

New insights into Earth's mantle conductivity and water distribution using Macau Science Satellite-1 data

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Key Points:

- Time series of inducing coefficients from magnetospheric currents and induced coefficients from the conductive mantle show excellent agreement between data from the Macau Science Satellite-1 (MSS-1) and from the Swarm satellites.
- The first conductivity profile of the Earth's interior derived from MSS-1 data has been successfully and reliably constructed.
- Data from the MSS-1 indicate the presence of up to 300% of ocean water in the mantle transition zone, providing compelling evidence that supports the hypothesis of a deep water cycle within the Earth's interior.

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Abstract: Water content, whether as free or lattice-bound water, is a crucial factor in determining the Earth's internal thermal state and plays a key role in volcanic eruptions, melting phenomena, and mantle convection rates. As electrical conductivity in the Earth's interior is highly sensitive to water content, it is an important geophysical parameter for understanding the deep Earth water content. Since its launch on May 21, 2023, the MSS-1 (Macau Science Satellite-1) mission has operated for nearly one year, with its magnetometer achieving a precision of higher than 0.5 nT after orbital testing and calibration. Orbiting at 450 kilometers with a unique 41-degree inclination, the satellite enables high-density observations across multiple local times, allowing detailed monitoring of low-latitude regions and enhancing data for global conductivity imaging. To better understand the global distribution of water within the Earth's interior, it is crucial to study internal conductivity structure and water content distribution. To this aim, we introduce a method for using MSS-1 data to estimate induced magnetic fields related to magnetospheric currents. We then develop a trans-dimensional Bayesian approach to reveal Earth's internal conductivity, providing probable conductivity structure with an uncertainty analysis. Finally, by integrating known mineral composition, pressure, and temperature distribution within the mantle, we estimate the water content range in the mantle transition zone, concluding that this region may contain the equivalent of up to 3.0 oceans of water, providing compelling evidence that supports the hypothesis of a deep water cycle within the Earth's interior.

Keywords: Macau Science Satellite-1; mantle conductivity; water content

1. Introduction

The MSS-1 (Macau Science Satellite-1) mission is a scientific and technological project developed jointly by the Macau Special Administrative Region and the China National Space Administration (Zhang K, 2023). On May 21, 2023, at 16:21 (Beijing time), the Long March 2C rocket successfully launched the MSS-1 satellites from the Jiuquan Satellite Launch Center. The satellites entered their predetermined orbit, marking a successful mission. The

MSS-1 is the world's first attempt to monitor, by satellite, the geomagnetic field and space environment at low latitudes. It has the highest accuracy in Earth's magnetic field detection (less than 0.5 nT) among similar satellites, significantly enhancing China's capabilities in this area. MSS-1 uses a dual-satellite observation mode: Satellite A is equipped with high-precision magnetometers for Earth's magnetic field detection, while Satellite B carries high-energy particle detectors, a solar X-ray monitor, and other instruments for gathering space environment data. MSS-1 satellites complement observations by the European "Swarm" satellites and China's "Zhangheng-1" satellite, providing measurements of Earth's magnetic field and space environment changes at low latitudes, monitoring the South Atlantic Magnetic Anomaly, among other objectives. This mission will provide valuable data for the long-term study of geomagnetic field evolution.

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The Earth's magnetic field is a highly complex and coupled system. Satellite measurements can capture magnetic fields from various sources (Olsen and Stolle, 2012), including the Earth's liquid core dynamo, mantle-induced fields, lithospheric magnetization, large-scale oceanic movements, and currents in the ionosphere and magnetosphere. Using such observational data, scientists can explore six key research areas: (1) solar activity and Earth's space environment; (2) inversion of terrestrial planet core dynamics and numerical forecasting of the main magnetic field; (3) laboratory simulations of terrestrial planet core dynamics; (4) electromagnetic induction studies of the mantle and ocean; (5) investigations of the lithospheric magnetic field; and (6) establishment of high-precision four-dimensional models of the Earth's magnetic field.

The study of mantle electromagnetic induction is a central focus of geomagnetic satellites, including the MSS-1 (Zhang K, 2023). The primary sources of mantle electromagnetic induction at satellite altitudes originate from the randomly varying currents in the magnetosphere. The magnetic fields generated by these currents induce secondary currents within the Earth's interior, which, according to Ampere's law, generate time-varying secondary or scattered magnetic fields. At satellite altitudes, onboard magnetometers measure the combined effect of these primary time-varying fields and the scattered fields they induce. Typically, the amplitude of induced magnetic fields from magnetospheric currents at satellite altitudes ranges from 1 nT to 10 nT. Early geomagnetic satellites had magnetometers with an accuracy of higher than 1 nT, making it difficult to extract signals related to mantle electromagnetic induction. However, starting from the Swarm satellites, followed by the MSS-1, the precision of onboard magnetometers improved to higher than 0.5 nT. This increased precision has enabled researchers to extract mantle electromagnetic induction data from these high-precision measurements, drawing greater attention to mantle electromagnetic induction studies. Mantle electromagnetic induction studies are significant not only for developing more reliable Earth main magnetic field models but also for establishing accurate models of external current systems and providing valuable insights into the Earth's internal thermal state.

The thermal state parameters of the Earth's interior primarily include mineral composition, water content, and temperature. Generally, with an oxide composition system that constitutes more than 98 percentage of the Earth's interior mass (e.g., $\text{Na}_2\text{O}-\text{CaO}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$), thermodynamic equilibrium conditions can be used to calculate the corresponding phase diagrams of mantle minerals (Connolly, 1990; Stixrude and Lithgow-Bertelloni, 2011; Khan et al., 2011; Khan and Shankland, 2012; Khan, 2016). Based on the range of mantle pressure and temperature, the mantle mineral composition at different depths can be determined. Additionally, first-principles calculations and sample testing methods help calculate the Earth's mineral compositions. Extensive numerical and physical experiments have provided geophysicists with a deep understanding of the Earth's mineral composition, leading to the establishment of relatively reliable mantle composition models. It is generally accepted that olivine, orthopyroxene, clinopyroxene, and garnet are the main components of the crust

and upper mantle; garnet, wadsleyite, and ringwoodite are predominant in the mantle transition zone; ferropericlase, bridgmanite, and Ca-perovskite dominate the lower mantle. In addition to these key mineral components, small amounts of volatiles like H_2O in forms of free water or hydrogen and hydroxyl ions within the crystal lattice of nominally anhydrous minerals also exist (Karato, 2011). Numerous experiments show that H_2O volatiles significantly alter mantle properties, such as by reducing mantle rock viscosity, thereby increasing convection rates, accelerating volcanic eruptions, and influencing plate tectonics (Bercovici and Karato, 2003; Tarits et al., 2004; Cai C et al., 2018; Munch et al., 2018). H_2O volatiles also substantially lower the melting temperature of mantle minerals. As hydrous minerals migrate to greater depths, rising mantle temperatures can cause partial melting of hydrous mantle rocks (e.g., those from subducting slabs carrying significant free water), affecting mantle convection rates. During the ascent of hydrous mantle rocks, decreasing water solubility in shallow mantle minerals expels H_2O volatiles, leading to melting at depths where water solubility varies (e.g., the 410 km and 660 km discontinuities). For shallower hydrous mantle rocks (e.g., those in the asthenosphere), as they ascend (e.g., beneath mid-ocean ridges, oceanic islands, or in subduction zone mantle wedges), a decrease in pressure also lowers mantle mineral melting temperatures (Karato, 2011). The combined effects of water content and pressure reduction can significantly decrease the melting temperature, leading to noticeable melting of hydrous mantle rocks, which provides deep material sources for basaltic magma in volcanic eruptions. Therefore, water content (free or lattice-bound) is a critical factor in controlling volcanic eruptions, explaining melting phenomena, and influencing mantle convection rates (Bercovici and Karato, 2003; Naif et al., 2013; Fei HZ et al., 2017; Cai C et al., 2018; Peslier, 2020; Hou MQ et al., 2021; Zhang HQ et al., 2022; Miyazaki and Korenaga, 2022).

There are two main methods for calculating water content in the Earth's interior: geochemical (petrological) and geophysical (Karato, 2011). The petrological approach analyzes mantle rock samples from deep within the Earth to obtain physicochemical information, such as water content (Pearson et al., 2014; Nishi et al., 2014; Chen H et al., 2020b; Wang WZ et al., 2021; Gu TT et al., 2022). To eliminate interference that might affect the samples during their journey from the deep mantle to the surface, these samples are generally required to come from mantle xenoliths encased in deep mantle diamonds. However, such diamond-encased xenoliths are rare, so the petrological method can estimate only water content for specific depths in certain regions. To estimate water content over larger regions or globally, geophysical methods are necessary. Among these, natural seismic methods and global electromagnetic induction are feasible for detecting water content in the Earth's interior. However, theory and experiments show that seismic velocity is influenced not only by water content but also by mineral composition, temperature, and pressure, with these factors often having a more significant impact than water content. Thus, deviations in the Earth's interior parameters of mineral composition, temperature, and pressure can lead to significant errors in water content calculated from seismic velocity, potentially resulting in conclusions that contradict existing knowledge (Meier et al., 2009). In contrast, electrical conduc-

tivity obtained through global electromagnetic induction is most sensitive to water content in the Earth's interior, with temperature being a secondary factor (Bercovici and Karato, 2003; Utada et al., 2003; Bolfan-Casanova, 2005; Kuvshinov, 2008; Kelbert et al., 2009; Inoue et al., 2010; Karato, 2011; Grayver et al., 2016, 2017; Karato, 2019; Ohtani, 2020, 2021; Hu QY et al., 2020; Zhang HQ et al., 2022). Changes in mineral composition and pressure have minimal, often negligible, effects on conductivity values (Karato, 2011). Therefore, electrical conductivity is the most important geophysical parameter for understanding water content in the Earth's interior.

Since its launch, the MSS-1 geomagnetic satellite has been operational for nearly one year. Following orbital testing and magnetometer calibration, the satellite's magnetometer has achieved its target precision of higher than 0.5 nT (Zhang K, 2023). With an orbital altitude of 450 kilometers, the unique 41-degree inclination of MSS-1 allows high-density observations across multiple local times, enabling detailed monitoring of low-latitude regions over short times. This results in increased observational data for global conductivity imaging. To deepen understanding of the global distribution of water content within the Earth's interior, which are very helpful to explain the deep material sources of basalt in volcanic eruptions and to advance research on mantle convection rates and processes, studies on the Earth's internal conductivity structure and water content distribution using data from the MSS-1 are urgently needed.

We have conducted a preliminary study to invert the conductivity profile of the Earth's interior and estimate the associated water content using nine months of MSS-1 data. This study presents a method for extracting induced magnetic fields originating from magnetospheric currents from these MSS-1 geomagnetic data. By comparing these results with those from ESA's Swarm geomagnetic satellite data during the same period, the characteristics of the magnetospheric induction fields detected by MSS-1 are illustrated. We then briefly introduce an inversion method used to derive Earth's internal conductivity from the magnetospheric induction fields. To enhance the reliability of the conductivity inversion results, we employ a trans-dimensional Bayesian method, which not only provides the most probable conductivity structure but also includes an uncertainty analysis of the corresponding estimates. Finally, by integrating the mineral composition calculated along the established pressure and temperature pathways of the mantle, we estimate the range of water content in the mantle transition zone.

2. Data and Method

2.1 Data Processing

We employed vector magnetic measurements from MSS-1 (Zhang K, 2023) to develop a global averaged mantle conductivity structure, spanning from November 1, 2023, to July 31, 2024. In order to verify the precision and dependability of the MSS-1 data, vector magnetic data from the Swarm mission (Olsen et al., 2013) for the identical timeframe were also investigated. The recorded data mainly capture influences from the Earth's core, crust, ocean, ionospheric, and magnetospheric current systems, along with

induced effects within the mantle. Notably, magnetospheric currents and their time-dependent induced responses are crucial for understanding the conductivity structure of the mantle.

We employed a data processing method from Yao HB et al., (2023a) to estimate the global Q- and C-responses originated from magnetospheric currents, vital for visualizing mantle conductivity. First, the core and crustal magnetic fields as predicted by the latest CHAOS-7 geomagnetic model (Finlay et al., 2020) were eliminated from the unprocessed magnetic data. To further diminish the impact of ionospheric currents, data collected during daylight hours were significantly lowered (Kuvshinov et al., 2021). Figure 1 illustrates the three magnetic field components after removal of core and crustal effects. The MSS-1 satellite's low-inclination orbit results in data predominantly located in the middle and lower latitudes. Notably, the higher residuals detected at high latitudes for Swarm are indicative of polar current systems, which were then eliminated for alignment with MSS-1 and to lessen the polar system's effects. Additionally, outliers, described as those exceeding three standard deviations, were discarded. Figure 1 depicts the magnetic field components following this outlier exclusion.

Then, the residual magnetic field variations in the period range between a few days and a few months are assumed to be generated by the magnetospheric current system. In source-free regions, the residual magnetic field $\mathbf{B}$ can be described by the negative gradient of a scalar magnetic potential V , that is $\mathbf{B} = -\nabla V$ and the scalar magnetic potential V can be expressed by the following spherical harmonic (SH) expansion

$$V(\mathbf{r}, t) = a \sum_{n=1}^{N_{\text{ext}}} \sum_{m=0}^n [q_n^m(t) \cos m\phi + s_n^m(t) \sin m\phi] \left(\frac{r}{a}\right)^n P_n^m(\cos\theta) + a \sum_{k=1}^{N_{\text{int}}} \sum_{l=0}^k [g_k^l(t) \cos l\phi + h_k^l(t) \sin l\phi] \left(\frac{a}{r}\right)^{k+1} P_k^l(\cos\theta), \quad (1)$$

where $a = 6371.2$ km is the Earth's mean radius, r , θ , and ϕ represent the radius, colatitude, and longitude, respectively, $P_n^m(\cos\theta)$ is the Schmidt quasi-normalized associated Legendre function of degree n and order m (Winch et al., 2005), N_{ext} is the maximum degree used to describe the external or inducing field with q_n^m and s_n^m being the external SH coefficients; N_{int} is the maximum degree used to describe the internal or induced field with g_n^m and h_n^m being the internal SH coefficients.

By fitting Equation (1) using the residual magnetic field in bins of 1 day, we can obtain the time series of the magnetospheric inducing and induced SH coefficients. Following the work of Kuvshinov et al. (2021), we take $N_{\text{ext}} = 2$ and $N_{\text{int}} = 3$ to avoid the spectral leakage effects of smaller spatial scales on the degree 1 coefficients. Figure 2 shows the time series of the dominant SH coefficients q_1^0 and g_1^0 . We find good agreement between MSS-1 and Swarm satellite data. The small differences are due to the different orbits of MSS-1 and Swarm satellites.

Using the time series of the inducing q_1^0 and induced g_1^0 coefficients, we can estimate the global Q-responses $Q(\omega)$ using the section-averaging approach and the iteratively reweighted least-square method (Olsen, 1999; Semenov and Kuvshinov, 2012; Aster et al., 2018)

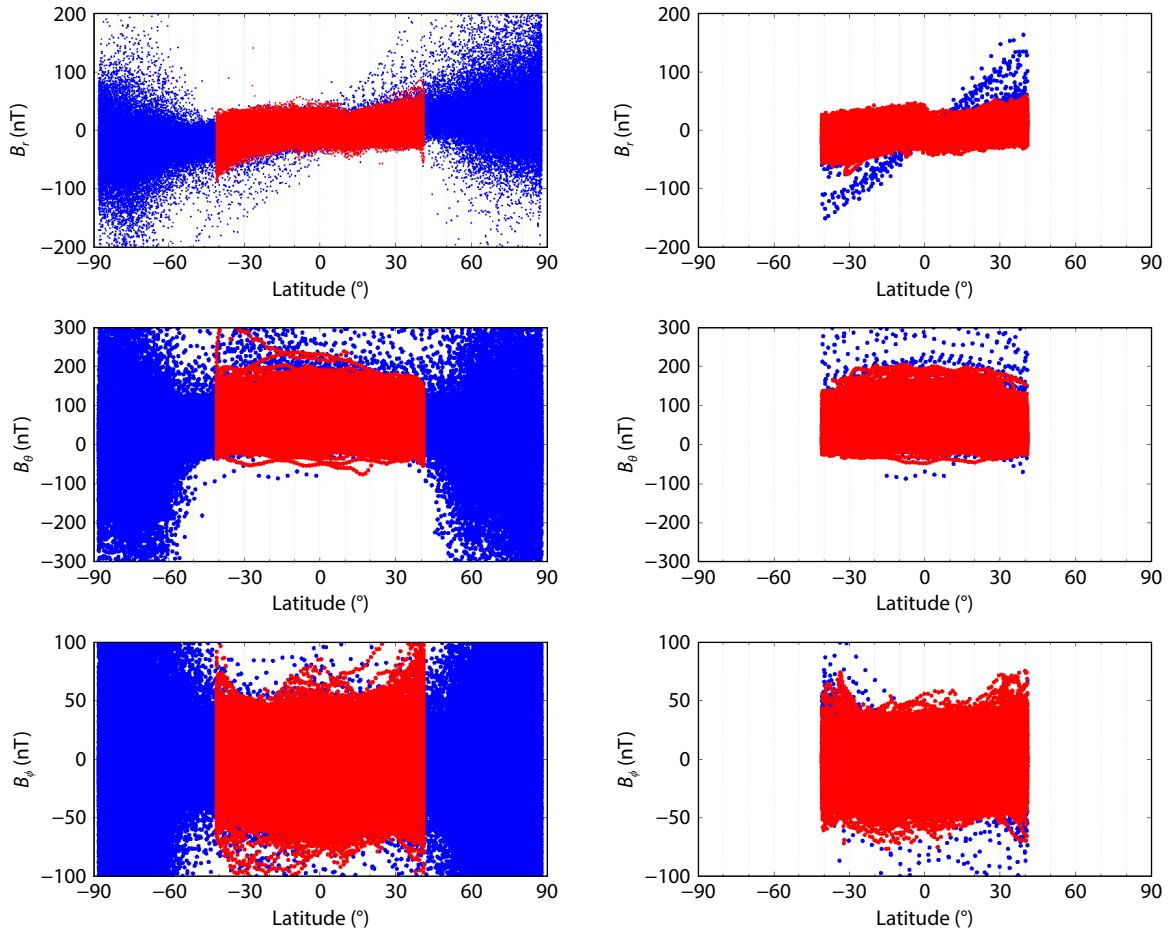


Figure 1. Magnetic field components from the Swarm and MSS-1 satellites for the period from November 1, 2023, to July 31, 2024. Results shown here are after removal of core and crustal magnetic fields (Finlay et al., 2020): (left) Before outlier removal; (right) After outlier removal within a latitude of 41 degrees, with red dots representing the MSS-1 satellite data and blue dots representing the Swarm satellite data.

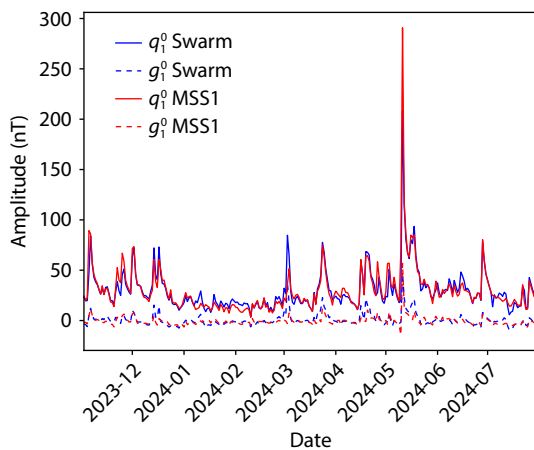


Figure 2. Comparison of the time series of external (q_1^0) and internal (g_1^0) coefficients from November 1, 2023, to July 1, 2024. The red line represents MSS-1 satellite data; the blue line represents Swarm satellite data.

$$Q(\omega) = \frac{g_1^0(\omega)}{q_1^0(\omega)}, \quad (2)$$

where ω denotes the angular frequency. The data uncertainty

$\delta Q(\omega)$ is estimated by the Jackknife approach (Chave and Thomson, 1989). Finally, the global Q-responses are converted to the widely used C-response functions (Kuvshinov and Olsen, 2006)

$$C(\omega) = \frac{a}{2} \frac{1 - 2Q(\omega)}{1 + Q(\omega)}, \quad (3)$$

$$\delta C(\omega) = \frac{3a}{2} \frac{1}{|1 + Q(\omega)|^2} \delta Q(\omega), \quad (4)$$

where $\delta C(\omega)$ is the uncertainty of the estimated C-response function.

2.2 Method

We employed an open-source trans-dimensional Bayesian inversion code developed by Yao HB et al. (2023b) to invert satellite geomagnetic responses for a radial mantle conductivity model. However, observed responses are significantly influenced by oceanic induction effects (Kuvshinov et al., 2002; Chen CJ et al., 2020a, 2023; Yao HB et al., 2021). To address this, we present a new scheme for the probabilistic inversion of satellite geomagnetic responses, combining 3-D multi-resolution finite-element modeling (Yao HB et al., 2022) with 1-D trans-dimensional Bayesian inversion (Yao HB et al., 2023b). The scheme is outlined below.

Step 1: Correcting the oceanic induction effect from the observed

global C-responses. A finite-element solver developed by Yao HB et al. (2022) is employed to compute global C-responses for both the 1-D and 3-D conductivity models. The 3-D model consists of a realistic distribution of oceans and continents, with the underlying 1-D model (Figure 3). The original global C-responses are then corrected for ocean effects following Kuvshinov et al., (2022); Utada et al., (2003); Chen CJ et al., (2020a):

$$C_{\text{obs,corr}}(\omega) = C_{\text{obs}}(\omega) \frac{C_{\text{mod,1D}}(\omega)}{C_{\text{mod,3D}}(\omega)}, \quad (5)$$

where $C_{\text{obs,corr}}(\omega)$ represents the observed responses corrected for ocean effects, $C_{\text{obs}}(\omega)$ is the original observed response, and $C_{\text{mod,1D}}(\omega)$ and $C_{\text{mod,3D}}(\omega)$ are the modeled responses for the 1-D and 3-D conductivity models, respectively.

Step 2: The corrected responses are then inverted using the trans-dimensional Bayesian algorithm to invert the 1-D conductivity model. Details of the trans-dimensional Bayesian algorithm are referred to Yao HB et al. (2023b).

Our inversion scheme offers two distinct advantages. First, it efficiently accounts for oceanic effects. Second, the trans-dimensional Bayesian inversion algorithm incorporated into the scheme provides a quantitative assessment of model uncertainty, which is essential for generating reliable geophysical interpretations. Note that correction of the ocean effect in Step 1 is slightly dependent on the subsurface 1-D model that is used in the 3-D modeling (Chen CJ et al., 2023).

3. Results

3.1 Conductivity Profile

In this section, we present the satellite-derived C-responses estimated from MSS-1 geomagnetic satellite measurements. We begin by validating the data processing approach described in Section 2.1 by estimating global C-responses using ten years of Swarm satellite geomagnetic data. The resulting C-responses, shown in magenta in Figure 4, are compared against those derived from six years of combined Swarm, CryoSat-2, and ground geomagnetic station data by Kuvshinov et al. (2021) (depicted in red). The C-responses estimated from the ten-year Swarm dataset show excellent agreement with those of Kuvshinov et al. (2021),

with only minor differences in the corresponding coherence values, which remain above 0.9, underscoring the high quality of the C-response estimates. The marginally better performance observed in Kuvshinov et al. (2021) can be attributed to the inclusion of both Swarm and CryoSat-2 data, while our validation uses only Swarm data. This comparison confirms the robustness and reliability of our data processing methodology.

We then utilize nine months of MSS-1 vector magnetic data (from November 1, 2023, to July 31, 2024) to estimate global C-responses for 15 logarithmically spaced periods ranging from 2.5 to 18.725 days, as shown in green in Figure 4. In comparison to the smooth and stable C-responses derived from the 10-year Swarm dataset, the nine-month Swarm dataset exhibits increased variability, reflecting the inherent limitations of shorter observation periods. Despite this, the MSS-1 (9-month) results show strong agreement with the 9-month Swarm dataset. Although the MSS-1 results exhibit slightly higher variability, especially at longer periods, they effectively capture the key features observed in both Swarm and CryoSat-2 data, thereby validating MSS-1's capability for high-resolution conductivity studies of Earth's interior. These findings suggest that even shorter-duration datasets from MSS-1 can provide reliable C-response estimates.

Next, we invert the global C-responses from the nine-month MSS-1 dataset using a trans-dimensional Bayesian inversion method. The Bayesian inversion algorithm achieves convergence to a root mean square (RMS) of approximately 1.0 after testing over 1.5 million model samples, demonstrating strong agreement between the estimated and modeled C-responses, as shown in Figure 4, within the associated uncertainties. The resulting mantle conductivity model is presented in Figure 5, accompanied by the posterior probability distribution. The red dashed lines indicate the 90% credible interval, while the magenta line represents the mean model, calculated by averaging all candidate models within this interval. Overall, conductivity generally increases with depth, with a notably narrow credible interval between 500 and 800 km, indicating a well-constrained conductivity structure in this range. In contrast, below 800 km, conductivity estimates become less constrained, as evidenced by a wider 90% credible interval. This limitation arises from the C-responses derived from the 9-month MSS-1 data, which span a period range of 2.5 to 18.725 days,

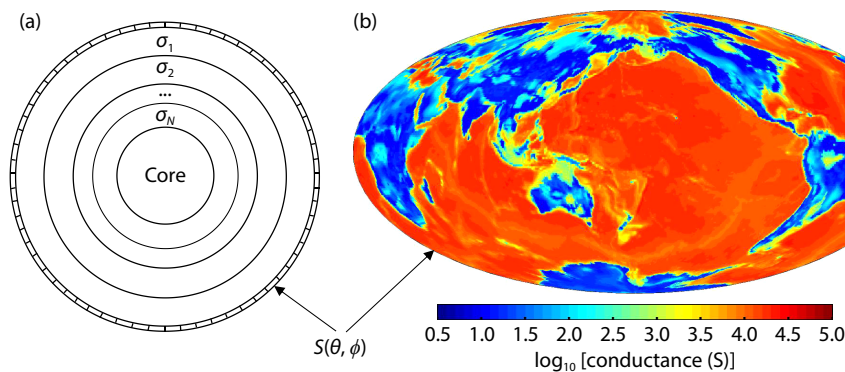


Figure 3. Illustration of the 3-D conductivity model used to correct for ocean induction effects. (a) A 1-D background conductivity model with a laterally heterogeneous surface conductance layer. (b) The near-surface conductance layer representing the realistic distribution of oceans and continents.

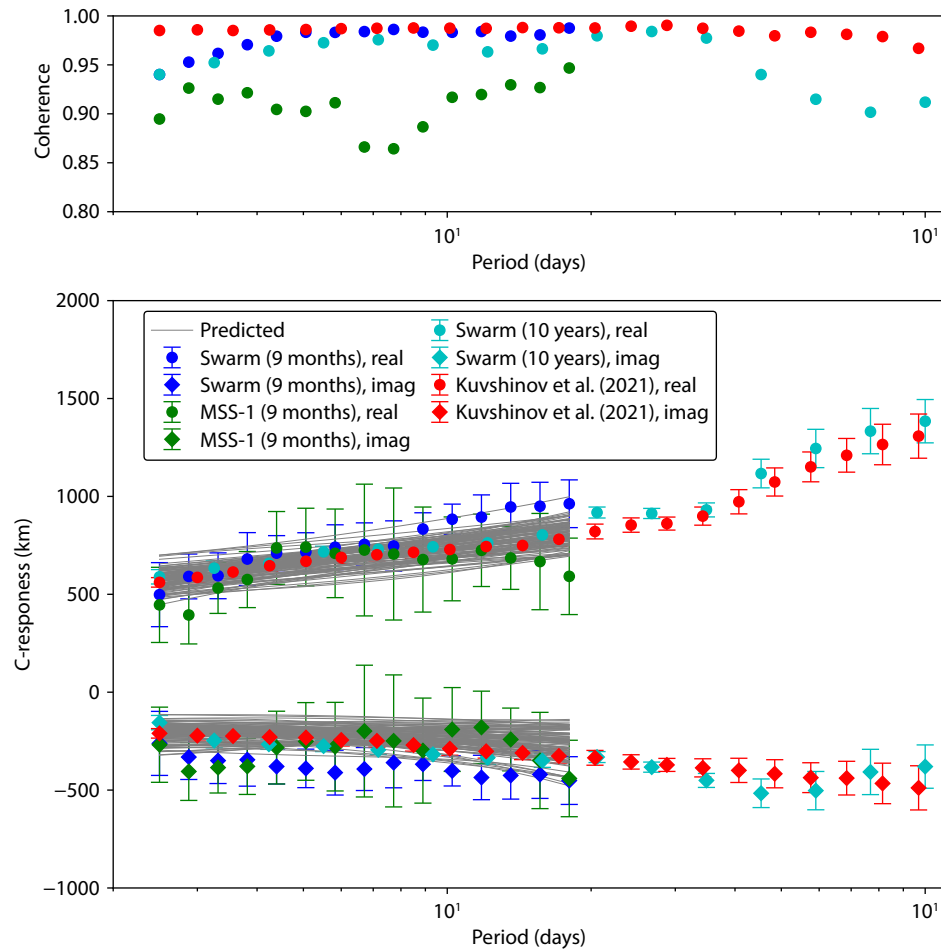


Figure 4. Comparison of the C-response (both real and imaginary parts) from 9 months of observations by the Swarm and MSS-1 satellites for the period from November 1, 2023, to July 31, 2024. Additionally, we include the C-responses extracted using the method in this paper from 10 years of Swarm data, as well as the C-response function estimated from 6 years of combined data from the Swarm and CryoSat-2 satellites, and from geomagnetic stations (Kuvshinov et al., 2021), to validate the reliability of the estimated C-response function for the MSS-1 satellite.

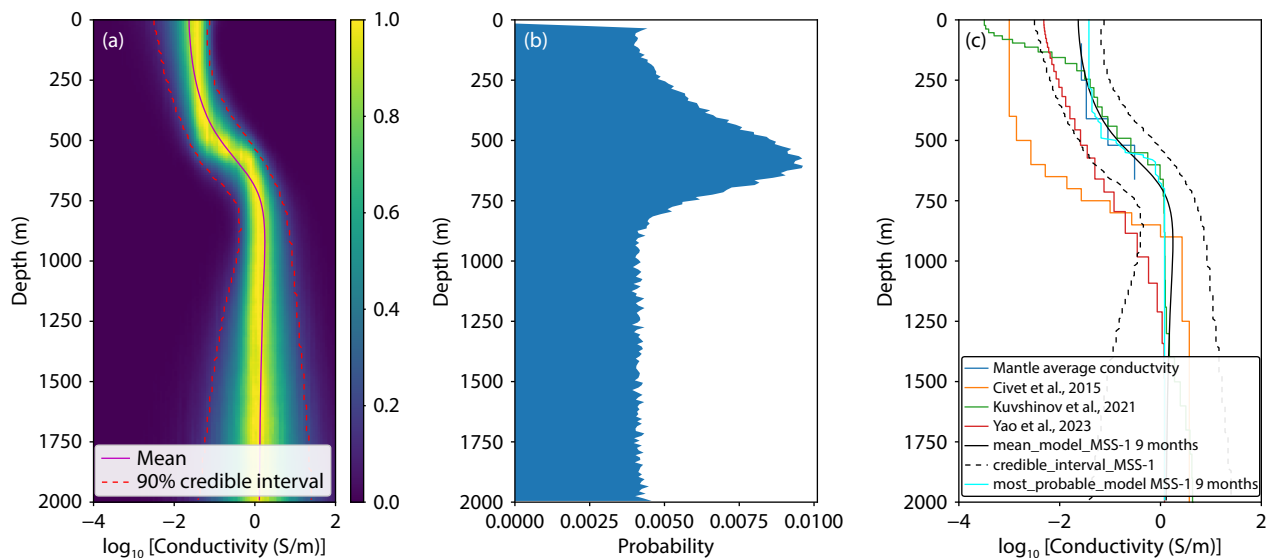


Figure 5. Illustration of the inverted global-averaged 1-D mantle conductivity model based on our trans-dimensional Bayesian inversion algorithm: (a) Posterior probability distribution of inverted conductivity profiles; (b) Interface existence probability; (c) Comparison of the inverted 1-D conductivity model with the locally-averaged conductivity model of Karato (2011), inferred from local geo-electromagnetic induction studies, and a set of 1-D conductivity models derived from previous satellite studies (Civet et al., 2015; Kuvshinov et al., 2021; Yao HB et al., 2023a).

resulting in limited sensitivity to the conductivity structure at depths greater than 800 km. Therefore, we focus our analysis on the conductivity structure between 500 and 800 km. A significant increase in conductivity, from 0.1 S/m to 1 S/m, is observed at approximately 610 km depth, as shown in Figure 5b. This is likely associated with the discontinuity that separates the Earth's upper and lower mantle, which is, however, different from the 660-km seismic discontinuity. The difference might be attributed to the heterogeneity of the mantle. What we have obtained in this study is thus the global averaged 1-D mantle conductivity.

In Figure 5c, we compare our newly constrained 1-D mantle conductivity model with various independent 1-D conductivity structures derived from previous studies. This analysis includes the locally averaged conductivity model proposed by Karato (2011), which synthesizes results from regional geo-electromagnetic induction studies (see Fig. 4 of Karato (2011)), as well as models based on previous satellite data analyses (Civet et al., 2015; Kuvshinov et al., 2021; Yao HB et al., 2023a). Notably, the averaged regional models from Karato (2011) and the conductivity estimates derived from six years of data from the Swarm and CryoSat-2 missions (Kuvshinov et al., 2021) fall within the 90% credible interval of our MSS-1 results. Both our mean model (depicted in black) and the most likely conductivity model (shown in cyan), duplicated from Figure 5a with the highest yellow color, align closely with these references. In contrast, we observe significant discrepancies between our 1-D mantle conductivity structure and those presented by Civet et al. (2015) and Yao HB et al. (2023a). These discrepancies may arise from the non-uniqueness issue associated with the inversion methodology employed in the study (Yao HB et al., 2023a), where the preferred model generated by the L-BFGS algorithm potentially overlooks other viable solutions. Additionally, the model by Civet et al. (2015) was based on only six months of Swarm data and did not account for ocean induction effects, which could further contribute to the observed discrepancies. These comparisons underscore the reliability and robustness of our newly constrained 1-D mantle conductivity model, providing valuable insights into the electrical properties of the mantle.

3.2 Water Content

The interpretation of inverted conductivity profiles relies on mineral composition, pressure, temperature, and water content. Water content is a critical parameter influencing the thermal and dynamic state of the Earth's interior, with significant implications for volcanic activity, melting processes, and mantle convection dynamics (Bercovici and Karato, 2003; Naif et al., 2013; Fei HZ et al., 2017; Cai C et al., 2018; Peslier, 2020; Hou MQ et al., 2021; Zhang HQ et al., 2022; Miyazaki and Korenaga, 2022). Consequently, a key focus for Earth scientists is extracting water content information from inverted conductivity profiles, as electrical conductivity is more sensitive to variations in water content than to other geophysical parameters, such as seismic wave velocities. Recent geochemical studies suggest that the mantle's composition can be approximated by a homogeneous six-oxide system — $\text{Na}_2\text{O}-\text{CaO}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$ — which constitutes roughly 98% of the total mantle mass. This system consists of 0.382% Na_2O , 39.186% MgO , 3.736% Al_2O_3 , 44.99% SiO_2 , 3.01% CaO , and 7.8%

FeO , and can be modeled as a mixture of 20% mid-ocean ridge basalt and 80% ocean island harzburgite (Khan et al., 2011; Khan and Shankland, 2012; Khan, 2016). Based on this compositional framework, we utilized the equilibrium phase diagram software *Perple_X* (Connolly, 1990), which employs thermodynamic equilibrium theory and a thermodynamic database (Stixrude and Lithgow-Bertelloni, 2011), to determine the stable mineral phases and their volumetric proportions by minimizing Gibbs free energy. Using the mantle geotherm inferred from seismic data (Brown and Shankland, 1981), we computed the modal abundances of mantle minerals at various depths, as illustrated in Figure 6. The figure shows the modal abundances of key mantle mineral phases as a function of pressure, ranging from 8 GPa to 30 GPa. In the upper mantle (<13.7 GPa), olivine (O) is the dominant phase, comprising approximately 62% of the mantle composition, followed by orthopyroxene (Opx, 5%), clinopyroxene (Cpx, 15%–21%), and garnet (Gt, 24%–13%). As pressure increases, olivine transitions into wadsleyite (Wad) and subsequently into ringwoodite (Ring) within the mantle transition zone (13.7–23.4 GPa). Wadsleyite dominates the upper transition zone, accounting for 61% of the composition, while garnet makes up 24%–39%. In the lower transition zone (19.0–23.4 GPa), ringwoodite becomes dominant, constituting 61% of the composition, with garnet at 39%. In the lower mantle (>23.4 GPa), ringwoodite transforms into bridgmanite (Pv), which becomes the primary mineral phase, representing 74% of the composition. Ferropericlase (Per) increases in abundance to 18%, while calcium silicate perovskite (Ca–Pv) accounts for 4%–6%. Additional phases, such as akimotoite (Aki) and wüstite (Wus), also emerge and gain stability at higher pressures. These simulated mantle mineral phases align well with known mantle models such as pyrolitic model (Xu WB et al., 2008; Stixrude and Lithgow-Bertelloni, 2012; Khan, 2016).

Using the calculated modal abundance of mantle minerals and laboratory-based conductivity measurements for these minerals, we assess the water content in the upper mantle and transition zone. Several independent laboratory studies have explored the effects of water on the conductivity of mantle minerals, but unfortunately, their outcomes vary significantly (Karato, 2011; Yoshino and Katsura, 2013; Karato, 2019). To minimize bias in our analysis, we employed two distinct datasets: one from the work of Karato, Dai, and collaborators (referred to as KD), and the other from Yoshino, Katsura, and collaborators (referred to as YK). The KD dataset includes conductivity measurements for Olivine (Wang DJ et al., 2006), Orthopyroxene (Dai LD and Karato, 2009b), Clinopyroxene (Dai LD and Karato, 2009b), Garnet (Xu YS and Shankland, 1999), Wadsleyite (Dai LD and Karato, 2009a), Ringwoodite (Huang XG et al., 2005), and Bridgmanite (Xu Y et al., 1998). Similarly, the YK dataset incorporates measurements for Olivine (Yoshino et al., 2008, 2009), Orthopyroxene (Zhang BH et al., 2012), Clinopyroxene (Xu YS and Shankland, 1999), Garnet (Yoshino et al., 2008), Wadsleyite (Yoshino et al., 2012a,b), Ringwoodite (Yoshino et al., 2012b), Ferropericlase (Yoshino et al., 2011), Bridgmanite (Xu Y et al., 1998), and Ca-perovskite (Xu Y et al., 1998). In cases where laboratory-based conductivity measurements for a particular mineral are not available, we can safely ignore its effect if its modal abundance is less than 10% (Khan and Shankland, 2012; Khan, 2016).

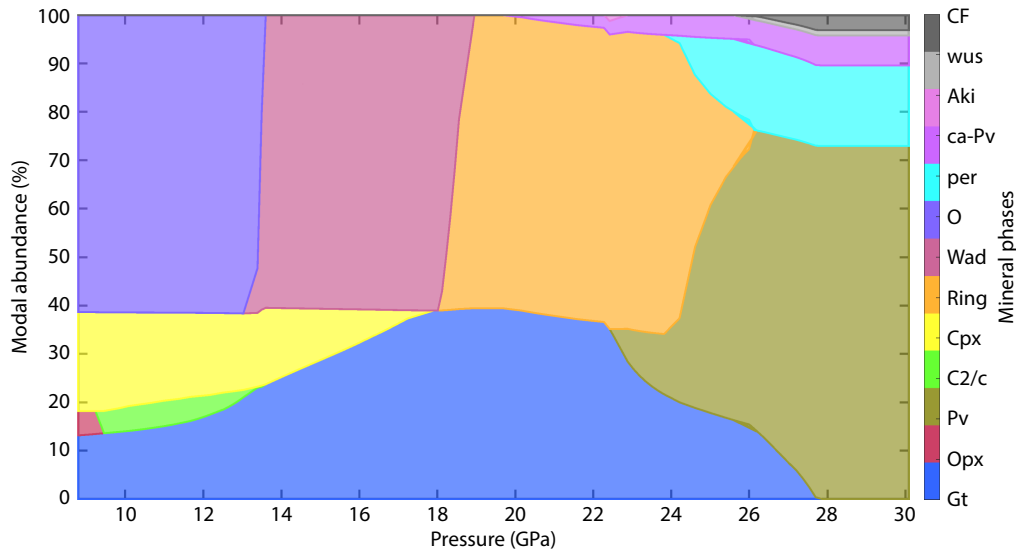


Figure 6. Modal abundance of mantle minerals computed using the equilibrium phase diagram software Perple_X (Connolly, 1990) based on thermodynamic equilibrium theory and the thermodynamic database (Stixrude and Lithgow-Bertelloni, 2011) along the mantle geotherm (Brown and Shankland, 1981). The mantle is assumed to have a homogeneous chemical composition in the NCFAMS system ($\text{Na}_2\text{O}-\text{CaO}-\text{FeO}-\text{MgO}-\text{Al}_2\text{O}_3-\text{SiO}_2$), represented as a mixture of 20% basalt and 80% harzburgite (Khan et al., 2011; Khan and Shankland, 2012; Khan, 2016). The modeled mineral phases include olivine (O), orthopyroxene (Opx), bridgmanite (Pv), highpressure Mg-rich clinopyroxene (C2/c), clinopyroxene (Cpx), ringwoodite (Ring), wadsleyite (Wad), ferropericlasite (Per), calcium silicate perovskite (Ca-Pv), akimotoite (Aki), wüstite (Wus), and calcium ferrite (CF).

Subsequently, the conductivity profiles as a function of depth are independently calculated using laboratory-based conductivity measurements of hydrous minerals from the KD and YK databases. We test the effects of various water content levels (C_w), ranging from a dry mantle to 1 wt%. The mantle's conductivity is computed as the aggregate conductivity of each mineral phase employing the Hashin and Shtrikman model, which provides both upper and lower bounds for the aggregate conductivity (Hashin and Shtrikman, 1962; Karato, 2011). Our tests indicate that the upper and lower bounds are closely aligned; therefore, we utilize their average as the final calculated conductivity values.

The depth-conductivity curves for varying water contents from both the YK and KD datasets, illustrated in Figure 7, reveal a common trend of increasing conductivity with higher water content, underscoring the crucial role of water in enhancing mantle conductivity. We also observe that, at the same water content level, conductivity decreases from the upper mantle to the transition zone, indicating that mineralogical change, temperature and pressure increasing with depth, may influence conductivity behavior. Furthermore, the KD dataset exhibits greater sensitivity to variations in water content; an order of magnitude change in water content results in a nearly equivalent shift in conductivity. In contrast, the YK dataset demonstrates a more moderate sensitivity to similar variations in water content. We conclude that the YK dataset generally indicates a more hydrated upper mantle and transition zone than the KD dataset, as the KD model predicts equivalent conductivity values while requiring less water content. The differing sensitivities of conductivity measurements to water content between the two datasets highlight the necessity of refining these datasets or conducting more indepen-

dent laboratory-based conductivity measurements.

Using Figure 7, we estimate the water content in the upper mantle and transition zone by applying the mean conductivity profile from the MSS-1 data to the KD and YK datasets. Results from both datasets suggest that the upper mantle contains very little water. The KD dataset estimates a water content of approximately 0.001 wt%, while the YK dataset suggests even drier conditions, close to zero wt%. This alignment between the datasets highlights the dry nature of the upper mantle. In contrast, a more significant discrepancy arises in the transition zone (410–660 km), where the KD dataset estimates a moderate water content of around 0.01 wt%, whereas the YK dataset suggests a much higher value of 0.1 wt%. Despite this divergence, both datasets agree that the transition zone is significantly more hydrated than the upper mantle. The relatively dry upper mantle findings align well with previous studies, such as those based on globally distributed geomagnetic observatory data (Zhang HQ et al., 2022; Chen CJ et al., 2023). The YK dataset's higher estimate is also supported by earlier studies suggesting a more hydrated transition zone with up to 0.1 wt% water, as indicated by satellite-detected tidal and magnetospheric signals (Grayver et al., 2017).

If we use the the upper bound of the 90% credible laboratory conductivity profiles to estimate the water content showing in Figure 7, we will get significantly higher water content estimates. For instance, in the upper mantle, the estimates based on the KD dataset reach a water content as high as 0.005 wt%; the YK dataset suggests still higher water content, ranging from 0.1 wt% to 0.5 wt%. In the transition zone, the KD dataset estimates a moderate water content of 0.1 wt%; the YK dataset predicts a much higher water content of 1 wt%, indicating the possibility of

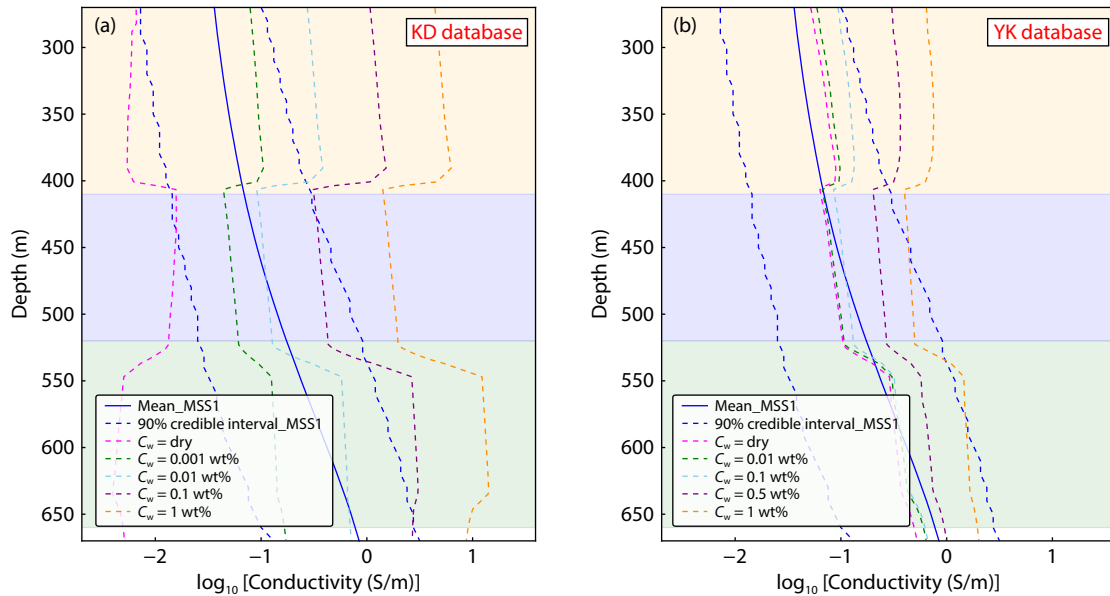


Figure 7. Comparison of our newly obtained global averaged 1-D conductivity model with the laboratory conductivity models constructed using KD and YK databases respectively.

a very significantly hydrated transition zone.

If 0.01 wt% of water content is present in the mantle transition zone, as indicated by the mean conductivity profile applied to the KD dataset, the estimated water content in this region could equal approximately 3% of Earth's total ocean water. The YK dataset suggests water content as high as 30% of Earth's ocean water. Use of the upper bound of the conductivity profiles to estimate the water content in the mantle transition zone raises this to at least 30% of Earth's ocean water, according to the KD dataset, and up to 300% according to the YK dataset. This significant discrepancy between the KD and YK dataset stems from the fact that the KD dataset's conductivity is highly sensitive to water content, whereas the YK dataset's conductivity is less so. In any case, these findings offer crucial insights into the potential variability of water content in the Earth's mantle, particularly suggesting that the transition zone may be a major water reservoir.

The discrepancies in the estimated water content in the deep Earth may arise from two primary factors, the non-uniqueness of inversion and the inconsistent laboratory-based conductivity measurements. First, the non-uniqueness of inversion is evident from the significant variations in conductivity profiles with depth, as obtained through our trans-dimensional Bayesian inversion method. Although all conductivity profiles within the 90% credible intervals provide an acceptable fit to the data, the variations in conductivity — and consequently the estimated water content — can be substantial. The issue of non-uniqueness of inversion is in addition to the large uncertainties of the estimated C-response function (as shown in Figure 4) due to the short MSS-1 observation time. This issue will be reduced by when more MSS-1 data are available. Second, these discrepancies can also be attributed to the differing laboratory-based conductivity measurements of hydrous minerals reported by the KD and YK groups. To minimize these inconsistencies, it is essential to refine the existing laboratory-based conductivity measurements or to conduct inde-

pendent laboratory measurements of hydrous minerals. Such improvements would significantly enhance the accuracy of our estimates and reduce the current large variability in water content estimations. Furthermore, to address the non-uniqueness of inversion, we should integrate other geophysical data, such as seismic measurements, to better constrain the water content in future studies.

4. Conclusion

In this study, we successfully applied a validated methodology to estimate global C-responses from nine months of MSS-1 satellite geomagnetic data. The time series of inducing coefficients from magnetospheric currents and induced coefficients from the conductive mantle show excellent agreement between observations from MSS-1 and from the Swarm satellites. The results also reveal a remarkable level of accuracy; the estimated C-responses demonstrate impressive agreement with those derived from a comprehensive 10-year dataset collected from the Swarm satellite mission, as well as with results obtained from other satellite data sources. This strong correlation not only reinforces the reliability of the MSS-1 measurements but also highlights the potential for these data to provide precise and detailed insights into the Earth's electromagnetic properties.

Utilizing the estimated C-responses, we have derived the first conductivity profile of the Earth's interior from MSS-1 data while also evaluating the water content present within the mantle. Our analysis indicates that the mantle transition zone may hold as much as several times the amount of water in the Earth's oceans. This is compelling evidence in support of the hypothesis that there is a water cycle deep within the Earth's interior. Such insights are crucial for advancing our knowledge of the Earth's interior and the complex processes occurring within it.

By extending the observation to longer periods and integrating data from additional satellite missions and other geophysical

datasets, MSS-1 can significantly contribute to advancing our understanding of the thermal parameters of the Earth's interior. We also point out that to better constrain the water content, it is essential to refine the existing laboratory-based conductivity measurements or to conduct independent laboratory measurements of hydrous minerals. The capability of MSS-1 to accurately capture the Earth's electromagnetic properties opens up exciting new avenues for understanding mantle dynamics and their influence on various geophysical processes. As we look to the future, leveraging the strengths of MSS-1 could lead to groundbreaking insights that deepen our comprehension of the Earth and its complex geodynamics.

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