Investigating regional outer core flows using the magnetic field

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WHY DOES THE EARTH'S MAGNETIC FIELD CHANGE?

The Earth's core consists largely of iron, and is very hot from when the Earth formed. Pressure keeps the inner core solid, but the outer part is liquid, about as runny as water. A magnetic field is generated in the outer core by complex motions of the liquid.

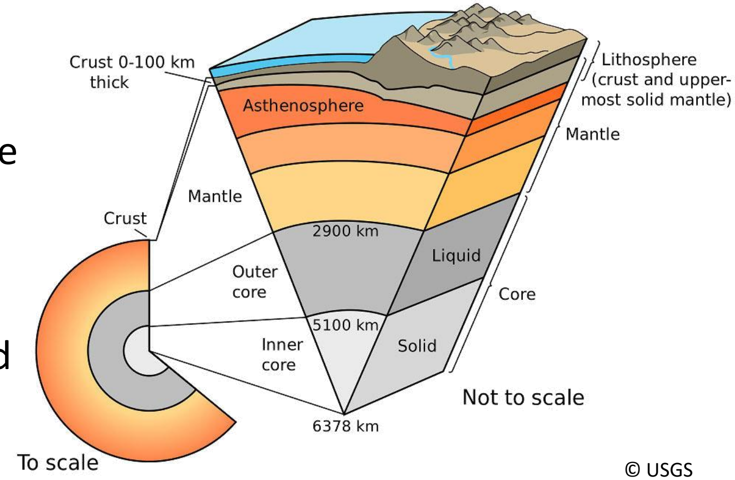
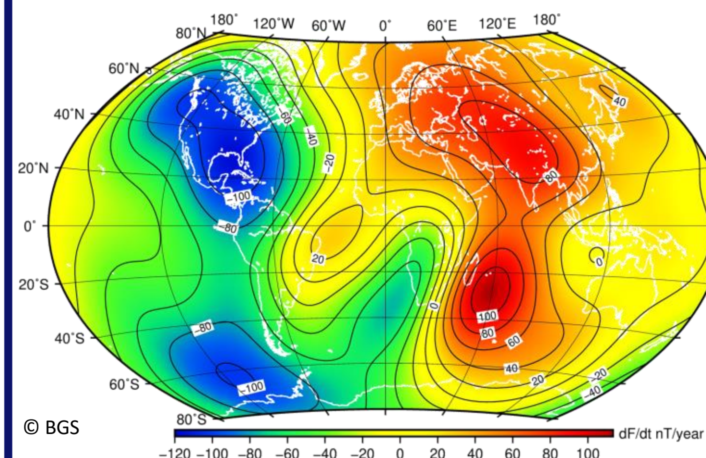


Fig. 1: Cross-Section of Earth showing outer-core



We want to know how the liquid in the outer core is moving and use it to forecast changes to the magnetic field. This is useful for multiple reasons, such as navigation and satellite orientation.

Fig. 2: Map of predicted annual rate of change of total intensity from IGRF 2020-2025

The International Geomagnetic Reference Field (IGRF) model is updated every 5 years but, due to our poor understanding of how the core flow is changing, the 2015-2020 forecast error was larger than expected.

IS THE MAGNETIC FIELD CHANGE RELATED TO FLOW IN THE OUTER CORE?

One way we can measure how the liquid in the outer core is moving is by observing how magnetic field lines change. However, there are ambiguities so we have to make assumptions in order to produce sensible models.

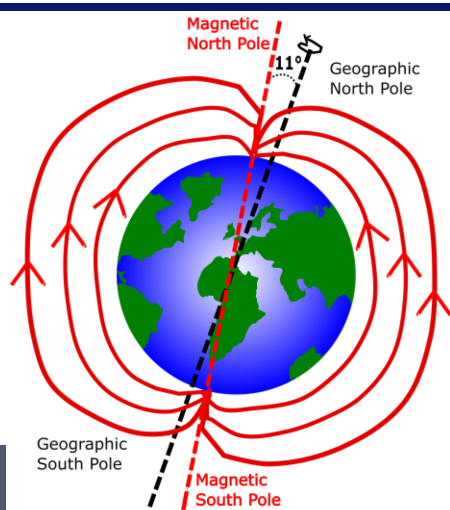
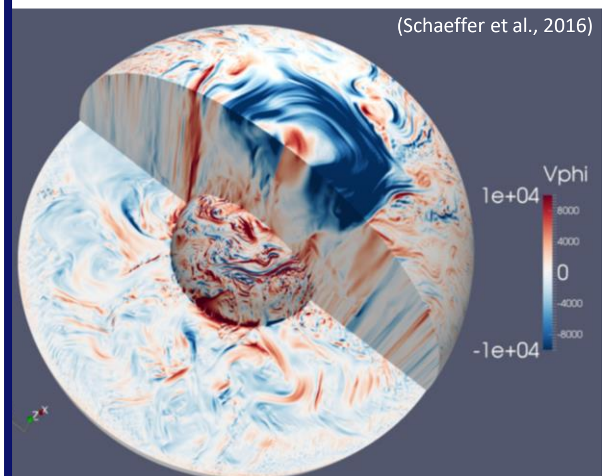


Fig. 3: On a planetary scale, magnetic field lines extend from the south to north pole



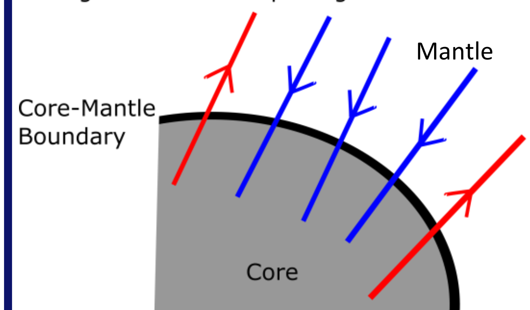
These assumptions are generally based on the physical properties of the way that fluids move in rotating spheres. These provide a reasonable solution over the majority of the core-mantle boundary but not the entire surface.

Fig. 4: Cross-Section of Earth's outer core showing the east-west flow component from a computer simulation of magnetic field generation. The magnetic field at the core-mantle boundary becomes less dipole dominated closer to the CMB and we need small scale flows to generate that complexity

HOW DO FIELD LINES MOVING RELATE TO CORE FLOW MOVING?

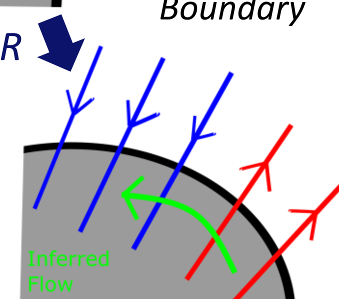
To solve for core surface flow, we invert the change of the magnetic field strength (known as secular variation). As the liquid iron moves along the surface of the Earth's outer core, the field lines are dragged along with it.

Magnetic field lines pointig inwards and outwards



Field lines are tied to the pockets of flow on the Core-Mantle Boundary

PERIOD OF TIME LATER



We can calculate the flow on the CMB by seeing how the field lines have moved

WHAT DOES CORE SURFACE FLOW LOOK LIKE?

This is an example flow from June 2005 from data from the CHAMP satellite. We can see that the main features of the flow are 1) strong westward flow in the Atlantic Ocean, 2) much weaker flow under the Pacific Ocean, and 3) an eccentric gyre the region of the CMB below eastern Russia, across Africa and up to the north pole over eastern United States. The average flow speed is ~15 km/yr (about as quick as a snail moves).

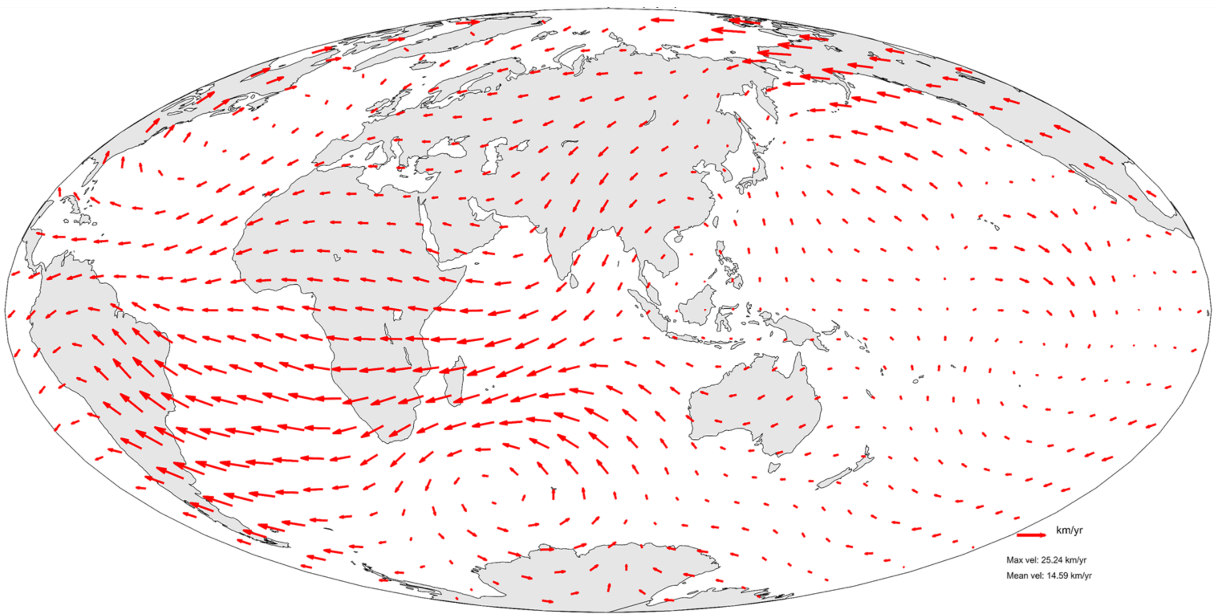


Fig. 6: A core surface flow inversion from CHAMP satellite data from June 2005. Continents are marked on for reference. The maximum velocity is 25 km/yr.

WHY ARE WE INVESTIGATING REGIONAL FLOWS?

We want to improve forecasts of magnetic field change by better understanding individual regions. These individual regions are motivated by:

- some assumptions applied when inverting from field to flow define the flow over only part of the core surface, e.g. tangentially geostrophic flow (Le Mouël, 1984)
- investigating different fluid motions in different regions of the sphere, e.g. the column above and below the inner core – the tangent cylinder (Amit & Pais, 2013)
- spatially uneven data collection or the wish to use higher quality data that are only collected over a select area (Kim & von Frese, 2017)
- investigating how features on the base of the mantle affect flow on the outer core surface, e.g. seismic velocity anomalies

The technique we use is called *spherical Slepian functions*, which we are applying to core flows for the first time.

AN EXAMPLE OF REGIONAL FLOW USING SPHERICAL SLEPIAN FUNCTIONS

Large low shear velocity provinces (LLSVPs) are features on the base of the mantle which slow any seismic waves passing through these regions (e.g. Garnero et al, 2016). There is debate about how LLSVPs formed and the impact that they have on the Earth's system. The outlines of LLSVPS are shown in green in figure 7.

We have managed to separate the flow within the LLSVP relatively well and minimised flow outside of the region we specified. However, there is some unwanted signal generated at the region's edges. The energy spectra show than the flow energy within the LLSVP is weaker than the input at low spherical harmonic degrees but significantly stronger than the input at higher degrees.

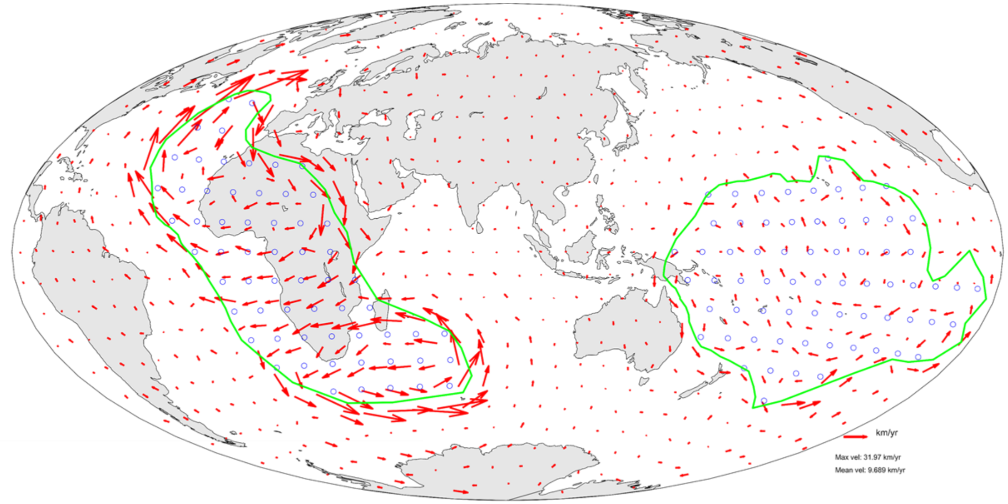


Fig. 7: A core surface flow inversion from CHAMP satellite data from June 2005 restricted to inside the LLSVP. Continents are marked on for reference. Mean velocity is 10 km/yr and maximum velocity is 32 km/yr.

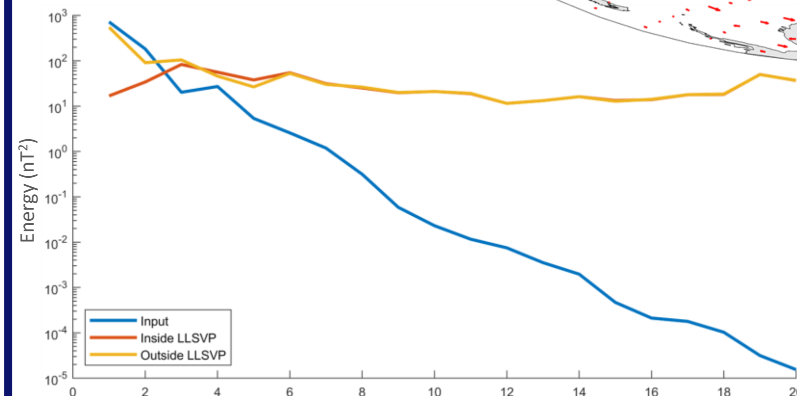


Fig. 8: The spectra for the decomposition of a global inversion (blue) into the area inside (orange) and outside (yellow) the LLSVP.

CURRENT CONCLUSIONS

Despite spherical Slepian functions being a promising technique, we have generated significant unwanted signal at the edge of the LLSVPs caused by the limited bandwidth of core surface flows (maximum spherical harmonic degree = 20). We are investigating ways of overcoming or reducing this, and other aspects of the technique applied to core surface flows.

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