# Gyre-driven decay of the geomagnetic dipole

Chris Finlay[1], Julien Aubert[2] and Nicolas Gillet[3]

[1]DTU Space, Denmark, [2]IPGP/CNRS, France, [3]ISTerre Grenoble/CNRS, France

## Summary

Direct observations show that the magnitude of the Earth's magnetic dipole has steadily decayed over the past 170 years; it is now more than 10% weaker than it was in 1840. Here, we explore the possibility that a planetary-scale gyre in the outer core, previously revealed by core flow inversions, plays an important role in dipole decay with its meridional arms simultaneously transporting reversed flux poleward and strong normal flux equatorward.

We present simple kinematic experiments that demonstrate the basic mechanism together with results from frozen-flux, quasi-geostrophic, core flow inversions that display similar characteristics. Moving to a more realistic scenario, we present initial investigations of dipole decay in a 3D, convection-driven, numerical dynamo with an Earth-like magnetic Reynolds number. This allows for the evolution of the magnetic field by both advection and diffusion processes. The numerical dynamo model studied naturally generates a planetary-scale quasi-geostrophic gyre (Aubert et al., 2013) and is initialized to be in a state consistent with the observed core surface magnetic field (Aubert, 2014). We find that this system can reproduce the general characteristics of current dipole decay episode, and that advection by the planetary gyre plays an important role.

## Observed dipole decay

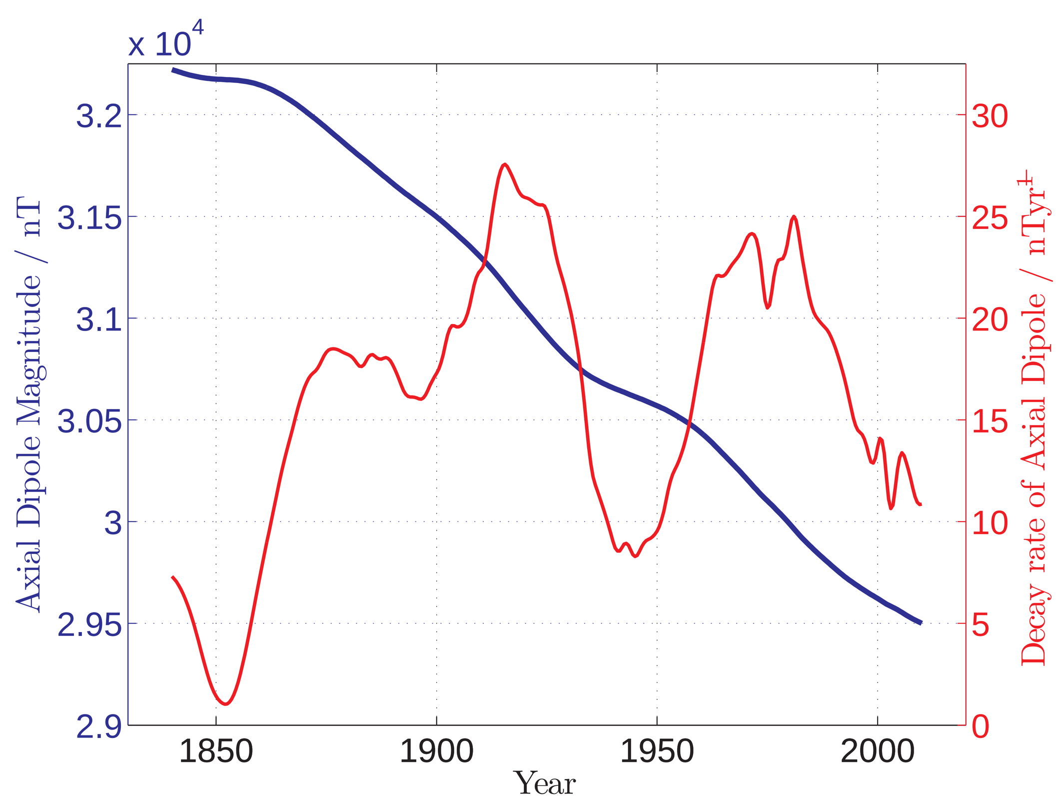


**Fig. 1:** Evolution of axial dipole magnitude since 1840, from the COV-OBS model of Gillet et al., (2013).

- Axial dipole has decayed monotonically since 1840
- Rate of decay has fluctuated around 15 nT/yr and has been decreasing since 1980

## Present-day core surface field and flow

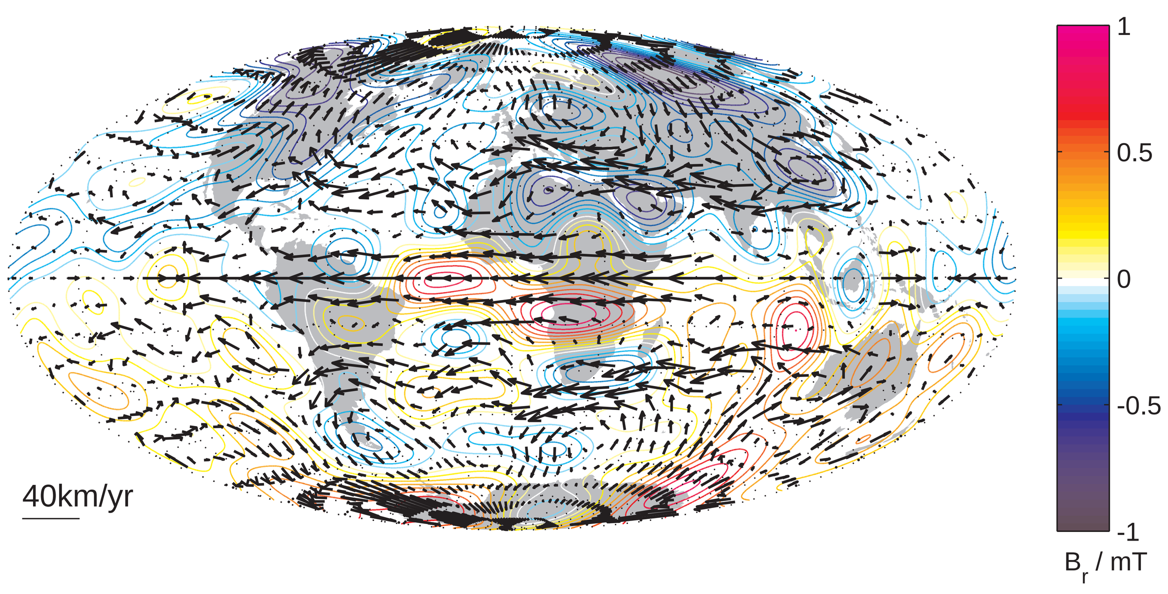


**Fig. 2:** Radial field and flow at the core surface, averaged over the decade 2000-2010, from Gillet et al., (2013, 2014).

- Now have more than a decade of global, high-quality, satellite observations of the geomagnetic field
- Dipole decayed throughout, but no clear evidence for dramatic flux expulsion during this time
- New estimates of electrical conductivity in the core imply $Rm$ is higher than previously thought
- Suggests the majority of secular variation should be accounted for by flux transport mechanisms
- Frozen flux flow inversions, with quasi-geostrophy(QG) constraints, account well for the observations
- Evidence for a planetary-scale gyre

**But, how do such flows cause the dipole to decay?**

## Proposed mechanism

The rate of change of the dipole moment is

$$\frac{d\mathbf{m}}{dt} = \frac{1}{2}\int \hat{\mathbf{r}} \times \frac{\partial \mathbf{J}}{\partial t}\, dV = \frac{3}{2\mu_0}\int \frac{\partial \mathbf{B}}{\partial t}\, dV. \quad (1)$$

Substituting from the induction equation

$$\frac{d\mathbf{m}}{dt} = \frac{3}{2\mu_0}\int [\nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}]\, dV. \quad (2)$$

Taking the axial component and re-arranging, the axial dipole moment (ADM) change can be written as

$$\frac{dm_z}{dt} = \underbrace{-\frac{3}{2\mu_0}\int u_\theta \sin\theta B_r\, dS}_{\text{ADM change due to meridional advection}} + \frac{3\eta}{2\mu_0}\int \hat{\mathbf{z}} \cdot \nabla^2 \mathbf{B}\, dV. \quad (3)$$

Following Olson and Amit (2006), maps of $u_\theta \sin\theta B_r$ at the core surface show the advective contributions to ADM change.

**Example I: Simple gyre acting on field asymmetry**

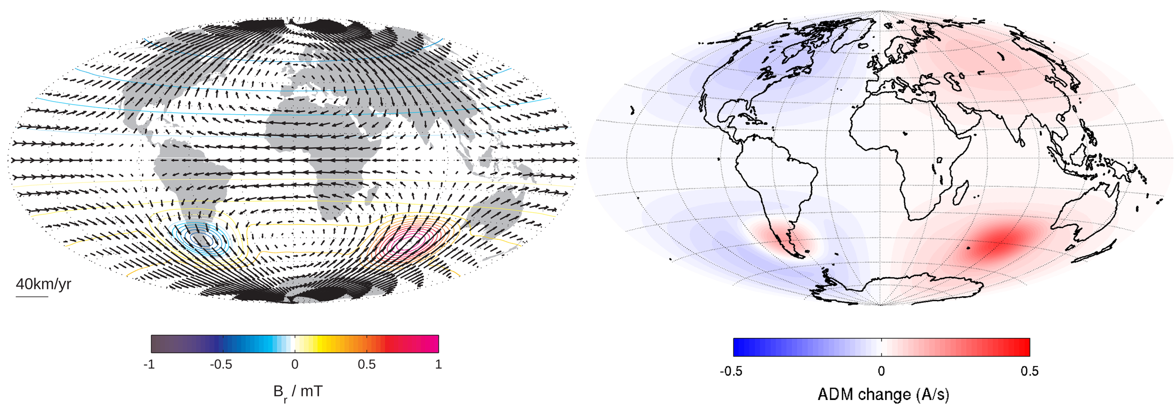


**Fig. 3 :** Single flow harmonic $T_2^1$ acting on axial dipole plus symmetry breaking anomalies (left) and related contributions to ADM change (right). Axial dipole decay rate = 13.26 nT/yr.

**Example II: Realistic gyre acting on observed field**

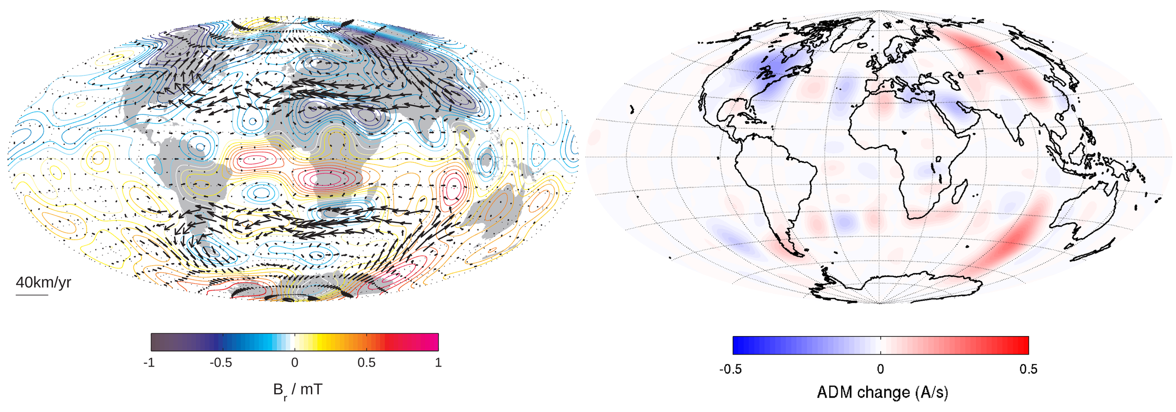


**Fig. 4:** Filtered version of QG flow from Fig.2 (gyre only) acting on observed core surface field (left) and related contributions to ADM change (right). Axial dipole decay rate = 8.25 nT/yr.

## Results from QG flow inversions

- Gillet et al., (2014): new ensemble of QG flow models
- Account for observation errors and modelling errors due to unresolved scales (with time correlations)
- Don't strongly penalize small scale flow

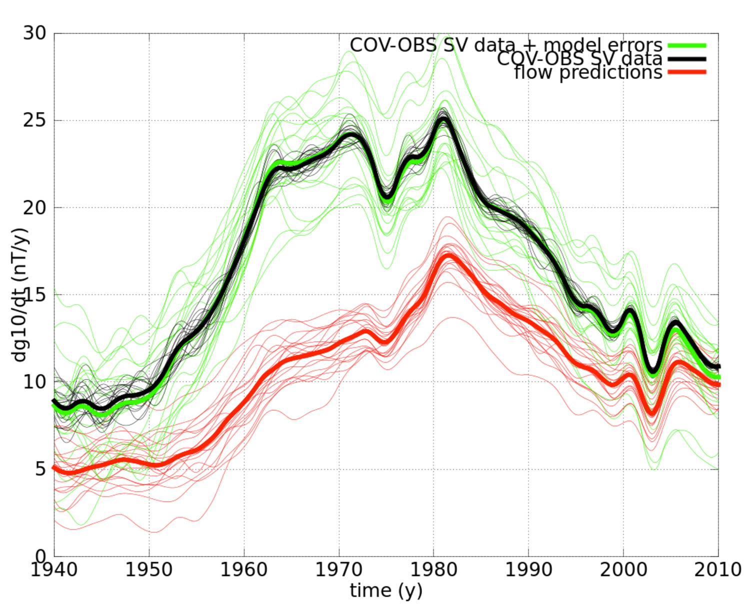


**Fig. 5:** Dipole decay predictions of QG flow ensemble derived by Gillet et al. (2014). The observed dipole decay, its errors and errors due to unresolved small scales are shown for reference.

- QG flows can indeed reproduce general dipole decay and its rapid fluctuations
- But systematically under-predict rate of dipole decay
- However, diffusion has been neglected. To properly investigate this we need to resort to 3D models

## References

Aubert, J. (2014) Earth's core internal dynamics 1840-2010 imaged by inverse geodynamo modelling, *Geophys. J. Int.*, 197, 1321-1334.

Aubert, J., Finlay, C. C., Fournier, A. (2013) Bottom-up control of geomagnetic secular variation by the Earth's inner core, *Nature*, 502, 219-223, 2013.

Gillet, N., Jault, D., Finlay C. C., and Olsen, N. (2013) Stochastic modeling of the Earth's magnetic field: Inversion for covariances over the observatory era. *Geochemistry, Geophysics, Geosystems*, 14, 766-786.

Gillet, N., Jault, D., Finlay C. C., (2014) Planetary gyre and time-dependent midlatitude eddies at the Earth's core surface. *in prep.*

Olson, P. and Amit, H. (2006) Changes in Earth's Dipole. *Naturwissenshaften*, 93, 519-542.

## 3D numerical dynamo model

Use numerical dynamo of Aubert et al., (2013):

- $E = \frac{\nu}{\Omega D^2} = 3\times10^{-5}$, $Pr_m = \frac{\nu}{\eta} = 2.5$, $Pr = \frac{\nu}{\kappa} = 1$, $Ra = \frac{g_0 f}{\rho \Omega^3 D^2} = 9.3\times10^{-5}$
- Enhanced buoyancy flux, eastern hemisphere of IC
- EM coupling at ICB, gravitational coupling btw IC and mantle
- Relatively high magnetic Reynolds number, $Rm = 942$
- Produces a planetary-scale gyre as in core flow inversions

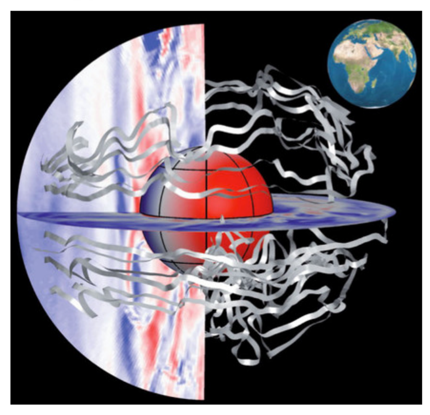

**Fig. 6:** Flow stream ribbon and azimuthal velocity field, along with excess buoyancy imposed at ICB, from Aubert et al. (2013).

## Results from 3D inversions and free runs

- Inverse geodynamo modelling method (Aubert, 2014): linear correlations between dynamo field and flows used to reconstruct 3D field and flow within the core
- Input COV-OBS and make series of epoch analyses
- Retrieval of 3D core state allows assessment of advective and diffusive contributions to field change
- Also used inferred states in1980 and 2010 as initial conditions for free 'assimilation' forward runs

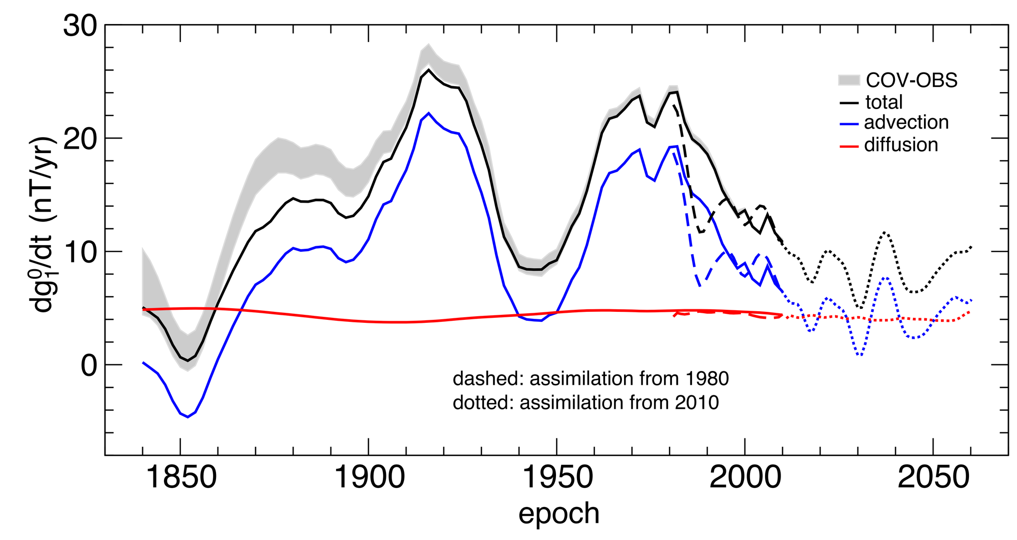


**Fig. 7:** Rate of change of AD: input (grey), retrieved by inverse modelling (black) - advective part (blue) and diffusive part (red).

- Succeed in reproducing the dipole decay
- Diffusion makes constant contribution $\sim$ 5nT/yr
- **Most of decay, and fluctuations, due to advection**
- Core surface flows again show a planetary QG gyre, driven by upwellings in eastern hemisphere

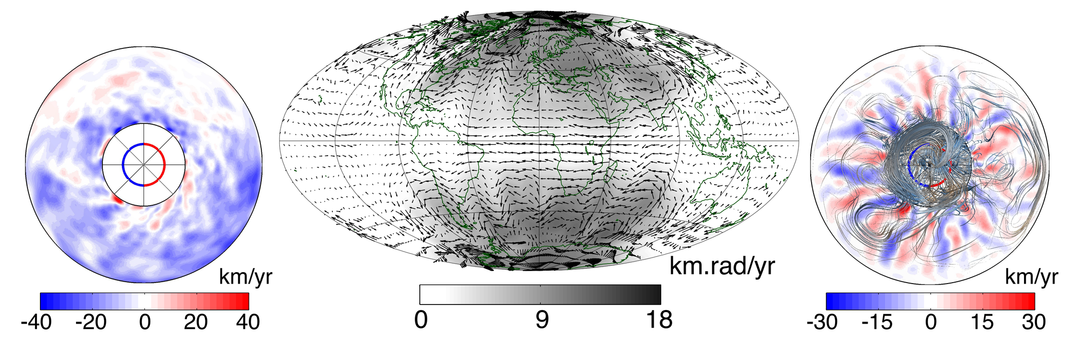


**Fig. 8:** Field and flow within core in 2015: azimuthal flow (left), core surface flow (center) and radial flow / field lines (right). From free run initialized in 2010 using state from inverse analysis.

## Dipole decay and gyre fluctuations

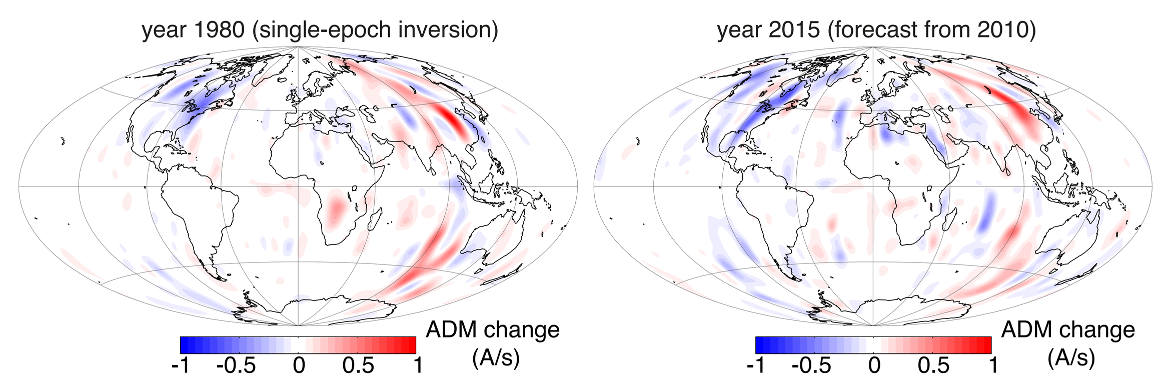


**Fig. 9:** Maps of advective contributions to ADM change in 1980 and 2015. Dipole decay was stronger in 1980 when gyre was transporting more normal flux equatorward west of Australia and less normal flux poleward west of South America.

## Concluding Remarks

- Equatorward transport of normal flux and polarward transport of reversed flux by a planetary gyre plays an important role in driving the present dipole decay
- Mechanism requires an asymmetric CMB field (e.g. reversed flux in the South Atlantic) hence diffusion and flux expulsion may still play a role
- Rapid fluctuations in the dipole decay rate can reflect fluctuations in meridional flux transport by the gyre
- Planetary-scale gyre would likely penetrate into a stratified layer, so it could still drive the background dipole decay in this possible scenario

DTU Space, Technical University of Denmark, Electrovej 327, Kngs. Lyngby, Denmark

cfinlay@space.dtu.dk