Title:	Electromagnetic ocean effects
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Electromagnetic ocean effects

The oceans play a special role in electromagnetic induction (qv Electromagnetic Induction), due to their relatively high conductivity and the dynamo effect of ocean currents. Typical crystalline rocks of the Earth's crust have electrical conductivities in the range of 10^{-6} to 10^{-2} Siemens (1/Ω) per meter. In comparison, sea water, with 2.5-6 S/m, is a very good conductor. Electrical currents are induced in the oceans by two different effects: Induction by time varying external fields and induction by motion of the sea water through the Earth's main field (qv Main Field).

Ocean conductivity

While fresh water has a very low conductivity, a salt concentration of about 35 grams per liter turns the oceans into good conductors. In contrast to the electron and electron-hole conductivity of solid-Earth materials, the carriers of charge in the oceans are the hydrated ions of the dissolved salts. Positive ions are called anions and negative ions are cations. The conductivity of sea water depends on the number of dissolved ions per volume (i.e. salinity) and the mobility of the ions (i.e. temperature and pressure). Conductivity increases by the same amount with a salinity increase of 1 gram per liter, a temperature increase of 1° C, and a depth (i.e. pressure) increase of 2000 m. The change in conductivity is dominated by temperature, with a range of about 2.5 S/m for cold, deep water to about 6 S/m for warm surface water.

Motional induction

When the ions are carried by ocean flow through the Earth's magnetic field, they are deflected by the electromagnetic Lorentz force. The direction of the Lorentz force on the anions is given by the right hand rule: thumb pointing in the direction of ocean flow, index finger in the direction of the magnetic field, then the middle finger indicates the direction of the deflection of the anions. The cations are deflected into the opposite direction. This separation of charge sets up large scale electric fields. Depending on the conductivity structure of the ocean and solid Earth, these fields drive electric currents which in turn generate secondary magnetic fields.

GOVERNING EQUATIONS

Motional induction is governed by the following equations: The local current density **J** in a conductor moving with velocity **u** is given by

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}_{main}), \qquad (1)$$

where σ is the local conductivity and $\mathbf{B}_{main}$ is the ambient main magnetic field (qv Main Field). The $\mathbf{u} \times \mathbf{B}_{main}$ term is the driver of the motionally induced electric current, while the induced electric field **E** counteracts this driver and results in the actual current **J**. This current generates a magnetic field $\mathbf{B}_{ocean}$ as

$$\nabla \times \mathbf{B}_{ocean} = \mu_0 \mathbf{J} \,. \tag{2}$$

Combining equations (1) and (2), and rearranging, yields an equation for the induced electric field

$$\mathbf{E} = \frac{1}{\mu_0 \sigma} \nabla \times \mathbf{B}_{ocean} - \mathbf{u} \times \mathbf{B}_{main} \,. \tag{3}$$

While the irrotational (divergent) part of this electric field is maintained by an induced charge, the rotational part is induced by the temporal variations of the ocean magnetic signal as

$$\partial_t \mathbf{B}_{ocean} = -\nabla \times \mathbf{E} \,. \tag{4}$$

Taking the curl of equation (3) and combining with (4) gives the motional induction equation

$$\partial_t \mathbf{B}_{ocean} = \nabla \times (\mathbf{u} \times \mathbf{B}_{main} - \frac{1}{\mu_0 \sigma} \nabla \times \mathbf{B}_{ocean}) \,, \tag{5}$$

which is valid inside the oceans and the solid Earth. The fields above the surface are then determined by Laplace's equation $\nabla^2 V = 0$ for the scalar potential V of the magnetic field $\mathbf{B}_{ocean} = -\nabla V$ in the current-free region outside of the Earth.

ELECTRIC FIELDS OF MOTIONAL INDUCTION

Already in 1832, Faraday predicted a motionally induced electric field for the river Thames but failed to detect it, due to a lack of adequate instrumentation. Such fields were then observed in 1851 by Wollaston in a telegraphic cable across the English Channel. Young demonstrated in 1920 the recording of electric fields in the oceans by ship-towed electrodes. Submarine cables and towed electrodes are still the principal methods of measuring ocean flow by electromagnetic methods. Overviews of the theory and instrumentation are given by Sanford (1971) and by Filloux (1973).

MAGNETIC FIELDS OF MOTIONAL INDUCTION

Motionally induced magnetic fields can be divided into toroidal (strictly horizontal) and poloidal (both horizontal and vertical) parts. The toroidal magnetic field is generated by electric currents closing in vertical planes and is estimated to reach 100 nT in amplitude. It is confined to the oceans and solid Earth and is therefore only observable by subsurface measurements, for example by ship-towed or ocean-bottom magnetometers. Indeed, Lilley *et al.* (2001) showed that a magnetometer lowered by a cable from a ship can be used to determine vertical profiles of the ocean velocity.

The much weaker poloidal field, with amplitudes up to 10 nT, results from electric currents closing horizontally. It has a significant vertical component and reaches remote land and satellite locations. Much attention has been given to the periodic magnetic signals of ocean flow which is driven by the lunar tides. In interpreting tidal magnetic signals one has to take into account that lunar tidally driven winds in the upper atmosphere induce tidal electric fields and currents in the ionosphere which also contribute to the magnetic signal at these periods. However, the strength of the ionospheric currents depends on the conductivity of the ionosphere, which varies with the time of day. This additional solar-time modulation of the ionospheric lunar tidal fields can be used to separate them from the oceanic lunar tidal signals (Malin, 1970). The dominant M2 lunar tidal ocean flow magnetic signal has also been identified in CHAMP (qv CHAMP) satellite data [Tyler et al., 2003]. A map of this signal at surface level is displayed in Figure 1.

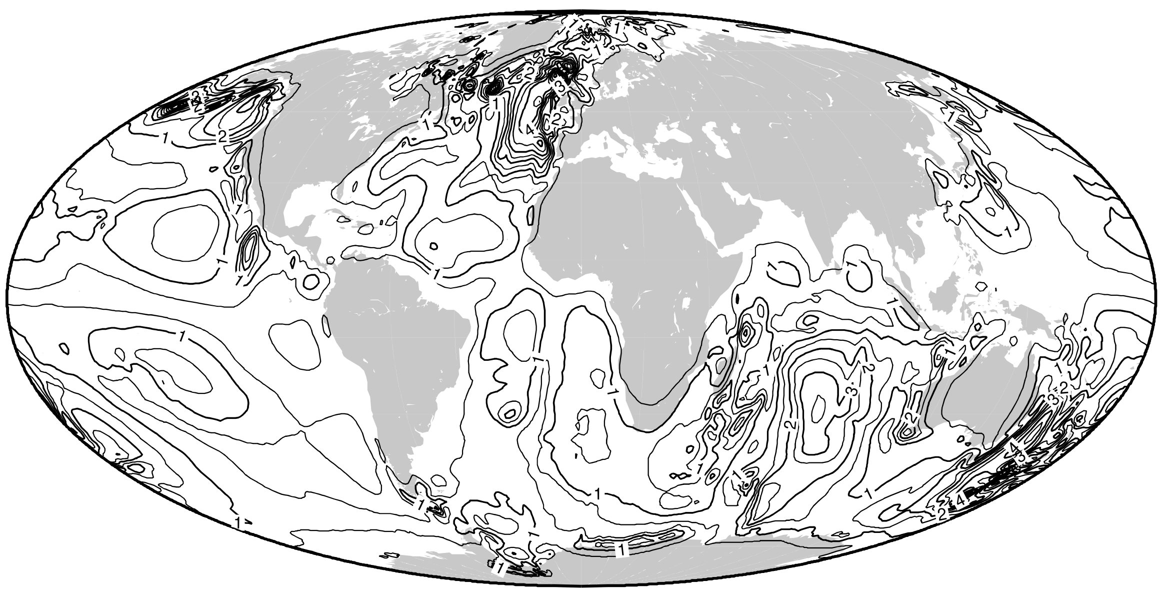

Figure 1: Predicted amplitude of the vertical component of the magnetic field at the Earth's surface generated by ocean flow due to the lunar M2 tide. Reproduced from Kuvshinov and Olsen (2005b).

Using high resolution ocean circulation models, predictions of the magnetic signal of non-tidal ocean flow have been made by several authors. Amplitudes at surface level are predicted to be comparable to those of tidal ocean flow signals. However, the magnetic signal of the steady ocean circulation is impossible to distinguish from the crustal magnetic field (qv Crustal Magnetic Field). Observations must therefore concentrate on the much weaker time varying part of the signal. For example, the annual variation in the Indian Ocean is predicted to generate a signal with only about 0.3 nT at satellite altitude. It is a great challenge to separate this weak ocean signal from ionospheric fields, which have similar periodicities and may even share some of the atmospheric driving forces. At this point of time, non-tidal ocean currents have not yet been convincingly identified in land observatory or satellite magnetic measurements.

Induction by time varying magnetic fields

External magnetic fields, generated in the ionosphere (qv Ionosphere) and the magnetosphere (qv Magnetosphere), vary strongly in time, exhibiting regular daily variations (qv Geomagnetic temporal spectrum) and occasional strong magnetic storms (qv Storms and substorms) caused by coronal mass ejections from the sun. These time varying magnetic fields induce electric fields and currents in the oceans, generating secondary induced magnetic fields.

GOVERNING EQUATIONS

A time varying magnetic field induces an electric field **E** in the oceans, given by

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}, \qquad (6)$$

where **B** is the sum of the inducing and the secondary induced magnetic field. The induced electric field drives electric currents

$$\mathbf{J} = \sigma \mathbf{E}, \qquad (7)$$

generating a secondary induced magnetic field

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}_{induced}. \qquad (8)$$

Combining equations (6), (7) and (8) yields

$$\partial_t \mathbf{B} = -\nabla \times \frac{1}{\mu_0 \sigma} \nabla \times \mathbf{B}_{induced}, \qquad (9)$$

which is the equation for induction by time-varying magnetic fields inside the oceans. In contrast to the motional induction discussed above, the oceans are assumed here to be stationary in the Earth fixed reference frame. The field in the source-free region above the Earth’s surface and below the external current systems is again given by Laplace’s equation.

SKIN DEPTH

Low frequency electromagnetic waves penetrate deeper into an electrical conductor than high frequency waves. For a periodic external field with frequency ν, equation (9) demands that the amplitude in a uniform conductor decays exponentially with depth. The depth at which the amplitude is reduced to 1/e is called the skin depth δ, given by

$$\delta = \sqrt{\frac{1}{\pi \mu_0 \sigma \nu}} \approx \frac{270m}{\sqrt{\nu}}, \qquad (10)$$

where the frequency ν is given in Hz and a sea water conductivity of 3.5 S/m is assumed. Thus, to effectively penetrate through a sea water column of 5 km, magnetic disturbances have to have periods longer than about 6 minutes. However, even up to periods of several days, induced fields are strongly influenced by the highly conducting oceans.

OCEAN INDUCTION BY MAGNETIC STORMS

While daily variations during solar quiet conditions generate significant induction in the oceans, a much stronger effect is caused by magnetic storms. Strong magnetic storms generate ocean induced magnetic fields reaching magnitudes of more than 100 nT. An overview of induction in the oceans by solar quiet and storm time fields is given by Fainberg (1980). The induced currents are concentrated near the coasts, the horizontal boundaries of the conductor. Their magnetic signal is also known as the coast effect (qv Coast effect of induced currents). The ocean induced fields can be predicted for a given external storm signature using a 3D conductivity model of the oceans, crust and mantle. The induction equation (9) is solved either directly in the time domain, or separately for all contributing frequencies with a subsequent inverse Fourier transform to the time domain. The result of a simulation using the latter approach (Kuvshinov and Olsen, 2005a) for a strong magnetic storm is shown in Figure 2.

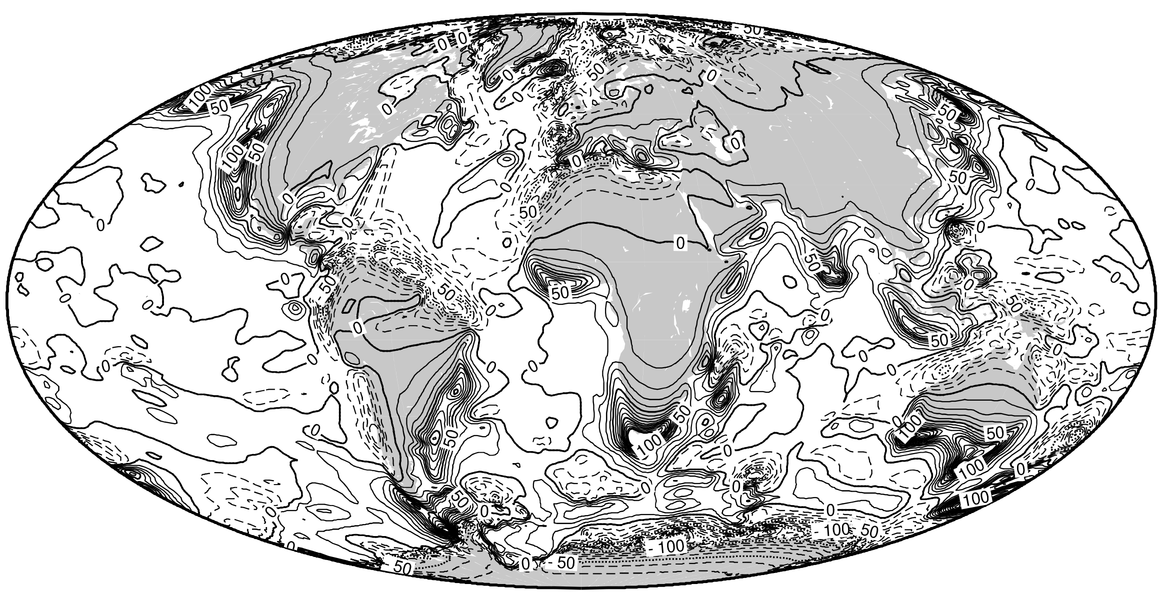

Figure 2: Magnetic field induced in the oceans by the Bastille-day magnetic storm of July 15, 2000. Shown is the vertical component of the induced magnetic field at 21:30 universal time at the Earth's surface. Reproduced from Kuvshinov and Olsen (2005a).

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Cited (qv):
Electromagnetic Induction
Main Field
CHAMP
Crustal Magnetic Field
Ionosphere
Magnetosphere
Geomagnetic temporal spectrum
Storms and substorms
Coast effect of induced currents