24th Electromagnetic Induction Workshop

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Abstracts Session 7

SESSIONS DESCRIPTION

Session 7. Global and Planetary Studies

We solicit new contributions on induced electromagnetic fields at a planetary scale. We invite presentation of studies that shed light on the progress in our understanding of global electrical conductivity structures in the Earth´s mantle. Development of new methods of global forward and inverse modelling, use of new transfer functions, joint inversion for ionospheric sources and mantle conductivity, and interpretation of satellite magnetic field data are welcome. New methods that incorporate space physics constraints on the sources of electromagnetic induction at periods relevant to the Earth's mantle conductivity structures are particularly welcome. We also call for studies dedicated to magnetism and induction on other planets.

Conveners: Joan Campanya, Jakub Velimsky, Svetlana Kovacikova

On the boundary between the brittle and ductile parts of the continental Earth's crust.

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Keywords: brittle, ductile, electromagnetic soundings, Earth's crust

During the last century it has been developed an idea of a two-layered structure of the continental crystalline earth's crust, consisting of the upper, brittle 'layer and the lower ductile one (Sadovsky, 1945; Gzovsky, 1975 Nikolaevsky, 1996; Ranalli, 2000; Moisio & Kaikkonen, 2001). The depth of the boundary between the brittle and ductile states of the Earth's crust is the most important parameter for fundamental research, but it is the most difficult to determine, because of many a priory properties of the Earth interior need to be taken into account such as heat generation, temperature, plasticity. composition of rocks, fluid regime, stress-strain state etc.

In that article the boundary between the brittle and ductile states of the Earth crust is investigated on the base of geoelectrics. Results of "MHD Khibiny" and "FENICS" experiments are analyzed in complex with Kola super deep hole drilling data. From these data the Earth crust can be divided into two contrasting parts by electrical properties. The upper part is of moderate average resistivity (around of 10^4 Ω·m) and a sharp horizontal heterogeneity due to wide distribution of electronically conducting structures and presence of fluid containing DD-layer. The lower part of the Earth crust (from 10-15 to 40 km) is of high resistivity (10^5-10^6 Ω·m) and horizontal homogeneity. Crystalline rocks at these depths exist at a semi-ductile state; the porosity and content of free fluids in them reduced sharply. All these properties signify that the electric conductivity at depths of more than 10-15 km is determined mostly by the planetary physical-chemical parameters (pressure, temperature, viscosity), the phase transitions of the substance, and the geodynamic peculiarities of evolution of different segments of the Earth, rather than by the geological processes mainly observed near to the day surface.

Acknowledgments.

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Can seafloor ocean tidal electromagnetic field data provide more constraints on the conductivity of the lithosphere and asthenosphere?

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SUMMARY

Secondary magnetic fields generated by the motional induction of ocean tides are measurable by satellite and seafloor instruments. Previous studies have proven that satellite measurements of the M_2 tidal magnetic field are capable of sounding Earth's deep interior. However, to further understand and utilize the tidal electromagnetic (EM) signals using a multiple observation approach, thorough research with more simulations are needed. The primary goal of this study is determining the influence of oceanic lithosphere and asthenosphere electrical properties on the distribution and amplitude of ocean tidal EM fields on the seafloor and at satellite altitude. A new 3D forward modeling tool for tidal EM studies has been developed. The code is based on the finite difference method in spherical coordinate, and allows modeling at global and regional scales. Simulation results of theoretical models demonstrate that if the lithospheric conductivity varies, there are large and spatially dependent amplitude and phase changes of horizontal magnetic fields on the seafloor, while and phase fluctuation of the vertical magnetic field is limited to ocean margins. All components of the magnetic field drop uniformly with increasing asthenospheric conductivity except for the horizontal magnetic field on the seafloor which changes in the opposite way. We conclude that the horizontal magnetic field on the seafloor that involves galvanic effects and the toroidal magnetic (TM) mode could recover the structure of resistive lithosphere better, and satellite observations are more suitable to probe the conductive asthenosphere due to the inductive nature of the poloidal magnetic (PM) mode.

Keywords: tidal EM fields, conductivity of the oceanic lithosphere and asthenosphere, 3-D forward modeling

INTRODUCTION

Gravitational tides drive electrically conductive seawater through the Earth's ambient magnetic field, inducing secondary electromagnetic fields. Thanks to the development of satellite altimetry, which boosts accurate global ocean tide models, and satellite magnetic field measurements, the last decade has seen remarkable progress in research on the EM signals produced by ocean tides. A recent study has successfully imaged the sharp lithosphere-asthenosphere conductivity boundary using satellite-detected tidal magnetic fields (Grayver et al, 2017). Synthetic models also demonstrated that the signal is a promising tool to monitor seawater conductivity variations (Saynisch et al, 2017). Generally speaking, the radial component of the satellite magnetic field (Maus and Kuvshinov, 2004) is the main focus of current studies, and the integral equation method implementing a heterogeneous surface shell with an underlying 1-D global model is the mainstream numerical method.

However, it should be noted that the toroidal magnetic (TM) mode that is associated with vertical electric currents only exists inside the earth, and is more sensitive to resistive structures. Long term observations using ocean-bottom EM stations concentrated in the Pacific Ocean over the past 30 years provides a database to extract the toroidal magnetic signal from records of the horizontal magnetic field. In addition, regions with lateral conductivity variations such as subduction zones calls for a forward mod-

eling technique that can easily handle 3-D arbitrary electrical conductivity distributions.

In this study, a spherical coordinate staggered grid (SG) finite difference approach was utilized to simulate global ocean tidal EM fields. Our solution shows good agreement with satellite observations and previous studies. To gauge the sensitivity of seafloor data to the lithospheric and asthenospheric conductivity structure, we designed a series of global models and tried to investigate the relationship between the magnitude of the tidal magnetic field and earth's electrical conductivity structure via numerical simulation.

METHODS

Motional induction by ocean tides can be described by the Maxwell equations under the magneto-quasistatic approximation in the frequency domain. Assuming harmonic time dependence $e^{-i\omega t}$, the electric field $\mathbf{E}$ satisfies the following second order partial differential equation:

$$\nabla \times \nabla \times \mathbf{E} - \mathbf{i}\omega\mu\sigma\mathbf{E} = \mathbf{i}\omega\mu\sigma_{\mathbf{s}}(\mathbf{V} \times \mathbf{B^m}) \qquad (1)$$

The right-hand term $J_s = \sigma_s(\mathbf{V} \times \mathbf{B^m})$ is the current source due to tidal flow $\mathbf{V}$, σ_s is the seawater electrical conductivity and $\mathbf{B^m}$ is the stationary main geomagnetic field.

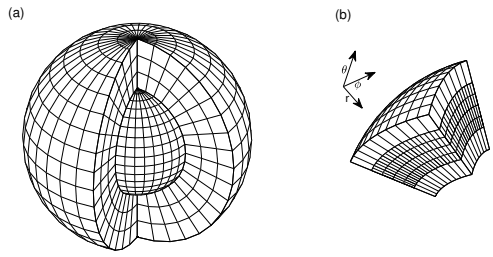

Figure 1: Sketch of the mesh division in spherical coordinates for (a) a global model and (b) a regional model.

Equation 1 was discretized by the finite difference method on a 3D staggered grid in spherical coordinate. For global modeling, the derivation of the coefficient matrix system of equations is similar to Uyeshima and Schultz (2000)'s recipe of solving for the magnetic field. The solver uses an iterative biconjugate gradient-stabilized (BiCGstab) solver with an ILU preconditioner, and a divergence correction is implemented to the total electric current after the BiCGstab solver. We have validated the method by comparison of the analytical spherical harmonics and SG numerical solutions. As shown in Figure 1(b), we are working on an extension of the multi-resolution grid studied by Cherevatova et al (2018), which allows refinement only with depth.

All modeling results presented here use the same global mesh division. The top 10^6 km thick atmosphere and the conductive earth down to a depth of 760 km is discretized into $90 \times 180 \times 90$ blocks (20 air layers). The horizontal grid spacing is $2^\circ \times 2^\circ$ and the radial grid length starts from 50 m underneath the earth's surface then increases both downward and upward.

The M_2 tidal electric current source J_s was calculated using a 3-D global seawater conductivity dataset (Tyler et al, 2017), the high-resolution tidal model TPXO8 (Egbert and Erofeeva, 2002) and the main field model IGRF-12. The conductivity model incorporates a realistic ocean bathymetry and sediment thickness map and solid earth model. The solid earth model consists of a 70-km-thick lithosphere with a resistivity ρ_l, an asthenosphere between 70-250 km with a resistivity ρ_a, and three underlying mantle layers with constant resistivity of 20 Ωm, 10 Ωm and 3 Ωm. Figure 2 illustrates one of our modeling result.

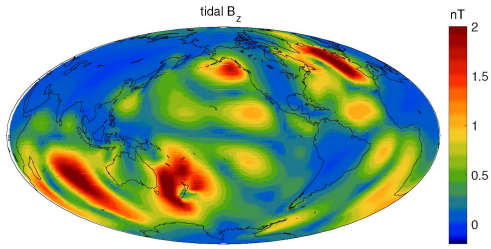

Figure 2: Amplitude of the B_z component of the oceanic M_2 tidal magnetic field at 430 km altitude.

RESULTS

The variation in the ocean tidal EM signal caused by different earth conductivity models can be evaluated by the integration of Fréchet kernels or forward modeling. Chave (1984) examined the behavior of the 1D TM and poloidal magnetic (PM) mode of the EM field generated by a Kelvin wave source using the former approach, and the result showed that

the TM mode on the seafloor has a better resolution ability for conductivity contrasts at depth, especially for a resistive layer. Here we chose the forward modeling to investigate the magnetic field's sensitivity to ρ_l and ρ_a by comparing simulation results for different earth models. In the default earth model, $\rho_l = 4000\,\Omega m$ and $\rho_a = 100\,\Omega m$.

Figure 3 suggests that a change in ρ_l can cause large and widespread differences in the seafloor horizontal magnetic field, but the effect on B_z is limited along the coastline. In contrast, change in ρ_a gives rise to rather steady variation of magnetic fields. As shown in Figure 4, the amplitude of the magnetic field at satellite altitude decreases with ρ_a over the sea and the change of ρ_l is only reflected near coast. There is no obvious difference in magnetic fields' phase $(< 10°)$ in these cases.

Models integrating lateral variations of lithospheric thickness (Conrad and Lithgow-Bertelloni, 2006) were considered. Figure 5 provides a closer inspection at regions near the northeastern Pacific basin and the Indian Ocean ('NP' and 'IN' in Figure 3a). In the northeastern Pacific basin, B_x on the seafloor is very sensitive to ρ_l, but ρ_a also can affect the magnetic field where the oceanic lithosphere is thin. As for the Indian Ocean, the satellite observations of B_z seem to depend on ρ_a exclusively. Different characteristics of the EM field may be related to the behavior of tidal currents.

Generally speaking, the oceanic lithosphere is much more resistive than the asthenosphere. On the seafloor, B_x contains the TM mode, which is strongly affected by resistive material and vanishes at the ocean-air surface, so horizontal magnetic fields within the ocean possess high sensitivity to the lithospheric conductivity and thickness. In contrast, there is only the PM mode magnetic field in the air which is more sensitive to conductive zones, hence satellite observations could reflect the structure of the asthenosphere.

Conclusions

A 3D finite difference tool for ocean tidal EM modeling has been developed. The results indicate that the horizontal magnetic field on the seafloor exhibits great sensitivity to the electrical structure of the lithosphere including its resistivity and thickness, which can be attributed to the galvanically-coupled TM mode. Satellite magnetic data and seafloor vertical magnetic field measurements can better constrain the resistivity of the asthenosphere because the PM mode is biased toward conductive zones as in the case of magnetotellurics. In all, the combination of seafloor, island/coastal observatory and satellite tidal EM data would provide more complete information about the electrical properties of the deep earth beneath the ocean.

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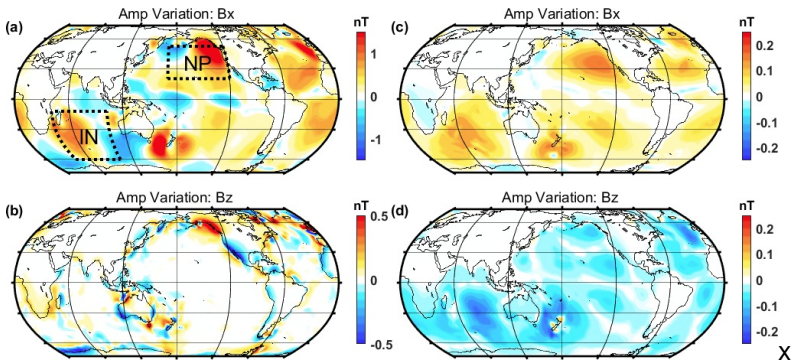

Figure 3: Changes in amplitude of B_x and B_z on the seafloor due to more conductive earth models, (a)-(b) if ρ_l decreases to 1000 Ωm. (c)-(d) if ρ_a decreases to 40 Ωm. Areas bordered by black dashed lines and labeled as 'NP' (the northeast Pacific basin) and 'IN' (the Indian Ocean) are studied in Figure 5.

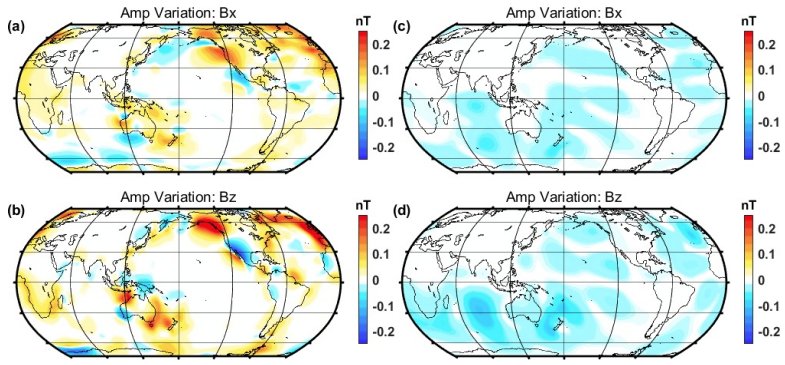

Figure 4: Changes in amplitude of magnetic fields B_x and B_z at satellite altitude, similar to Figure 3.

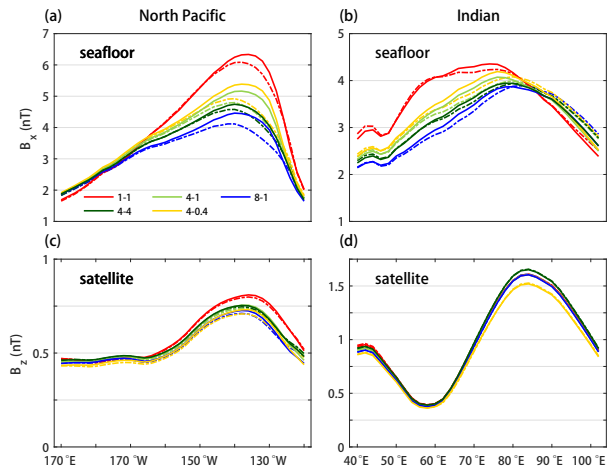

Figure 5: The amplitude of (a)-(b) B_x on the seafloor and (c)-(d) B_z at satellite altitude in regions labeled as 'NP' and 'IN' in Figure 3. Solid lines depict results of models with lateral lithosphere thickness variation, and dashed lines are from 1D models. Color legends in the form of 'x-y' indicate $\rho_l = 1000 \times x\,\Omega m$, $\rho_a = 100 \times y\,\Omega m$.

Current-loop parameterization of external field sources for satellite induction studies

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SUMMARY

In order to recover the three-dimensional distribution of electrical conductivity from the Swarm satellite data, an accurate model of the magnetospheric field is needed. Until now, the satellite signals of magnetospheric origin were parameterized using spherical harmonics. However, the 3-D inversions of Swarm data using this approach have not yet provided acceptable results. We propose to use alternative parameterization based on a current-loop model of the external sources in the time domain, following a similar frequency-domain approach by Sun et al. (2015). Such approach should be able to achieve more detailed spatial description of the magnetospheric currents, while avoiding the use of large number of model parameters. As an added value, such parameterization will permit us to account for the electric currents flowing in polar ionosphere (PEJ), and hopefully to extend the usefulness of high-latitude data. We will present the general methodology that allows for an arbitrary position and orientation of any number of current loops, taking into account the induction effect from an a-priori conductivity model. A Bayesian method based on the parallel tempering approach (prospectively even trans-dimensional) is used to solve the inverse problem. Our initial computations are aimed to exploit the ground-based observatory data, and to establish the sensitivity of model parameters.

Given the ground-based external field model, we proceed with the formulation of the three-dimensional inverse problem to recover the mantle conductivity distribution, using Swarm residua along the satellite tracks. This comprises the definition of the misfit and the formulation of the adjoint problem.

Keywords: mantle conductivity, satellite measurements, external sources

Do ocean tidal signals influence recovery of solar quiet variations?

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SUMMARY

The solar quiet (Sq) source morphology changes on a daily basis and becomes disturbed during periods of increased magnetic activity. Therefore, it may be preferable to use single-day magnetic field recordings for the analysis of Sq variations. However, in short recordings, Sq and ocean tidal magnetic signals are often indistinguishable because of the close periods. As a result, the tidal magnetic signals can be erroneously attributed to signals of Sq origin, which can potentially lead to wrong interpretations, especially when small signals, such as those induced by the 3-D heterogeneities in the mantle, are sought.

In this work, we quantitatively estimate the effect of ocean tidal signals in daily variations by performing rigorous 3-D modeling and comparing the results with real measurements from ground and sea floor observatories. We found that the vertical magnetic field component, Z , is affected the most such that at some locations the tidal signals explain the majority of the observed daily variation. Further, horizontal tidal magnetic fields at the sea floor are larger in amplitude and exhibit different spatial structures compared to signals estimated at the sea level. We propose a scheme aimed at correcting data for the ocean tidal signals and show that such correction suppresses the tidal signals in the observed field variations.

Keywords: Electromagnetic induction, solar quiet variations, ocean tidal magnetic fields

EM Induction from Space: The Swarm Satellite Constellation Mission and its Data Products

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SUMMARY

Determination of the electrical conductivity of the mantle and lithosphere using electromagnetic sounding is one of the scientific research objectives of the *Swarm* satellite constellation mission. After almost five years in orbit, high-precision magnetic field observations taken by the three *Swarm* satellites resulted in improved global 1D (radially symmetric) conductivity models in the depth range down to 1600 km.

This talk will present the *Swarm* satellite trio, its magnetic data products relevant for induction studies, and examples of their use for estimating conductivity-depth profiles.

Keywords: Geomagnetic Depth Sounding, Satellites, Mantle conductivity

INTRODUCTION

Determination of mantle conductivity using magnetic satellite data has recently attracted increasing interest, thanks to the availability of high-precision magnetic measurements taken by low-earth-orbiting (LEO) satellites. An overview of the situation 20 years ago was given at the 14th EM Induction Workshop in Sinaia/Romania (Olsen, 1999). Since then much more high-precision magnetic satellites have collected more and more data, by the Danish Ørsted satellite (1998 – 2014), The German CHAMP satellite (2000 – 2010), and more recently by the *Swarm* satellite trio. Kuvshinov (2012) gives a recent overview of how magnetic observations taken by satellites can be used for induction studies.

THE *Swarm* SATELLITE TRIO

Swarm, a satellite constellation mission comprising three identical spacecraft, was launched on 22 November 2013. Two of the *Swarm* satellites, *Swarm Alpha* and *Swarm Charlie* are flying almost side-by-side in near-polar orbits of inclination $87.4°$ at an altitude of about 455 km (in July 2018) above a mean radius of $a = 6371.2$ km. The East-West separation of their orbits is $1.4°$ in longitude, corresponding to 155 km at the equator. The third satellite, *Swarm Bravo* flies at a slightly higher (about 520 km altitude in July 2018) orbit of inclination $88°$.

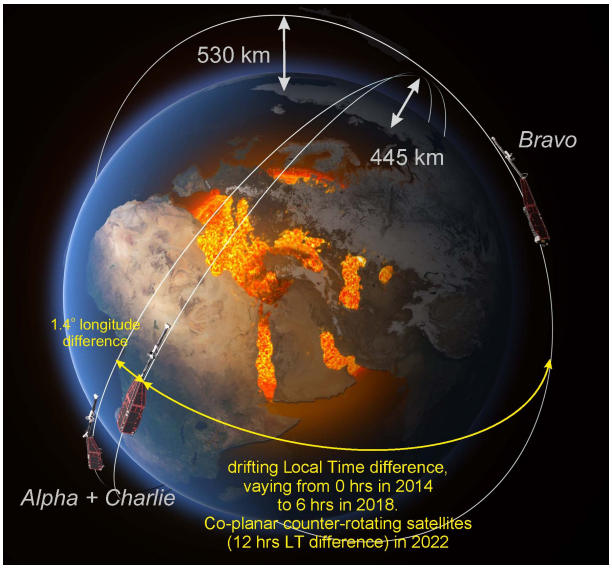

Figure 1: The *Swarm* satellite trio and its orbital configuration

Each of the three satellites carry an **A**bsolute **S**calar **M**agnetometer (ASM) measuring Earth's magnetic field intensity, a **V**ector **F**luxgate **M**agnetometer (VFM) measuring the magnetic vector components, and a three-head **S**tar **TR**acker (STR) mounted close to the VFM to obtain the attitude needed to transform the vector measurements of the VFM magnetometer to a known coordinate frame. Time and position are obtained by on-board GPS.

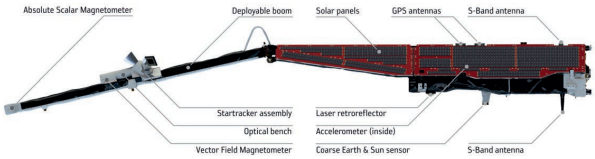

Figure 2: Configuration of the various scientific instruments on board each of the three *Swarm* satellites (ESA/AOES Medialab)

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Swarm Data Products

For electromagnetic induction studies relevant *Swarm* data products include

`MAGx_LR` 1 Hz calibrated and corrected magnetic vector and scalar measurements, interpolated to UTC seconds and provided in the North-East-Center coordinate frame for each of the three *Swarm* satellites;

`MMA_SHA_2` Time series of Spherical harmonic model coefficients of the large-scale magnetospheric field and its Earth-induced counterpart. This product is determined by combing Swarm-satellite and ground observatory data;

`MTI_SHA_2` Spherical harmonic expansion coefficients of the magnetic effect of the oceanic lunar M_2-tide.

A description of the Swarm data products can be found in Olsen et al (2013) and at `http://earth.esa.int/swarm` where also further information on how to obtain the data are given. All *Swarm* data products are freely available to everybody.

Some selected results of using *Swarm* satellite data for EM induction studies

As part of the preparation for the Swarm satellite mission a number of sophisticated and state-of-the-art 3-D inversion schemes have been developed and thoroughly tested, in order to properly process, analyse and interpret the *Swarm* magnetic observations Püthe and Kuvshinov (2013a,b); Velímský (2013); Püthe and Kuvshinov (2014)

Examples of studies that directly use time series of *Swarm* magnetic vector field observations to determine mantle conductivity include the work by Civet et al (2015) and Martinec et al (2018).

An example of using derived Swarm data products like time series of spherical harmonic expansion coefficients of the magnetospheric and induced field for estimating mantle conductivity is the work presented by Püthe et al (2015).

A joint analysis of the magnetic tidal signal of the oceanic M_2 lunar tide in combination with time series of the large-scale magnetospheric and Earth-induced contributions has been performed by Grayver et al (2017) to determine the conductivity of the lithosphere and mantle at depths down to 1600 km. This novel approach combines advantages of the EM induction method (which is sensitive to *conductive* structures) with that of a geoelectric sounding (which is more sensitive to *resistive* structures).

Fig. 3 shows an example for a conductivity-depth profile determined from such a combination of satellite-derived data (Grayver et al, 2017).

See also the presentation by Grayver et al. "*Swarm* in global EM induction studies", to be given at this EM workshop.

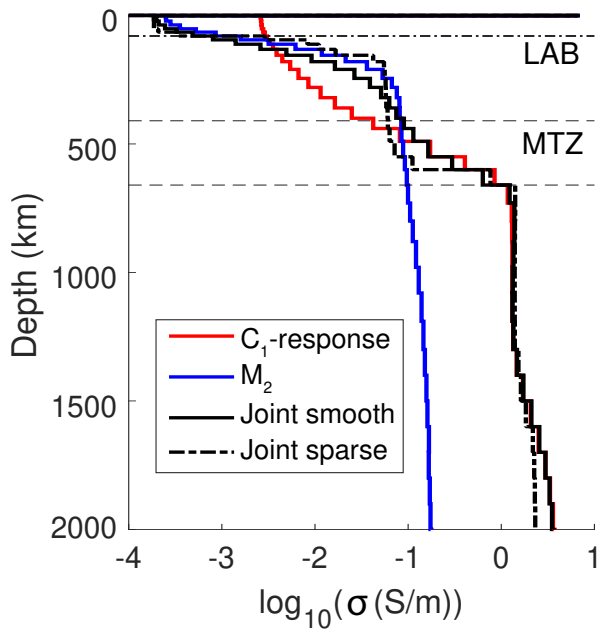

Figure 3: Global conductivity models derived from separate and joint inversions of satellite data. The model denotes with "C-response" is obtained by inverting the response of the magnetospheric ring current, while that denoted as "M_2 model" is derived from the magnetic tidal signals due to semi-diurnal oceanic M_2 tide. Joint inversions were performed using a smoothing and structurally sparse (L1-norm) regularization. From Grayver et al (2017).

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Estimation of electrical conductivity structure of the mantle by using Sq source model of GAIA

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SUMMARY

We've tried to estimate the electrical conductivity of the mantle structure by using the Sq variation derived from the GAIA (Ground-to-topside model of Atmosphere and Ionosphere for Aeronomy).

The GAIA assimilates the meteorological reanalysis data (JRA-55) to the whole atmosphere-ionosphere coupled model and thus it is the well-modelled Sq field. We use this Sq model as the inducing field.

First we executed spherical harmonic expansion of the magnetic field of the GAIA for 3 day time series up to 50 degree, which correspond to three sequent solar quiet days. And then, three-dimensional forward modeling in the spherical coordinate was executed in the frequency domain. Now, we suppose the 1-D structure in the Earth under the ocean-land lateral contrast. As the results, the calculated geomagnetic data inversely converted to the time domain could be closer to the observed time series data, compared to the GAIA Sq field itself, that is, total of RMS data misfit at 71 stations decreases by 40%.

Next, we tried to find the best fit 1-D model in the mantle. We supposed the basic 1-D model as a standard model in the northwest Pacific by Baba (2017), and also tried other models which are more conductive and less conductive. As the results, the original model or slightly more conductive model is the best to explain the vertical magnetic field data of Sq variation. We also try to estimate the 3-D electrical conductivity model in the Earth's mantle by using the Sq model of GAIA, and discuss it.

Keywords: Global induction, Sq field, GAIA, mantle structure

External initiation of the geodynamo via inductive heating

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SUMMARY

Magnetic variability of solar-type stars can deliver significant amounts of time-varying flux to hosted planets. In the early Sun-Earth case, it is not known whether the associated electromotive forces generated sufficient inductive heat to power a long-lived dynamo, keeping in mind that the conversion of convective fluid kinetic energy to magnetic energy may operate at low thermodynamic efficiency. Standard geodynamo models specify an initial seed field of indeterminate provenance; herein a causative mechanism to power up the geodynamo is considered. Conditions on the amplitude of solar magnetic variability are determined here in order that the required power would have been continuously available during the critical but poorly understood dynamo initiation phase early in Earth history. The shielding of Earth's interior by an early-developing magnetosphere reduces the effective power of inductive heating once the geomagnetic field is established.

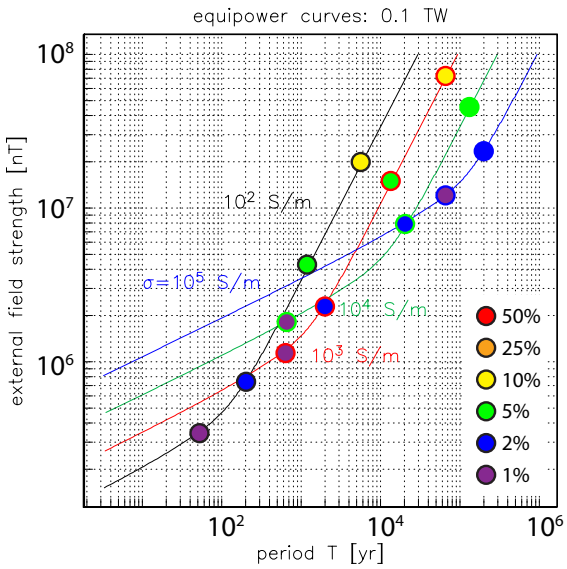

Figure 1. The external magnetic field strength required to generate 0.1 TW of power into a sphere of variable electrical conductivity, as a function of period T. The colored symbols represent skin depth as a percentage of sphere radius.

Paleomagnetic evidence is ambiguous as to the time of origin of the large-scale geomagnetic field. Models of the thermal evolution of Earth's core support a long-lived geodynamo if the mantle extracts enough heat such that the liquid iron and light elements are well-mixed, with the mixture undergoing vigorous convection. The geodynamo operates through conversion of the kinetic energy of these convective fluid motions into magnetic energy; the power consumed in this process is estimated to be ~0.1 TW. The mathematical formula for the power absorbed by a homogeneous sphere in the presence of a uniform oscillating external magnetic field is well known. Using this formula, shown in Figure 1 is the field amplitude at a given period T that is required to supply 0.1 TW of power to a sphere of variable conductivity and Earth's radius. The corresponding skin depths are also shown as percentages of the sphere radius, these provide an indication of the depth of the Ohmic current flow. The results suggest that large external fields $>10^6$-10^8 nT are required to continuously power a thermodynamically efficient early geodynamo. These values are much larger than present-day great magnetic storms but may be commensurate with the intense magnetic variability of the early Sun. New astrophysical observations and theoretical models on magnetic field variability of solar-type stars are becoming available and these might shed light on the magnitude of solar inductive heating that was available to continuously supply power to the nascent geodynamo.

Keywords: electromagnetic induction, electromotive force, geodynamo, geomagnetic induction

Forecasting Solar Wind Velocities from Coronal Hole Properties using Machine Learning Techniques

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SUMMARY

Solar coronal holes (CH) are regions of open magnetic fields that appear as dark areas on the solar disk in extreme ultra-violet pass-bands. These regions are associated with the high-speed solar wind and can increase the geomagnetic activity on Earth, being a geomagnetic source for electromagnetic induction studies at periods relevant to the Earth's mantle conductivity.

In this study we predict the solar wind speed at L1, between the Sun and the Earth, with correlation coefficient of ~0.7 between measured and forecast solar wind velocities and define the main variables and areas of interest on the solar disk for solar wind forecasting.

Solar wind data was measured by the Advance Composition Explorer (ACE), and CH data was extracted by the CHIMERA algorithm from Solar Dynamics Observatory images. The forecast was performed using Machine Learning techniques, such as random forest regression, support vector regression, and neural networks. Inputs to the Machine Learning algorithm include CH area, CH magnetic field properties and CH disk locations.

Keywords: Solar wind velocities, solar coronal hole, forecasting, machine learning.

Modeling global magnetic fields in the daily variation band for mantle induction studies

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SUMMARY

We are developing new data-based global models of magnetic field variations in the "daily variation band", covering periods of roughly 10^4-10^5 s, for both active and quiet conditions. Accurate models of the spatial structure of source fields in this band will enable 3D exploration of upper mantle conductivity variations using GDS methods, extending to much greater depths than is typically possible with MT. This would allow new constraints on transition zone hydration, and deep melt layers which have been hypothesized (and occasionally inferred from seimsic data). Our approach is based on frequency domain principal components analysis (FDPCA) of a large collection of modern and historical observatory data, supplemented by magnetometers deployed (often for years) for space physics studies. Using PCA global scale signals are represented by a relatively small number of data modes (5-10/band). These modes are then fit using ionospheric current basis functions (20-30/ band) derived from a similar FDPCA of magnetic fields output from the TIE-GCM, a mature physics-based numerical ionospheric modeling code. We allow for induced fields with a 1D+thin sheet Earth model, and fit only horizontal components of the data modes, to minimize impact of errors in this simplified model. As improved reference Earth models are developed, this step can be refined Initial results are encouraging: 10 data modes explain over 90% of the total variance (more at mid-latitudes) in the observatory data, and 95% of the variance in the leading data modes can be fit by as few as 20 model modes. Extensions and refinements being explored, include regional models in areas with high observation density, conversion of models to time domain, and ultimately incorporating satellite magnetic field data.

Keywords: External source, daily variation, mantle conductivity

Modelling of electromagnetic signatures of global ocean circulation: Physical approximations and numerical issues

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Summary

The ocean-induced magnetic field is commonly modelled under certain approximations. We focus on the wind- and buoyancy-driven ocean-induced magnetic field; tides are not considered. The horizontal components of the flow possess significant vertical gradient and vertical flows are non-negligible. The forcing is thus rather complex and fully 3D. Despite that, it is common to e.g. vertically integrate the 3D ocean flow and work with the resulting transports, see e.g. Manoj et al (2006). Another popular approach utilizes the so-called thin layer approximation (TLA) of Tyler el al (1997), see e.g. Irrgang et al (2017) or Vivier et al (2004). Moreover, in their implementation of TLA, not only is the ocean treated as a single thin layer but also the vector electromagnetic induction equation is simplified to one scalar equation for the stream function, thus ignoring galvanic coupling between oceans and underlying mantle. The simplified approaches are certainly appealing, their implementation is less complicated and numerical expenses are reduced compared to the approach based on the full 3D electromagnetic induction equation. Unfortunately, the validity of approximations used is not clearly justified; the authors provide a scaling analysis at best. We thus present a numerical study in which the effects of several key physical aspects are quantified. In particular, we study the effects of mantle/core conductivity, galvanic coupling, self-induction and horizontal/vertical resolution. We believe that such study is important not only from the theoretical point of view but also from the perspective of the Swarm mission. One of the Swarm's objectives is "identifying the ocean circulation by its magnetic signature" which may finally lead to the assimilation of magnetic data into ocean circulation models (Irrgang et al, 2017). It cannot be done correctly without proper tools.

Keywords: motional induction, wind-driven ocean circulation, approximation

On the modelling of M_2 tidal magnetic signatures: Effects of physical approximations and numerical resolution

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SUMMARY

The magnetic signatures of ocean M_2 tides have been recently detected by the low-orbit satellite missions CHAMP and Swarm. They have been also used to constrain the electrical conductivity in the uppermost regions of the Earth's mantle. Here we concentrate on the problem of accurate numerical modelling of tidally induced magnetic field, using two different three-dimensional approaches: the contraction integral equation method, and the spherical harmonic-finite element method. In particular, we discuss the effect of self-induction, the galvanic and inductional coupling with the underlying mantle, and the applicability of simplified two-dimensional approximations, both in terms of using the surface conductance and the vertically integrated source terms. We also compare the results for different lateral and radial resolutions, and test the effect of the recent high-resolution ocean conductivity map.

Keywords Ocean induction, tides

Probing upper mantle electrical conductivity with solar quiet variations: An approach and results

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SUMMARY

We present our two-step approach for determining electrical conductivity of the upper mantle using solar quiet (Sq) variations. Sq variations are regular daily variations of the geomagnetic field with magnitude of a few tens of nanotesla. They originate from the Sq electric current system which flows on the sunlit side in a thin ionospheric E-layer at around 110 km altitude and is shaped as two whorls (see Figure 1). Due to their frequency content, Sq variations are known to be sensitive to Earth's mantle conductivity down to 600 km.

In the presented approach, we first determine the inducing part of the Sq variations (the source). We work with data from ground-based geomagnetic observatories and select magnetically quiet days from nearly 20 years of data. To exclude disturbances from equatorial and polar electrojets, we use magnetic fields from mid-latitudinal observatories. We adopt parameterization of the Sq source with spherical harmonics (SH). The analysis is performed in frequency domain. Using time spectra of horizontal magnetic field components, we determine SH coefficients for the selected days assuming a prior 3-D Earth's conductivity model. This prior model consists of a 1-D global averaged mantle model complemented by a thin 2-D conductance layer in the uppermost part, which captures the non-uniform distribution of continents and oceans and allows to account for the ocean induction effect (OIE).

Next, we estimate global-to-local transfer functions (TF) which relate SH coefficients and time spectra of a vertical magnetic field estimated at a specific location. With this approach we are not limited to stations we used to determine the source. We can determine TFs at arbitrary mid-latitude sites, including seabottom stations. Using 3-D forward operator to account for OIE, we invert the estimated TFs for local 1-D conductivity profiles using stochastic optimization method called Covariance Matrix Adaption Evolution Strategy (CMAES), which along with the model itself provides the model uncertainties.

We recover local 1-D conductivity profiles at multiple stations and discuss the detected differences.

Keywords: Electromagnetic induction, solar quiet variations, inversion

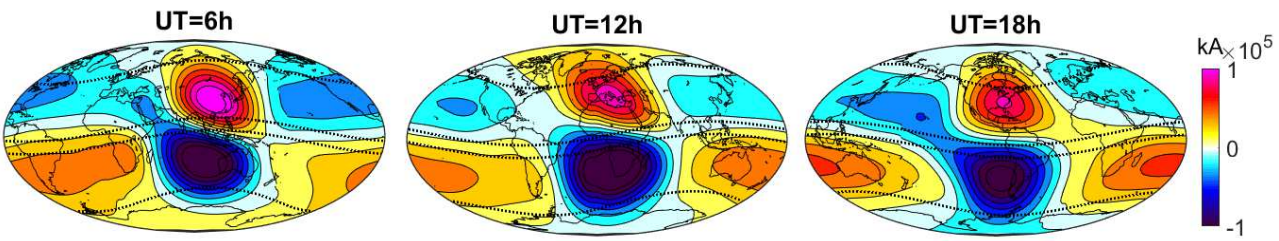

Figure 1. Snapshots of the recovered Sq source (in the form of current function) for a magnetically quiet day.

Swarm in global EM induction studies

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SUMMARY

Swarm is an ongoing multi-satellite mission aimed at measuring Earth's magnetic field. This contribution presents an overview of Swarm activities in the context of the global induction studies of the Earth's mantle. Specifically, we discuss derivation of magnetospheric Q-responses and present updated M2 tidal magnetic signals from the most recent Swarm data. Further, these data are inverted jointly to constrain the conductivity of the upper and lower mantle in the depth range between 10 and 1600 km. The challenging task of accounting for the ocean induction effect and motionally-induced signals was addressed by using the full 3D electromagnetic modeling as a forward operator, which incurs additional computational resources. Additionally, we present the methodology to estimate the uncertainty of the obtained conductivity models using stochastic sampling methods.

Keywords: global induction, satellite data, SWARM

Three-dimensional MT modeling in a spherical Earth

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SUMMARY

In this work, we present results of three-dimensional magnetotelluric modeling for the model of spherical Earth. We study the effects of earth curvature for continental scale MT surveys and investigate approaches aimed at mimicking the plane wave source on a sphere. To calculate MT responses for a spherical 3D Earth, we used the cartesian solver GoFEM based on the high-order finite-element method. In order to approximate spherical geometry accurately with fewer hexahedral elements, we use high-order meshes. That is, assume that edges and faces of hexahedral elements are not straight lines and surfaces, but can be curved. We show that combining high-order basis functions and locally refined high-order meshes (Figure 1) allows us to calculate accurate solutions with relatively small number of cells. Magnetotelluric responses calculated for a spherical Earth are then compared with corresponding responses calculated using an equivalent flat Earth model to quantify effects of the Earth curvature and plane wave source approximation.

Keywords: Electromagnetic induction, modeling, finite element