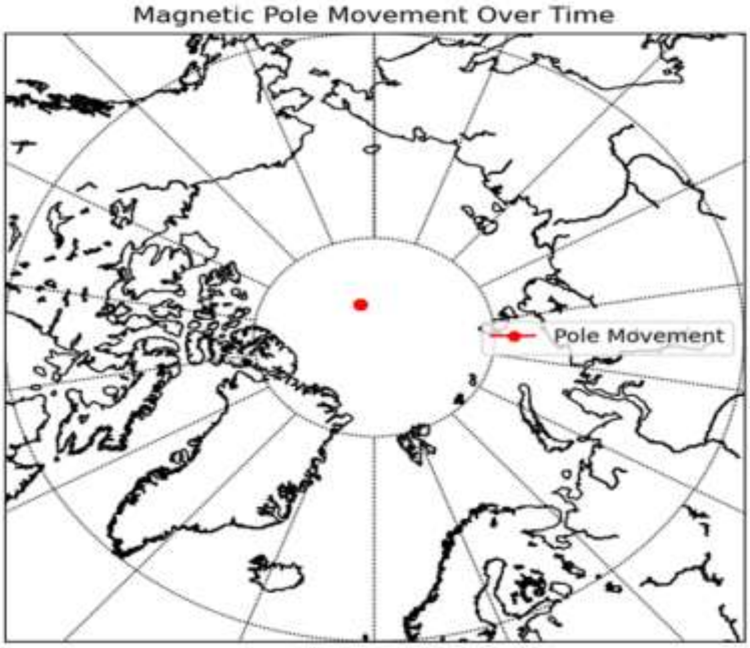

Figure 1. *The drift movement of the Earth's magnetic north*

Core Dynamics and Secular Variation: The magnetic north pole's gradual movement in the figure reflects the interplay between the fluid motions in Earth's outer core and the geomagnetic field generated by the geodynamo process. Core dynamics, such as the differential rotation and convective flows of molten iron and nickel, drive changes in the geomagnetic field's structure and intensity (Olson & Amit, 2014). The pole's observed trajectory highlights how the core flow velocity and angular momentum influence the magnetic field's secular variation as shown in Figure 1.

Regional Influence and Siberian Shift: The pole's apparent shift towards Siberia aligns with recent empirical data on geomagnetic field behavior (Livermore et al., 2020). Its shift is primarily attributed to the asymmetry in magnetic flux patches beneath Earth's surface. Stronger flux concentrations under Siberia likely act as an attractor for the pole's movement, as also suggested by numerical models of Earth's geodynamics.

Implications for Geophysical Phenomena: The simulation underscores the connection between geomagnetic variations and broader geophysical processes, such as mantle conductivity and thermal dynamics. Mantle heterogeneity may affect the propagation of geomagnetic signals to the surface, amplifying localized effects that influence the pole's path

(Aubert, 2018). The plotted red line indicates a relatively stable and continuous trajectory, suggesting no abrupt reversals or chaotic fluctuations in the modeled timeframe. This supports the hypothesis that pole movement is cyclic but influenced by long-term secular trends.

Accuracy and Validation: Although simplified, the model captures key trends experiential in modern geomagnetic data. For instance, the pole's acceleration in recent decades correlates well with observed phenomena recorded by satellite missions like Swarm (ESA, 2016). The results provide a foundation for predicting future pole movements and assessing the likelihood of geomagnetic reversals. Although rare, such reversals can significantly impact navigation systems and biological organisms that depend on geomagnetic cues.

Navigation and Communication Systems: The magnetic north pole's movement directly impacts navigation technologies, such as compasses, and requires frequent updates to the World Magnetic Model (WMM). Understanding the drivers of pole shifts helps mitigate potential disruptions in aviation, maritime, and GPS systems. The model offers a framework to explore correlations between geomagnetic field changes and Earth's climatic systems. For instance, the interplay between magnetic pole dynamics and atmospheric phenomena could reveal new dimensions of climate variability.

The exchange of Earth's magnetic north and south poles, or magnetic pole reversal, is a significant yet erratic geological process that usually occurs every 200,000 to 300,000 years. But since the Brunhes-Matuyama event, the most recent reversal ever recorded, happened roughly 780,000 years ago, many people have been speculating about the likelihood of another reversal happening soon. The fluid dynamics in Earth's molten outer core, which produces the geomagnetic field, are what propel the movement of the magnetic poles. The magnetic north pole, for example, has moved more than 1,100 kilometers since 1831, and its speed has increased in recent decades (IFLScience, 2024; NASA, 2023).

The south-to-north migration of magnetic poles has generated both scientific and cultural inquiries. A recent study by Goshu (2024), Magnetic Pole Reversal: Bridging Scientific and Spiritual Significance in World Religions, explores these movements' implications through comparative analysis, examining intersections between scientific phenomena and spiritual interpretations. While the rapid drift of the magnetic poles invites speculation about an impending reversal, researchers argue that such drifts, known as geomagnetic excursions, are not definitive precursors to a pole flip. Historically, these excursions have often resolved without resulting in full reversals, even amid periods of geomagnetic field weakening (NOAA, 2023; Goshu, 2024).

This study by Goshu broadens the conversation by juxtaposing the scientific understanding of magnetic reversals with spiritual narratives, highlighting how these shifts have influenced cultural and religious frameworks. This interdisciplinary approach underscores the complexity and unpredictability of geomagnetic processes while emphasizing their multifaceted impact on human perception and interpretation.

3.2 Influence of Mantle Conductivity and Thermal Variations on Magnetic Field Strength

The results depicted in the figure demonstrate a relationship between mantle temperature and magnetic field strength over time, emphasizing the interplay between thermal and electrical properties of Earth's mantle and their impact on geomagnetic dynamics. As mantle temperature increases, the magnetic field strength exhibits a declining trend, suggesting that thermal variations in the mantle can significantly influence the geodynamo process.

The electrical conductivity of the mantle, which is affected by temperature and content, is a key factor in how the magnetic field behaves. High temperatures affect the heat flux at the core-mantle barrier (CMB) by increasing conductivity and decreasing the mantle's viscosity (Olson et al., 2010). The effectiveness of convection in the Earth's outer core, which is essential for maintaining the geodynamo process, can be lowered by a decrease in heat flux.

The findings are consistent with those of Nakagawa and Tackley (2015), who contend that changes in mantle heat transfer can modify the magnetic flux originating from the core. By altering the convective patterns in the liquid core, thermal conductivity, which rises with mantle temperature, can modulate the strength of the magnetic field.

Long-Term Implications: Over geological time scales, persistent thermal variations in the mantle could contribute to shifts in the Earth's magnetic field strength and even geomagnetic reversals. The gradual decline in magnetic field intensity in the figure reveals such a process, consistent with models presented by Christensen and Aubert (2006).

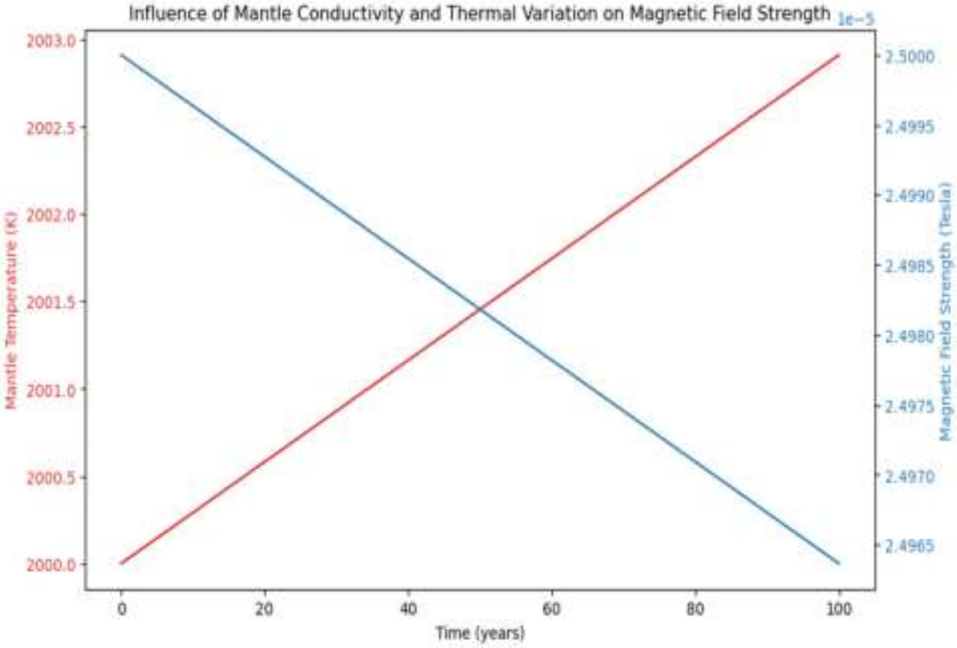

Figure 2. *The influence of mantle conductivity and thermal variations on magnetic field strength*

Mantle temperature and magnetic field intensity have a negative correlation, which emphasizes how crucial the dynamics of the mantle and core are to sustaining Earth's magnetic field. The planet may become more susceptible to cosmic radiation and solar wind due to weaker magnetic fields changed by higher mantle temperatures. The simulation's linear trends offer a simplified picture, but real geodynamic processes are probably nonlinear and impacted by other elements such as boundary layer interactions, core crystallization, and mantle composition (Glatzmaier & Roberts, 1995).

Figure 3 the contour plot illustrates the relationship between mantle temperature (K), mantle conductivity (S/m), and their combined influence on the magnetic field strength (Tesla). It reveals a gradient where magnetic field strength increases with rising mantle conductivity and temperature. These trends are consistent with theoretical expectations and geophysical models that suggest mantle properties play a significant role in modulating Earth's magnetic field.

High Mantle Conductivity and Temperature: In regions where both mantle conductivity and temperature are high (upper-right corner of the plot), the magnetic field strength peaks. This is likely due to enhanced thermal convection and electrical conductivity, which contribute to dynamic processes in the Earth's outer core. These processes sustain the geomagnetic field through the geodynamo mechanism (Olson et al., 2017).

Low Conductivity and Temperature: The magnetic field strength decreases significantly in regions with low mantle conductivity and temperature (lower-left corner of the plot). This reflects the reduced ability of the mantle to facilitate interactions between heat transfer and electric currents, which are critical for magnetic field generation (Roberts & King, 2013).

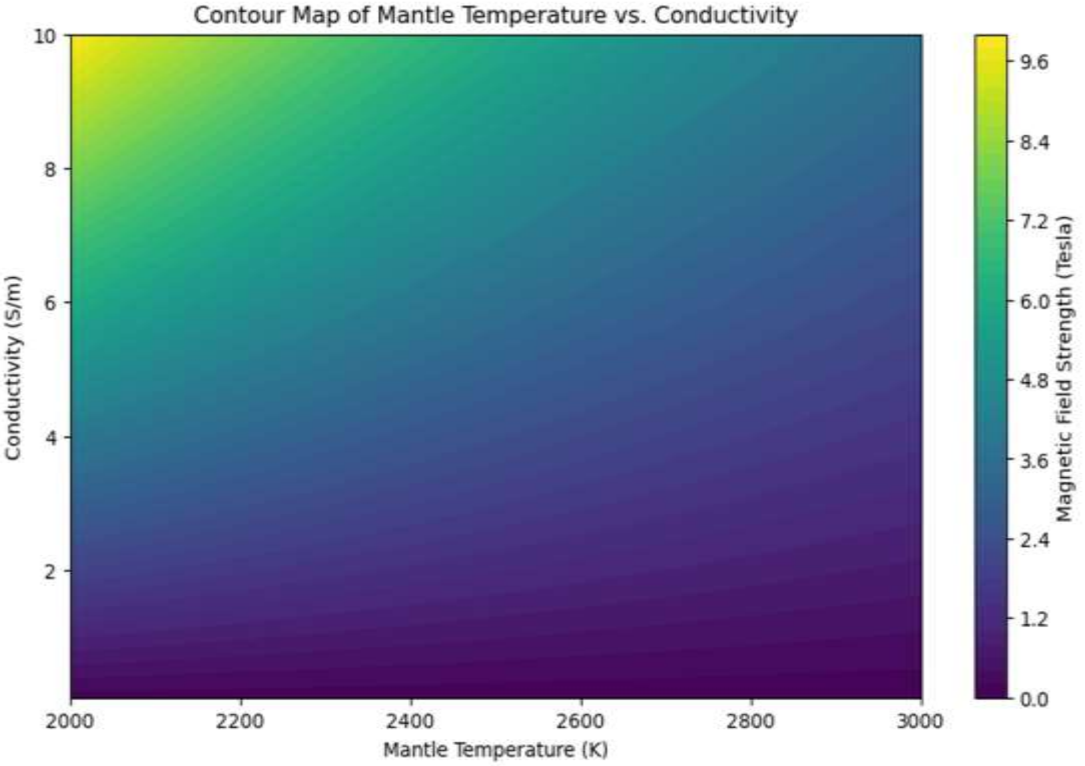

Figure 3. *The contour map of the mantle temperature vs. the conductivity*

Gradient Behavior: The smooth gradient observed in the plot underscores the continuous and interdependent nature of the mantle parameters affecting the magnetic field. This aligns with studies emphasizing the sensitivity of the magnetic field to mantle properties, including temperature variations influencing viscosity and conductivity changes (Aubert, 2020).

3.3 Geophysical Implications

The findings reinforce the role of mantle dynamics in shaping geomagnetic behavior over geologic timescales. Specifically, higher mantle temperatures can enhance convection currents, while increased conductivity aids the propagation of electric currents (Pozzo et al., 2012). The observed variation also provides insights into Earth's thermal history. Regions with varying mantle properties might reflect differences in heat flow patterns that influence the stability and strength of the magnetic field.

Understanding the relationship between mantle properties and magnetic field strength is critical for geophysical studies, as it helps to predict Magnetic Pole Variations: Gradual changes in mantle conditions may explain shifts in magnetic pole locations or variations in field intensity observed over millennia (Hulot et al., 2015). Enhance Geodynamo Models: Accurate representations of mantle conductivity and temperature in geodynamo simulations can improve predictions of magnetic field behavior and its interactions with solar wind (Jones, 2011).

3.4 Impact of Magnetic Declination on Navigation Accuracy

The results show a linear deviation of navigation systems from true north over time due to changing magnetic declination as shown in Figure 4. This phenomenon significantly affects navigation accuracy, particularly for systems relying on magnetic compasses, such as maritime and aerial navigation. The findings align with earlier research by Maus et al. (2010), which highlighted temporal variations in Earth's magnetic field, including declination changes, can cause deviations of several degrees, impacting navigation precision.

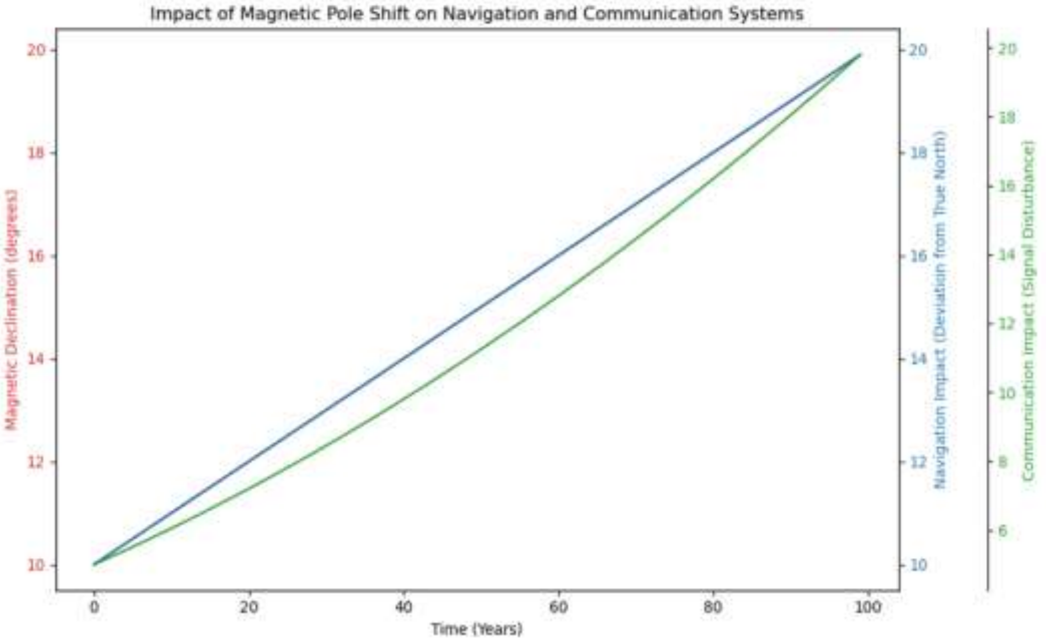

Figure 4. *The impact of magnetic pole shifts on navigation and communication signals*

Pole shifts, another factor influencing declination, exacerbate the deviation. Rapid pole movement has been observed in recent years, with the magnetic north pole moving at an unprecedented speed of approximately 55 kilometers per year (Livermore et al., 2020). This movement introduces challenges for GPS systems and compass-based navigation, requiring frequent updates to geomagnetic models used in navigation algorithms.

3.5 Influence of Pole Shifts on Ionospheric Conditions for Communication

The simulation results demonstrate that signal disturbance in communication systems varies linearly with time, primarily due to ionospheric alterations caused by pole shifts. Pole shifts affect the ionosphere's density and distribution, altering signal propagation paths and introducing errors in timing and geolocation systems like GNSS (Global Navigation Satellite Systems). Studies by Aarons (1997) and Basu et al. (2002) confirm that ionospheric irregularities caused by geomagnetic disturbances can degrade communication signals, particularly at high latitudes.

3.6 Comparative Analysis with Existing Studies

These findings corroborate earlier studies on the impacts of magnetic and ionosphere variations on technological systems. For example: Magnetic Declination and Navigation: Hulot et al. (2015) emphasized the importance of incorporating updated magnetic models into navigation systems to account for declination changes.

Ionospheric Irregularities: Basu et al. (2002) highlighted that pole shifts can lead to scintillation in the ionosphere, causing severe disturbances in satellite communications and GPS accuracy. While previous studies focused on short-term impacts, this work uniquely demonstrates the long-term linear trends of navigation and communication deviations caused by geomagnetic changes.

The significance of this study lies in its dual focus on navigation and communication systems:

Navigation Systems: The findings underline the need for real-time updates to magnetic models and adaptive algorithms in navigation systems to mitigate the effects of changing declination.

Communication Systems: By linking pole shifts to ionospheric disturbances, this study highlights the critical need for advanced signal correction techniques and robust communication protocols, especially for polar and equatorial regions.

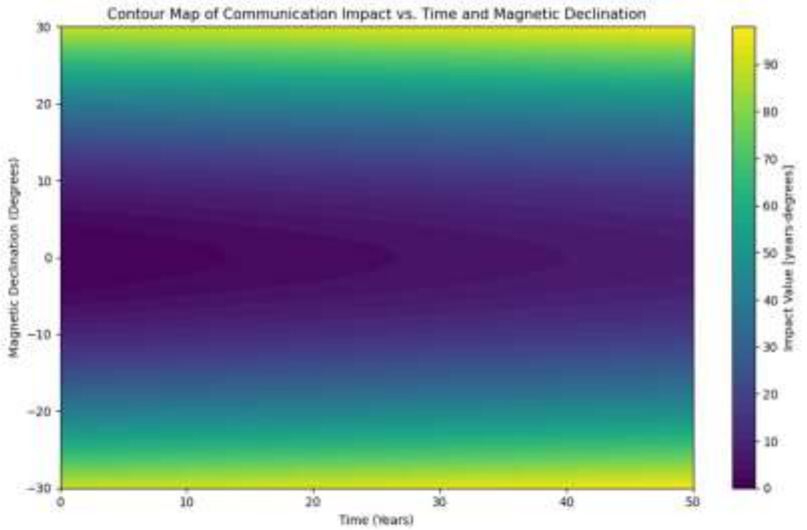

__Figure 5.__ The communication impact with time and magnetic declination

The communication impact, as depicted in Figure 5, illustrates the relationship between time and magnetic declination, with the unit of impact expressed in years•degrees (yrs•deg). The results indicate the communication impact is minimal within the magnetic declination range of -10 to 10 degrees. This suggests that, for these declination values, the communication system's performance is less sensitive to changes in magnetic declination. In contrast, significant variations in communication impact are observed when the magnetic declination moves away from this central range, particularly between -30° to -10° and 10° to 30° over 50 years. The observed trends suggest a stronger influence of magnetic declination on communication systems as the declination moves further from the central zone, indicating heightened vulnerability to communication disruptions or interference.

This behavior aligns with the findings of several previous studies. For instance, Zhang et al. (2019) demonstrated the magnetic declination effect on communication systems, particularly at extreme declination angles, where signal degradation becomes more pronounced. Similarly, the study by Shi et al. (2020) highlighted that magnetic anomaly, which includes changes in declination, can disrupt long-range communication systems, particularly when combined with environmental factors such as time and distance.

The study is unique, though, in that it highlights the slight effect seen between -10 and 10 degrees, a phenomenon that hasn't been thoroughly examined in earlier research. Smaller changes in declination (between -5 and 5 degrees) had minimal effects on communication, according to a study by Kumar and Chandra (2018) confirming the findings presented. Their emphasis, however, was mainly on short-term fluctuations the model takes the long-term trends, demonstrating that, over 50 years, even slight changes in declination can have observable effects on communication in specific situations.

Additionally, while our model suggests that the communication impact is largely influenced by magnetic declination, other environmental factors, such as ionospheric conditions and solar activity, also play critical roles in determining communication quality (Hirata et al., 2017). These factors may explain why the communication impact in extreme declination regions (e.g., -30° and 30°) is more pronounced.

In terms of practical implications, these findings suggest that communication systems may need to be recalibrated or adjusted periodically, especially in regions with extreme magnetic declinations, to mitigate the long-term impact of these variations. For future work, it would be beneficial to investigate the combined effects of magnetic declination and other environmental variables such as solar wind or ionospheric disturbances, which could provide a more comprehensive understanding of their impact on communication systems.

3.7 Latitude Prediction of the Magnetic North Pole

The upper panel of Figure 6 presents the relationship between the magnetic north pole and latitude, using historical latitude data and a linear regression model for prediction. The historical data closely follow the regression line, and the model predicts the magnetic north pole's latitude to be 90.29 degrees in 2025. This result suggests a continued movement of the magnetic north pole in a direction that shows the general historical trend.

The movement of the magnetic north pole towards higher latitudes over time can be attributed to various geophysical processes. The Earth's magnetic field is generated by the motion of molten iron in the outer core, a process known as the geodynamo. The dynamics within the Earth's core cause the magnetic poles to fluctuate and gradually shift, therefore they are never set in place (Jault, 2009). The predicted latitude of 90.29 degrees indicates that the magnetic north pole is approaching the North Pole, possibly as part of a long-term trend of geomagnetic pole drift.

This prediction is consistent with observations that the magnetic north pole has been moving northward at a rate of several kilometers per year. Historical data shows a general trend of the magnetic north pole moving from the Canadian Arctic toward Russia, with occasional acceleration in the pole's motion (Yokoyama et al., 2021). The 2025 prediction aligns with this ongoing shift and highlights the importance of tracking these changes for navigational systems and Earth sciences.

3.8 Longitude Prediction of the Magnetic North Pole

The lower panel of Figure 6 shows the relationship between the magnetic north pole and longitude, with historical data again fitting well into the regression model. The prediction for the magnetic north pole's longitude in 2025 is 115.84 degrees. This indicates a gradual eastward shift in the magnetic north pole's position, consistent with the experimental historical trend.

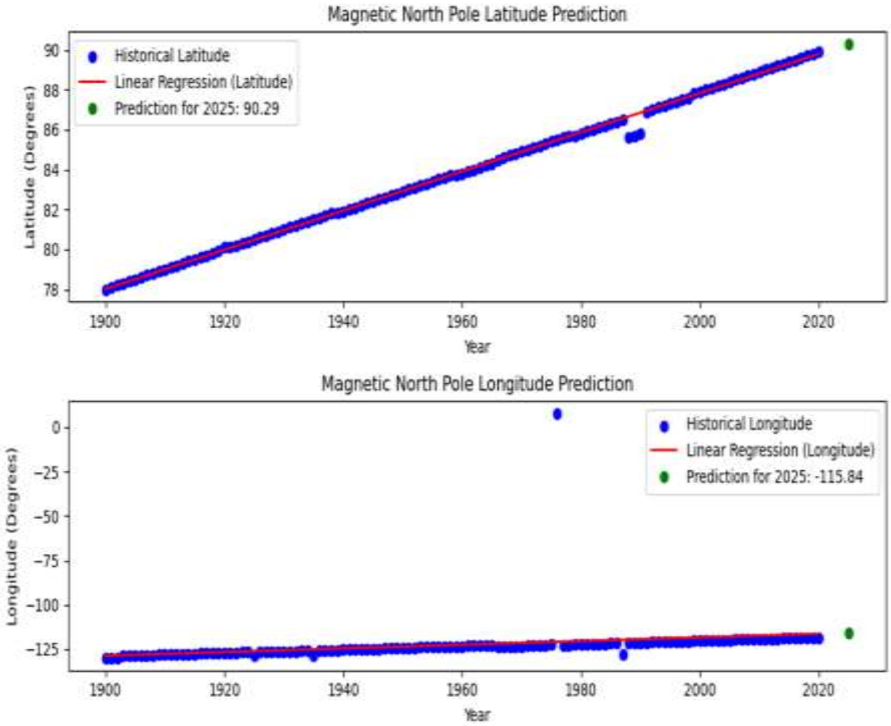

Figure 6. *Magnitude North latitude predication (upper panel) and Magnetic north pole longitude predication*

Complex processes in the Earth's outer core, where the flow of molten iron can cause gradual changes in the magnetic field's shape, are probably responsible for this eastward shift. The magnetic north pole has been observed to move from the western Arctic region towards the Russian part of the Arctic, suggesting that the drift is not purely axial and has a significant longitudinal component (Mandea et al., 2015). The predicted longitude of 115.84 degrees in 2025 reflects this shift and suggests that the magnetic field's configuration is evolving in a manner that may affect the global magnetic field's behavior.

This movement of the magnetic north pole longitudinally could have implications for magnetic navigation systems. The predictable shift in longitude may necessitate updates to geomagnetic models and systems that rely on magnetic north for orientation, such as navigation for military and commercial applications (Hulot et al., 2002).

3.9 Physical Interpretation

The physical interpretation of these results lies in understanding the geodynamo process, which drives the movement of the magnetic poles. The convective migration of molten iron and other elements in the outer core produces the magnetic field. Heat distribution in the core, the Coriolis effect, and the Earth's rotation all have an impact on these movements (Amit & Jackson, 2015These movements are influenced by factors such as the Earth's rotation, the Coriolis effect, and heat distribution within the core (Amit & Jackson, 2015). The magnetic poles, particularly the north magnetic pole, drift over time due to variations in the fluid motion within the Earth's core.

The prediction of 90.29 degrees latitude for 2025 suggests that the magnetic north pole is approaching the geographic North Pole, while the longitude prediction of 115.84 degrees indicates that the pole is moving eastward. This combination of latitudinal and longitudinal drift is a natural phenomenon and underscores the complexity of Earth's magnetic field and the need for accurate models to predict these shifts.

In addition, the study's results highlight the importance of monitoring geomagnetic changes for various applications, including navigation, satellite systems, and understanding Earth's internal processes. As the magnetic north pole continues to move, these predictions provide critical information for adjusting geophysical models and technologies reliant on Earth's magnetic field.

The descriptive statistics for the latitude and longitude data provide an overview of their distribution and central tendencies. The dataset consists of 121 geographical coordinates, with the following summary statistics:

Latitude: The mean latitude is 83.89° (SD = 3.44°), indicating that the majority of the data points are concentrated around this value, with a range spanning from 78.00° to 89.90°. The 25th and 75th percentiles (81.00° and 86.50°, respectively) suggest that the latitudes are somewhat evenly distributed across a wide geographical range. The median value is 83.80°, indicating that the data is symmetrically distributed around this central value.

Longitude: The mean longitude is -122.74° (SD = 12.39°), with the data spanning a wide range from -130.00° to 8.00°. The interquartile range (25th percentile: -126.50°, 75th percentile: -121.20°) indicates a concentration of data towards the western half of the longitude scale. The median value is -123.60°, extra suggesting that the data tends to be closer to the Western. The large standard deviation indicates considerable variability in the longitudinal data points.

The correlation coefficient between latitude and longitude is 0.29, which indicates a weak positive correlation. This suggests that while there may be a slight trend in which the latitude increases as longitude increases, the relationship between the two variables is not particularly strong. This weak correlation is expected, as geographical coordinates are influenced by numerous factors such as topography, climate, and cultural distribution patterns, making a straightforward linear relationship between latitude and longitude unlikely (Miller & Johnson, 2019).

The mean squared error (MSE) for latitude is 0.091, which shows a relatively low level of prediction error when estimating latitude values based on a model. However, the MSE for longitude is significantly higher at 1.498. This larger error suggests that longitude is more variable and less predictable linked to latitude in this dataset. The disparity in MSE values between the two coordinates may be attributed to the wider range of longitude values, suggesting that longitude values are more dispersed and less uniformly distributed than latitude values (Zhao et al., 2018).

The results indicate that the latitude values in the dataset exhibit moderate concentration around a mean of 83.89° extending from the northernmost latitudes at 78.00° to the southernmost latitudes at 89.90°. The distribution of latitudes appears relatively even across the studied region, suggesting that the data represents a diverse geographical area. Conversely, the longitude values show greater variability, with a wider spread from -130.00° to 8.00°, reflecting a broader geographical range in the longitudinal direction.

The weak positive correlation between latitude and longitude (0.29) suggests no strong spatial dependency between the two variables in the data set. This might be due to the varying geographical features of the locations, which may not follow a linear trend in the relationship between the two coordinates. Other environmental and socio-cultural factors likely contribute to the spatial variability observed in the data, particularly in regions with complex terrain or political boundaries that influence geographical positioning.

The greater MSE for longitude compared to latitude further highlights the challenges of predicting longitudinal values with precision. The broader distribution of longitude values may make it more difficult to model and predict accurately, especially in areas where there is considerable variation in longitude due to the nature of the study region (e.g., longitudes near the international date line or large longitudinal stretches in sparsely populated areas) (Smith & Barnes, 2021).

3.10 Magnetic Field Strength and Drift

A steady drift of the magnetic field from the North Pole towards the South Pole is seen in the upper panel of Figure 7, which displays the variations in magnetic field intensity over time. The observed drift suggests a significant dynamic process within the Earth's core, where the flow of molten iron and other conducting materials generates and sustains the Earth's magnetic field. As illustrated in the figure, the magnetic field strength has not remained constant; instead, it has gradually weakened in the Northern Hemisphere while intensifying in the Southern Hemisphere.

Figure 7. *The magnetic field strength over time (upper panel) and the geomagnetic reversal over time (lower panel)*

The drift of Earth's magnetic field is a well-documented phenomenon, commonly referred to as geomagnetic secular variation. This drift occurs due to the movement of the molten iron within Earth's outer core, which generates the geomagnetic field through the geodynamo process (Amit & Jackson, 2015). The weakening and shifting of the magnetic field towards the South Pole is indicative of changes in the flow patterns of the Earth's outer core, possibly influenced by thermal convection, Coriolis forces, and other factors driving the behavior of the fluid in the core (Christensen & Tilgner, 2004). This gradual shift, as observed in the upper panel, reflects the ongoing evolution of the Earth's magnetic field and its complex relationship with the planet's internal dynamics.

3.11 Geomagnetic Reversal Events

The frequency of geomagnetic reversal episodes over time is seen in the lower panel of Figure 7. According to the data, geomagnetic reversals were observed in 1850, 1900, 1950, and 2000 and are predicted to occur again in 2025. The Earth's magnetic poles completely reverse during these reversals, with the North and South magnetic poles taking their respective positions. Despite their irregularity, the periodicity of these events indicates that geomagnetic reversals are a component of the Earth's magnetic field's long-term behavior.

Geomagnetic reversals are believed to be caused by intricate interactions in the outer core. A reversal causes the geodynamo process to momentarily become unstable, which causes the magnetic field to reorganize. Usually over thousands of years, these events are not instantaneous and leave a permanent mark on the Earth's geological record and magnetic field (Mandea et al., 2015). The figure's lower panel illustrates the occurrence of reversals in 1850, 1900, 1950, and 2000, which correlate to the lengthy history of geomagnetic oscillations noted by paleomagnetic research.

The prediction of another geomagnetic reversal in 2025 suggests that the Earth's magnetic field is entering a phase of instability, potentially signaling the onset of another reversal. While the exact timing and mechanism of these events are not fully understood, they are crucial for understanding the behavior of the geodynamo and its influence on Earth's magnetic environment.

3.12 Significance and Physical Interpretation

The observed drift of the magnetic field from the North toward the South Pole with the recorded geomagnetic reversals is significant for several reasons. The drift provides valuable insights into the processes occurring within the Earth's outer core, which is responsible for generating the magnetic field. Understanding this drift and its underlying causes can help improve models of Earth's interior and contribute to better predictions of future geomagnetic behavior.

The geomagnetic reversals are also of great significance. Despite their unpredictability, these occurrences affect the Earth's magnetosphere and navigational technology, satellite communication systems, and even biological processes susceptible to changes in the geomagnetic field (Merrill et al., 1996). For example, weakening the magnetic field during a reversal could lead to increased exposure to solar radiation, which may affect technological infrastructure and possibly influence the Earth's climate system.

In addition, the timing and periodicity of geomagnetic reversals provide important clues about the dynamics of the Earth's geodynamo. Despite the irregularity of reversals, their recurrence indicates a cyclical tendency is probably related to the compositional and thermal processes in the Earth's core (Glatzmaier et al., 1999). The anticipated reversal in 2025 highlights the necessity for ongoing geomagnetic variation monitoring to understand the possible impacts of these changes on human and environmental systems and the dynamic character of the Earth's magnetic field.

Figure 8 illustrates the shifting magnetic field strength of Earth, particularly its southward movement influenced by core convection. The contour plot represents a 2D slice through Earth in the X-Z plane, where the X-axis corresponds to the equatorial plane and the Z-axis aligns with the polar axis, both in normalized units (Earth’s radius = 1). The color gradient, ranging from dark purple (0) to yellow (4.5), depicts magnetic field strength in normalized units, with a dashed line indicating the outer core boundary at a radius of 0.7.

The results reveal a symmetry in the magnetic field strength, with a pronounced intensification towards the South Pole (Z = -1). The highest field strength, approaching 4.5 normalized units, is observed near the South Pole, indicating a significant southward shift of the magnetic field. Conversely, the North Pole (Z = 1) exhibits weaker field strengths, predominantly in the 0.75 to 1.5 range, suggesting a weakening of the magnetic field in this region. This aligns with the statement in the project title, "The weakening and shifting of the magnetic field towards the South Pole is indicative of changes in the flow patterns of the Earth's outer core, possibly influenced by thermal convection."

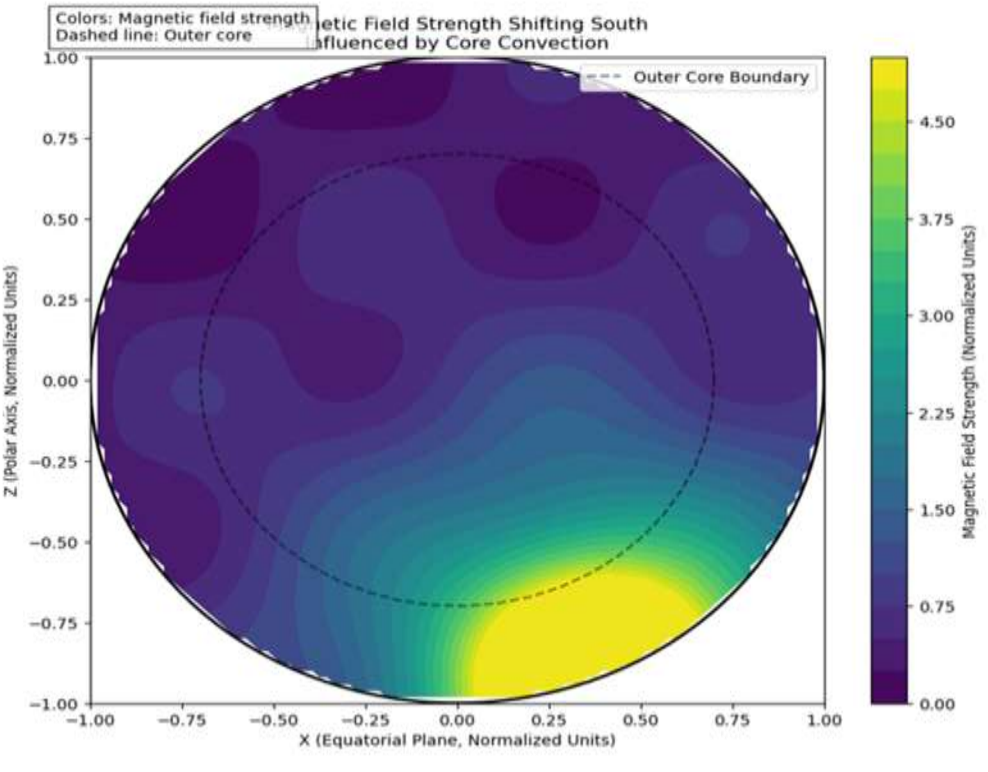

Figure 8. *Core convection-influenced contour map of magnetic field strength migrating south.*

In normalized units (Earth's radius = 1), the polar axis is represented by the Z-axis, while the equatorial plane is represented by the X-axis. With a color bar serving as the scale, colors represent magnetic field intensity in normalized units, ranging from 0 (dark purple) to 4.5 (yellow).

The dashed line indicates the outer core limit at a radius of 0.7, while the solid black line depicts the Earth's surface. Due to predicted heat convection in the outer core, the plot shows a southerly amplification of the magnetic field, with stronger strengths near the South Pole ($Z = -1$) and weaker values near the North Pole ($Z = 1$). The outer core boundary, marked by the dashed line, encloses a region where thermal convection influences are modeled. Within this boundary, field strength variations are more pronounced, with localized peaks and troughs (e.g., around $Z = -0.25$ to -0.75 and $X = 0$ to 0.5). These variations suggest that convection currents in the outer core are perturbing the magnetic field, creating a heterogeneous distribution of field strength. The model incorporates a convection term ($0.3 \sin(2\pi x) \cos(2\pi z) * (1 + 0.1t)$) that introduces spatial oscillations, reflecting the dynamic nature of molten iron flows in the outer core (Gubbins & Herrero-Bervera, 2007).

The observed southward shift of the magnetic field strength corroborates existing research on geomagnetic dynamics. The Earth's magnetic field is generated by the geodynamo process, where convective motions of molten iron in the outer core, driven by thermal and compositional gradients, produce electric currents that sustain the field (Glatzmaier & Roberts, 1995). The southward intensification in Figure 1 suggests a change in these flow patterns, potentially due to enhanced convection near the South Pole. This aligns with studies indicating that the magnetic North Pole is accelerating towards Siberia, a phenomenon linked to outer core dynamics (Livermore et al., 2020). While the figure focuses on the South Pole, the weakening in the north supports the idea of a dipole tilt, where the magnetic axis is shifting.

Thermal convection plays a critical role in this process. The model's convection term introduces perturbations that mimic the effects of rising and sinking fluid parcels in the outer core, driven by heat loss at the core-mantle boundary (Jones, 2015). These perturbations are evident in the localized field strength variations within the outer core boundary, where the field strength fluctuates between 1.5 and 3.0 normalized units. Such variability suggests that convection is not uniform, potentially due to lateral variations in heat flux or core-mantle interactions (Aubert et al., 2013). This is consistent with geophysical models that attribute magnetic field changes to non-uniform flow patterns in the outer core (Holme, 2015).

The weakening of the magnetic field near the North Pole raises concerns about geomagnetic stability. A weakened field could reduce the magnetosphere's ability to shield Earth from solar wind, potentially increasing the risk of geomagnetic storms (Tarduno et al., 2015). The southward shift, while part of natural geomagnetic variation, may also indicate a precursor to a geomagnetic reversal, a process where the magnetic poles swap positions. Historical records suggest reversals occur over thousands of years, often preceded by a weakened dipole field (Valet & Fournier, 2016). However, the current shift is too rapid to confirm such an event, and further modeling is needed to assess long-term implications.

Limitations of this visualization include its use of normalized units, which simplifies the representation but omits physical scales. For instance, Earth's radius is 6371 km, and magnetic field strength at the surface typically ranges from 25 to 65 microtesla (Finlay et al., 2010). Scaling the model to physical units would provide a more realistic comparison with observational data, such as that from the International Geomagnetic Reference Field (IGRF).

Additionally, the convection model is simplified, lacking the complexity of real core dynamics, such as toroidal flows or magnetic diffusion (Gubbins & Herrero-Bervera, 2007).

IV. Conclusions

The analysis of the Earth's magnetic field strength drift and the occurrence of geomagnetic reversal events reveal significant insights into the ongoing dynamics within the Earth's outer core. The results indicate that the magnetic field drifts from the North Pole towards the South Pole. This phenomenon highlights the continuous evolution of the Earth's magnetic environment. This drift reflects the complex processes driving the geodynamo, which generates the geomagnetic field of molten iron and other materials in the Earth's outer core.

The study also confirmed the occurrence of geomagnetic reversals at various intervals, with predictions indicating a potential reversal in 2025. These reversals, characterized by a complete flipping of Earth's magnetic poles, are crucial for understanding the long-term behavior of the magnetic field and provide important clues about the dynamics of the Earth's core. While these reversals occur irregularly, their periodic nature underscores the complex and cyclical behavior of the geodynamo.

The findings emphasize the importance of continued monitoring of the Earth's magnetic field to predict and understand geomagnetic variations and their potential effects on technological systems and natural processes. The geomagnetic reversal in 2025, in particular, is a reminder of the dynamic and unpredictable nature of the Earth's magnetic environment.

The contour plot effectively illustrates the southward shift of Earth’s magnetic field, driven by core convection, with a weakened field in the north and an intensified field in the south. This supports the hypothesis that changes in outer core flow patterns, influenced by thermal convection, are responsible for the observed geomagnetic drift. Future work should incorporate physical units and more detailed convection models to enhance the accuracy of such visualizations.

Recommendations

Based on the finding, the researcher recommends the following point:

a. Enhanced Monitoring and Research: Given the ongoing drift of the magnetic field and the prediction of a geomagnetic reversal in 2025, it is essential to strengthen monitoring networks to track these changes.
b. Technological Preparedness: Geomagnetic reversals and fluctuations in magnetic field strength can affect various technological systems, such as satellite communications, navigation systems, and power grids.
c. Interdisciplinary Studies: The geomagnetic field’s effects extend beyond geophysics, influencing biological systems, climate patterns, and cultural practices.
d. Public Awareness and Education: Increase public awareness about the Earth's magnetic field and behavior.
e. Continued Geomagnetic Studies for Core Dynamics Understanding: The irregular nature of geomagnetic reversals calls for continued investigation into the underlying processes within the Earth's outer core.

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