Probing the oceanic upper mantle using M_2 tidal magnetic field, waveform tomography, satellite gravity field, surface elevation and heat flow data

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Abstract

Conventional methods of seismic tomography, surface topography and gravity data analysis constrain distributions of seismic velocity and density at depth, all depending on temperature and composition of the rocks within the Earth. WINTERC-grav, a new global thermochemical model of the lithosphere-upper mantle constrained by state-of-the-art global waveform tomography, satellite gravity (geoid and gravity anomalies and gradiometric measurements from ESA's GOCE mission), surface elevation and heat flow data has been recently released. WINTERC-grav is based upon an integrated geophysical-petrological approach where all relevant rock physical properties modelled (seismic velocities and density) are computed within a thermodynamically self-consistent framework allowing for a direct parameterization of the temperature and composition variables. In this study, we derive a new three dimensional distribution of the electrical conductivity in the Earth's upper mantle combining WINTERC-grav's thermal and compositional fields along with laboratory experiments constraining the conductivity of mantle minerals and melt. We test the derived conductivity model over oceans by simulating a tidally induced magnetic field. Here, we concentrate on the simulation of M_2 tidal magnetic field induced by the ocean M_2 tidal flow that is modelled by two different assimilative barotropic models, TPXO8-atlas (Egbert and Erofeeva, 2002) and DEBOT (Einšpigel and Martinec, 2017). We compare our synthetic results with the M_2 tidal magnetic field estimated from 5 years of Swarm satellite observations and CHAMP satellite data by the comprehensive inversion of Sabaka et al. (2018).

The motionally induced magnetic field equation

The magnetic field $\vec{B}(\vec{r}, t)$ induced in the Earth's oceans by the motion of saltwater in the presence of the Earth's magnetic field $\vec{B}_0(\vec{r}, t)$ is governed by the magnetic induction equation

$$\frac{1}{\mu_0} \operatorname{curl} \left(\frac{1}{\sigma} \operatorname{curl} \vec{B} \right) + \frac{\partial \vec{B}}{\partial t} = \operatorname{curl}(\vec{u} \times \vec{B}_0), \tag{1}$$

where σ denotes the electric conductivity of saltwater and the Earth's mantle, respectively, and $\vec{u}$ is ocean flow velocity.

We deal with the magnetic field induced by ocean flows generated by tidal forcing with an angular frequency ω. We will assume that the ocean responds to the tidal forcing by a steady-state periodic circulation with an ocean velocity field $\vec{u}$ whose temporal variations are represented by the time-harmonic dependency $e^{i\omega t}$, that is $\vec{u}(\vec{r}, t) = \vec{u}(\vec{r})e^{i\omega t}$. Consequently, the induced magnetic field will be expressed in the form $\vec{B}(\vec{r}, t) = \vec{B}(\vec{r})e^{i\omega t}$.

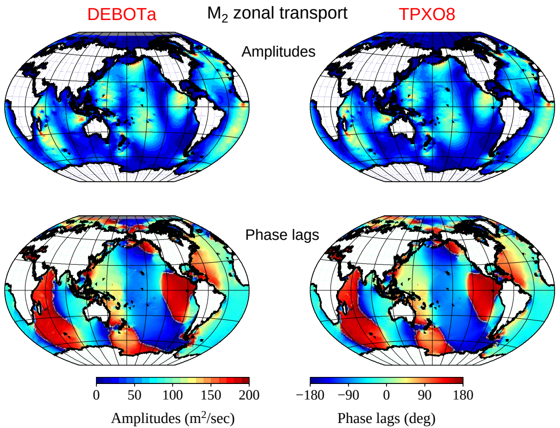
The boundary conditions are prescribed at interfaces across which the electrical conductivity σ changes discontinuously. The continuity of the tangential components of magnetic induction and electric intensity are required

$$\begin{aligned} \vec{n} \times [\vec{B}]_{-}^{+} &= \vec{0}, \\ \vec{n} \times [\vec{E}]_{-}^{+} &= \vec{0}, \end{aligned} \tag{2}$$

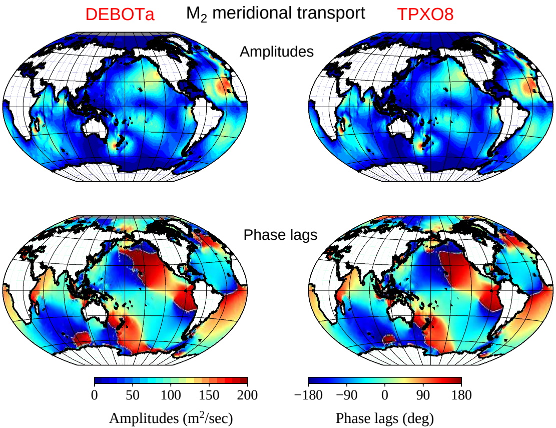
where $\vec{n}$ is the unit vector normal to a discontinuity and the electric intensity is expressed in terms of $\vec{B}$ by Ampere's current law in the quasi-static approximation,

$$\vec{E} = \frac{1}{\mu_0 \sigma} \operatorname{curl} \vec{B}. \tag{3}$$

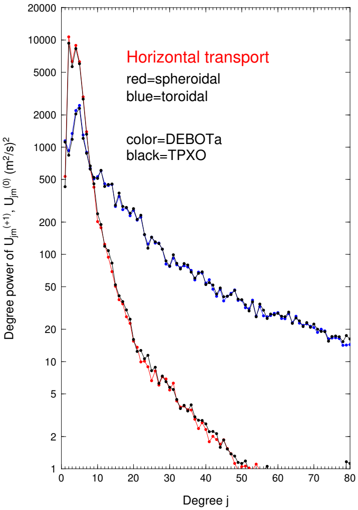
M_2 tidal barotropic ocean horizontal transport (φ comp.)



M_2 tidal barotropic ocean horizontal transport ($-\vartheta$ comp.)

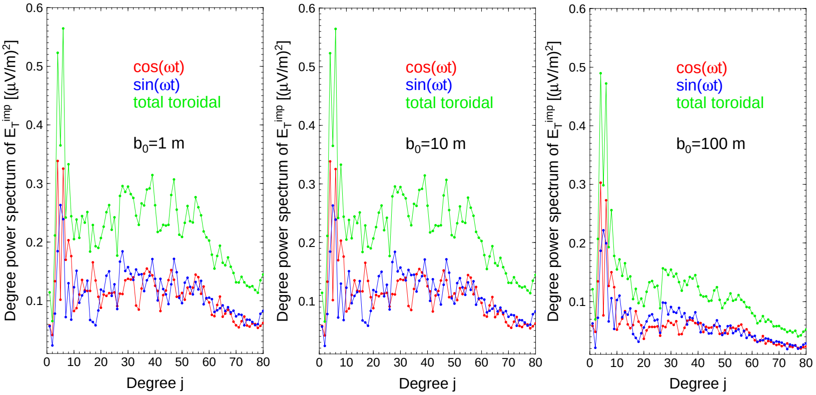


Degree power spectrum of horizontal transport

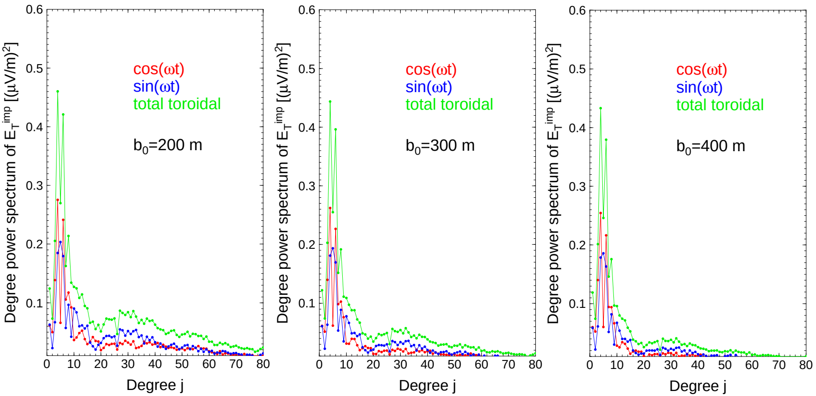


Degree power spectrum of Lorentz's force $u \times B_0$

$$\mathbf{u}(r,\Omega) = \begin{cases} \dfrac{\mathbf{U}(\Omega)}{b(\Omega)} & \text{for} \quad b(\Omega) \geq b_0 \\[2ex] \dfrac{\mathbf{U}(\Omega)}{b_0} & \text{otherwise} \end{cases}$$

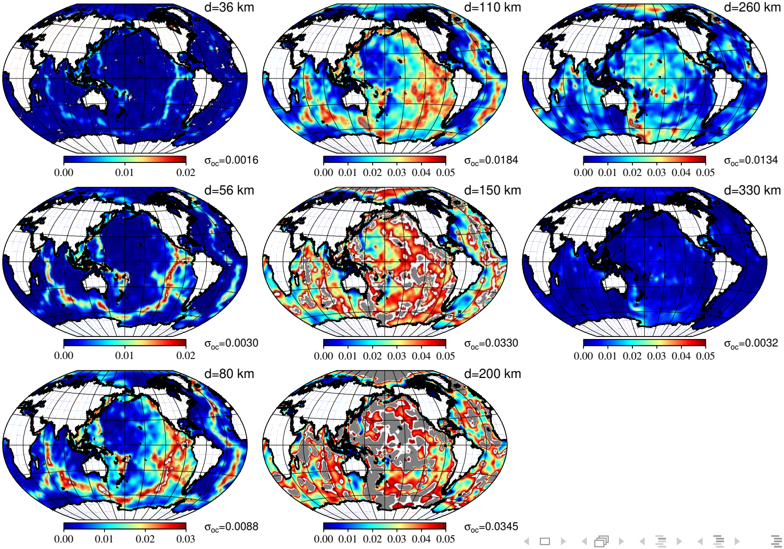


Degree power spectrum of Lorentz's force $u \times B_0$

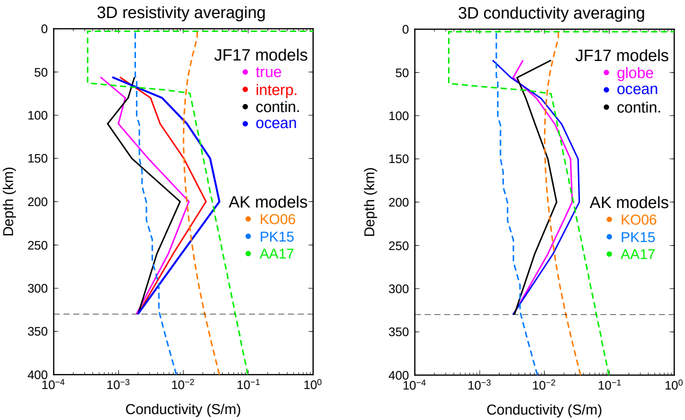


JF17 upper-mantle 3D electrical conductivity

A 3D electrical conductivity structure of the uppermost mantle (down to 330 km) has been constructed by J. Fullea in 2017 by inverting the seismic tomographic model of S. Lebedev. The approach transforms the seismic velocities to the temperature distribution, followed by calculation of the electrical conductivity according to the Arrhenius relationship.

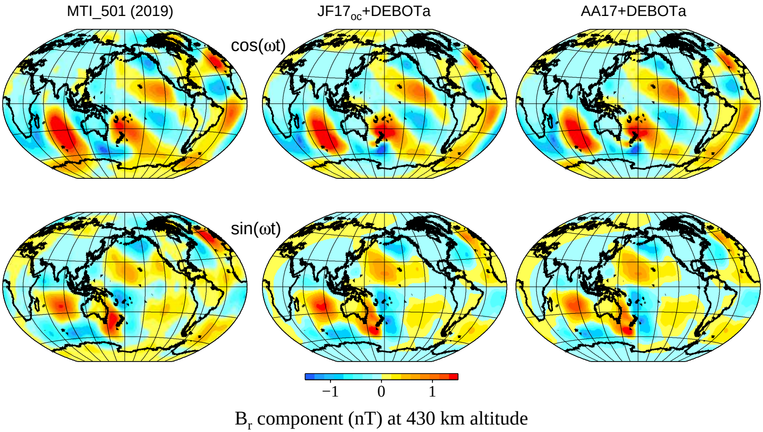


Upper-mantle 1D averaged conductivities of JF17 model



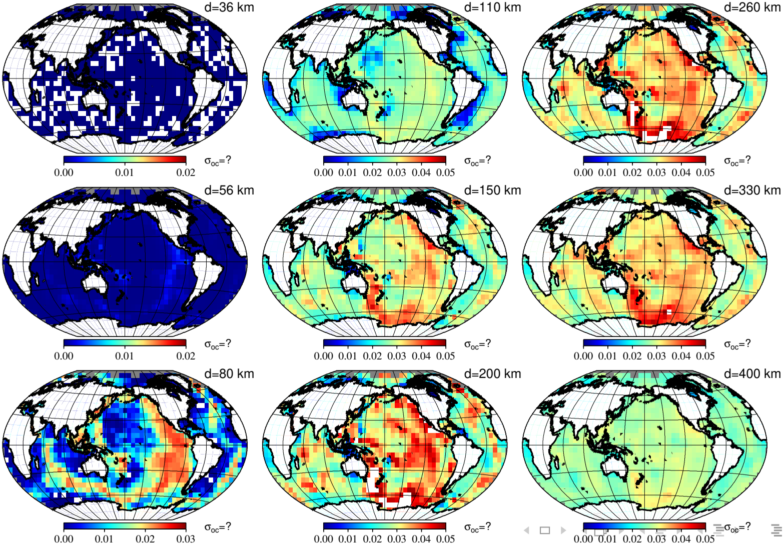
KO06 (Kuvshinov and Olsen, 2006)
PK15 (Püthe et al., 2015)
AA17 (Grayver et al., 2017)

Oceanic M_2 tidal magnetic field (cos and sin terms)

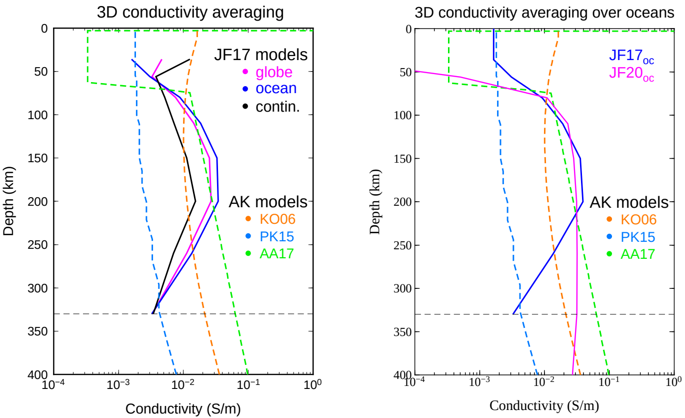


JF20 upper-mantle 3D electrical conductivity

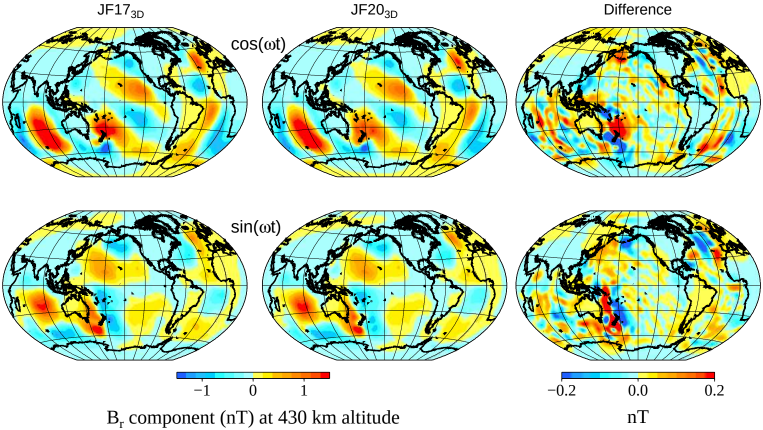
A new approach WINTERC (Fullea et al., 2018) provides thermal and compositional field of the lithosphere and upper mantle by inverting global waveform tomography, satellite gravity and gradiometry measurements, surface elevation and heat flow data in a thermodynamically self-consistent framework. Together with laboratory experiments constraining the electrical conductivity of mantle minerals and melt, and we derived a new model JF20 of a 3D electrical conductivity structure of the upper mantle down to 400 km depth.



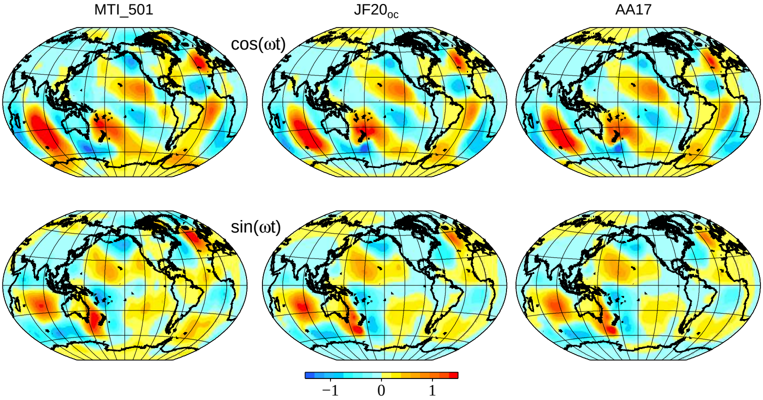
Upper-mantle 1D averaged conductivities of JF17 and JF20 models



JF17 vs JF20 oceanic M_2 tidal magnetic fields



JF20$_{oc}$ oceanic M_2 tidal magnetic fields



B_r component (nT) at 430 km altitude

Conclusions

- The tidal magnetic field due to a new 3D conductivity model JF20 captures the Swarm M_2 tidal magnetic field remarkably well though JF20 is not constrained by surface or satellite magnetic measurements.
- 1D conductivity model $\mathrm{JF20}_{oc}$ based on averaging of JF20's conductivities over oceans is a representative (alternative to model AA17 (Grayver et al., 2017)) of a spherical symmetric distribution of electrical conductivity in the upper mantle down to 400 km.
- The differences in tidal magnetic fields due to models JF20 and $\mathrm{JF20}_{oc}$ are up to 0.3 nT showing that lateral conductivity inhomogeneities of the oceanic upper mantle are rather weak to induced a stronger magnetic field.