Characterizing and understanding core field dynamics: lessons from MAGSAT, Oersted, CHAMP, SAC-C and the decade.

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Outline of the Talk

- Considerable progress has been made in modelling the geomagnetic field thanks to the Oersted (1999), Champ (2000) and SAC-C (2000) missions.
- In this talk, I will try to briefly review the progress these high resolution models (together with similar MAGSAT (1980) based models) have been bringing in terms of our understanding of core field dynamics.
- The talk will be split in three parts:
  - I will first recall some of the earlier findings from the Oersted and MAGSAT missions,
  - I will next focus on the progress brought (and questions raised) by the availability of high resolution secular variation models.
  - I will finally turn to the questions high resolution secular acceleration models could help address.

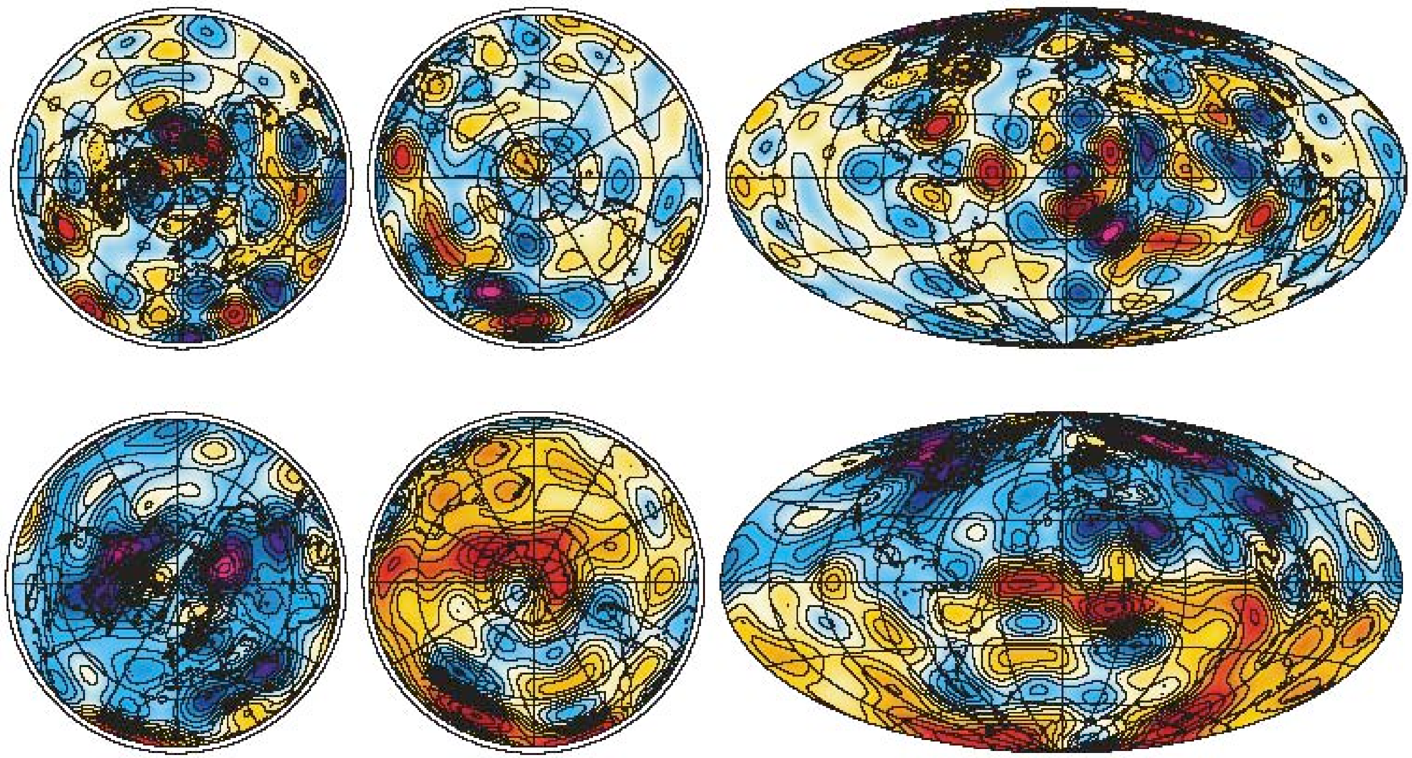
From Magsat to Oersted, 20 years in the life of Earth’s magnetic field

The field changes fast and in an asymmetric way at the CMB (within the vicinity of the « tangent cylinder » and in the « Atlantic hemisphere »)

North South Centered on O°

1980 to 2000
Field Changes
+/- 340μT

Field
in 1990
+/- 1,000μT



Hulot et al. (2002); Langlais et al., (2003)

Time scales for changes of the core field as a function of length scales:

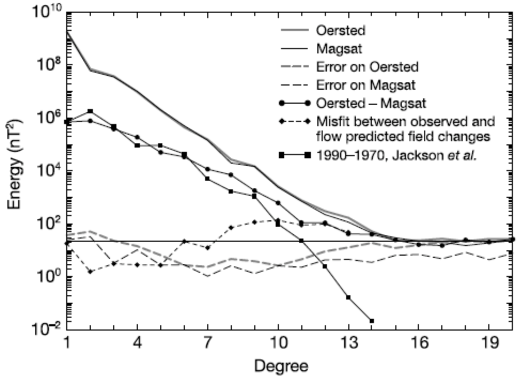
Use

$$\tau_c(n) = \left(\frac{W(n)}{W'(n)}\right)^{1/2}$$

$$W(n) = (n+1)\sum((g_n^m)^2 + (h_n^m)^2)$$

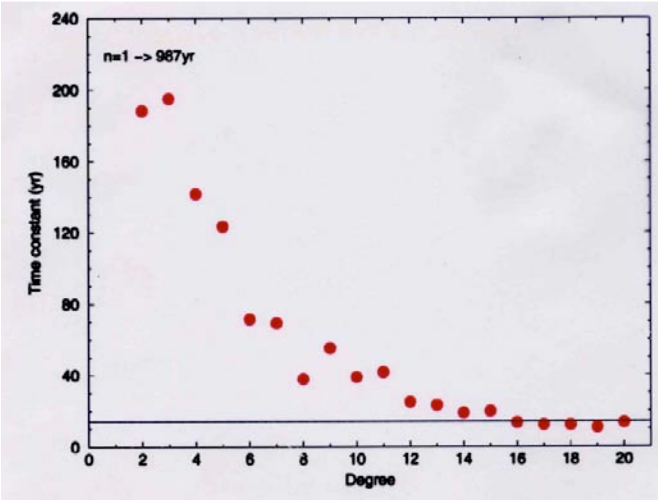
$$W'(n) = (n+1)\sum((\dot{g}_n^m)^2 + (\dot{h}_n^m)^2)$$

and

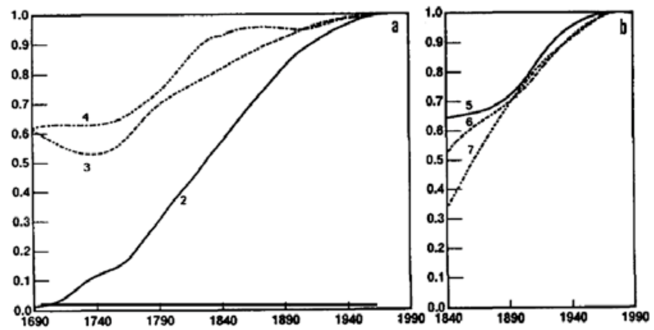


Hulot et al., 2002

to infer



confirming earlier estimates based on historical data:

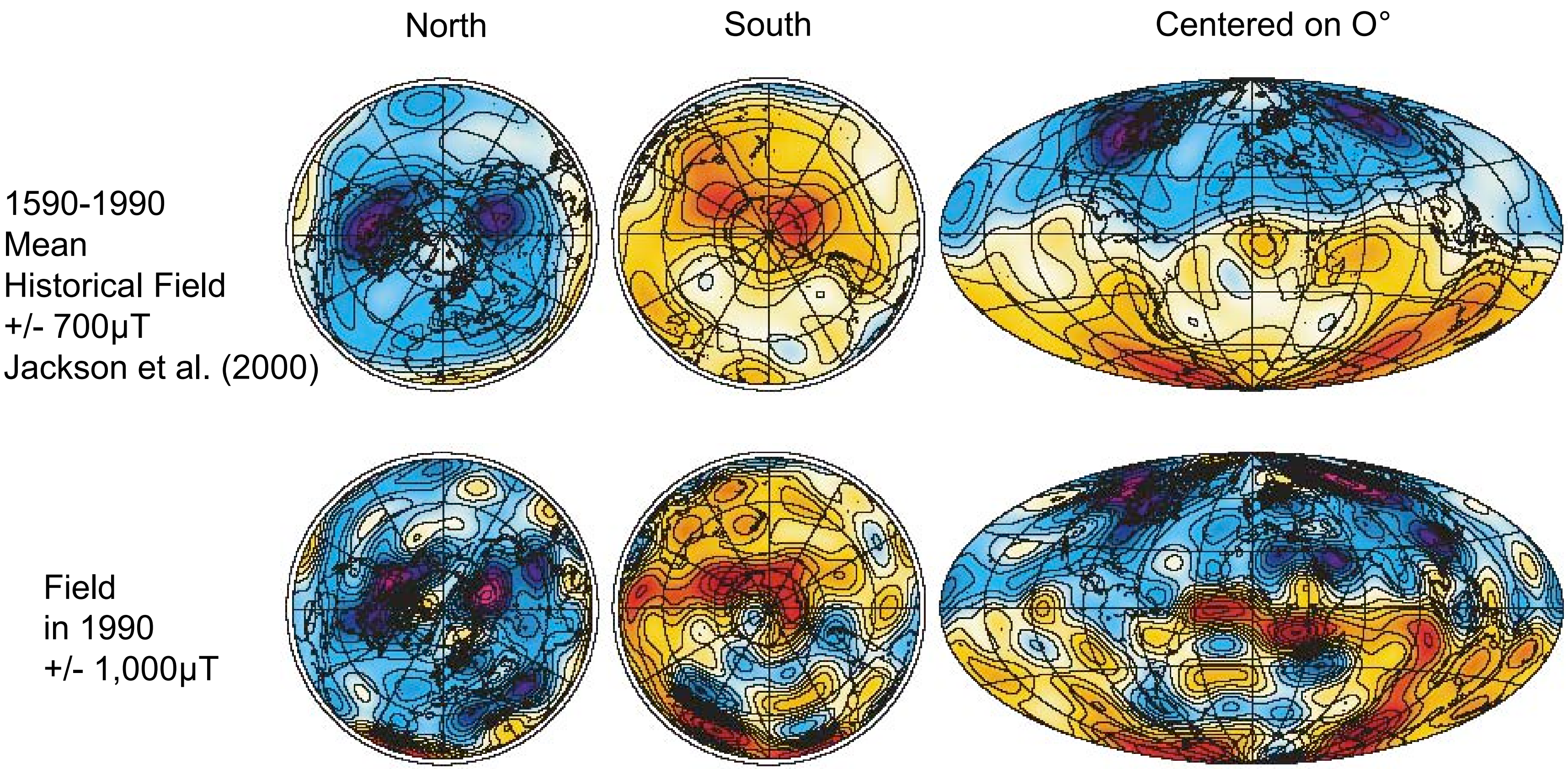


Hulot and Le Mouel, 1994

Fig. 8. The $K_n(t_0, \tau)$ empirical normalized correlation function. t_0 is 1980 and τ is the time lapse between 1980 and the date which is shown in ordinate, (a) for degrees 2 to 4; (b) for degrees 5 to 7.

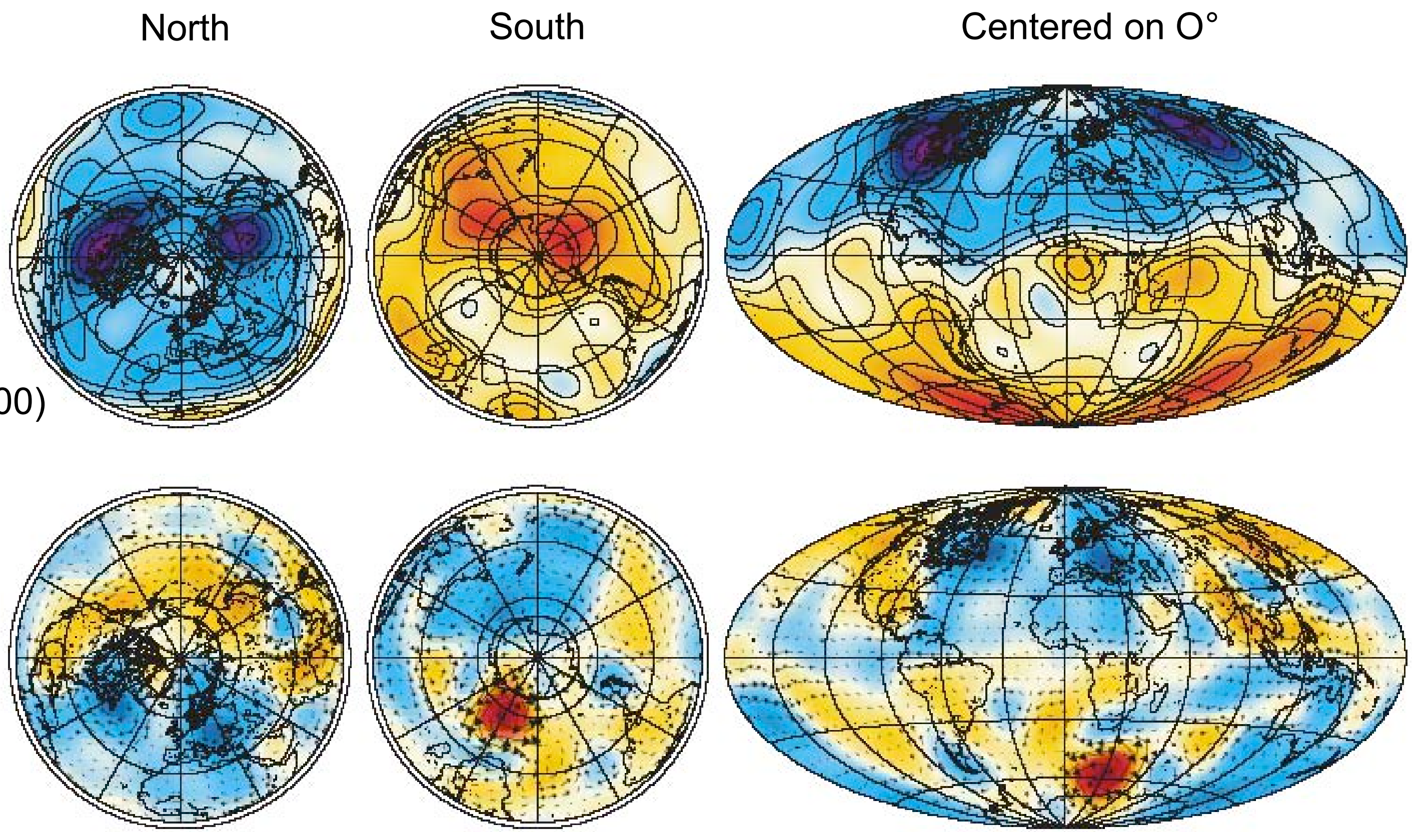
Small scales are renewed within a few decades

The South-Atlantic reversed patch is a few centuries old and growing in the « busy » hemisphere, whereas high-latitude lobes are stable in the « quieter » hemisphere



Hulot et al. (2002)

The S-Atlantic patch could be caused by strong retrograde vortices within the « busy » hemisphere

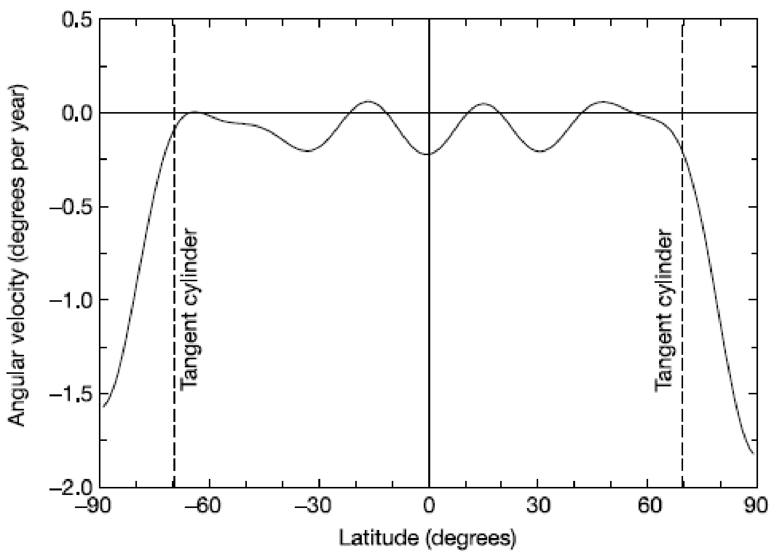


1590-1990
Mean
Historical Field
+/- 700µT
Jackson et al. (2000)

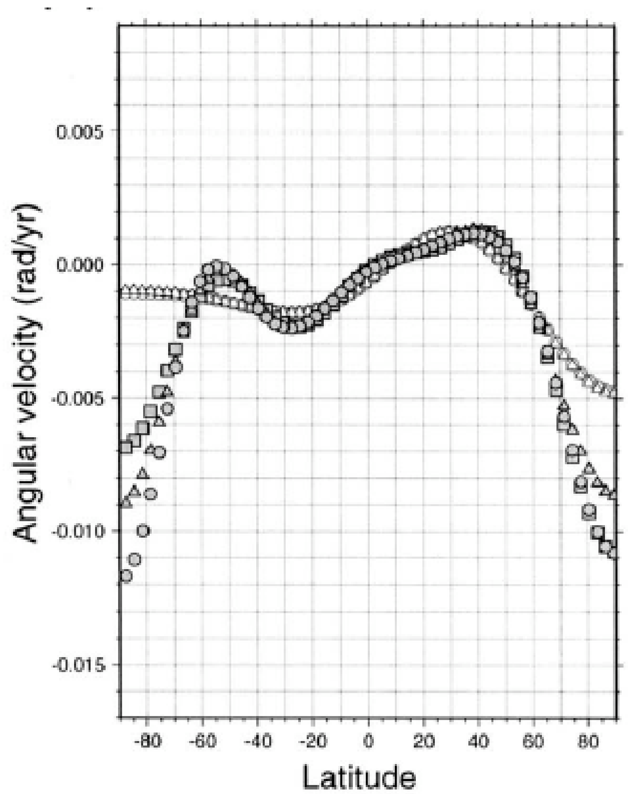
1990
non-axisymmetric
Flow
(up to 65 km/yr)

Hulot et al. (2002)

High-latitude secular variation are likely related to zonal flows within the « tangent cylinder », already « seen » in average flows from historical data



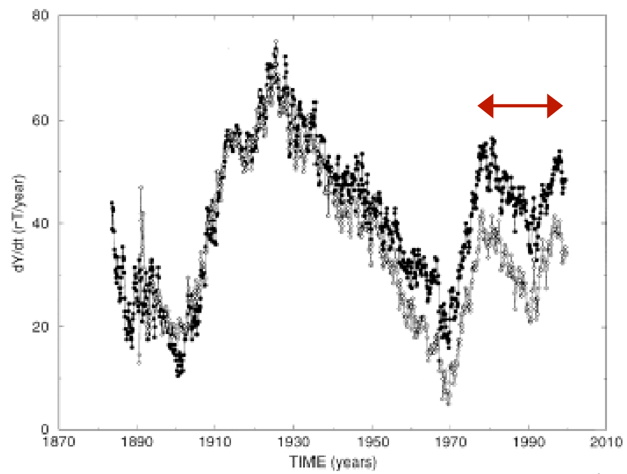
Zonal flows derived from Oersted-Magsat data
Hulot et al. (2002)



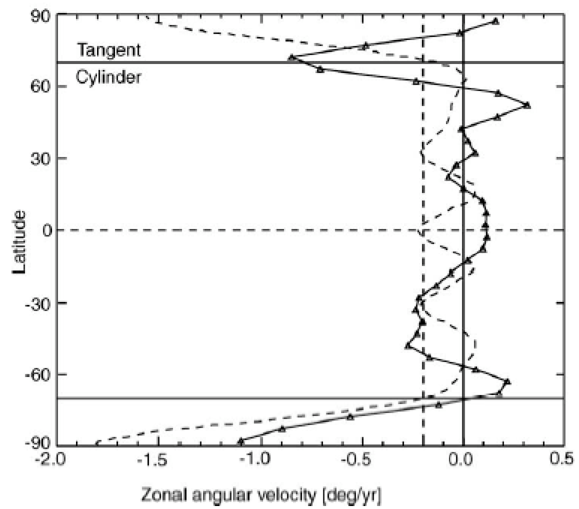
Average zonal flows over the 1840-1990 period derived from historical data (Bloxham and Jackson, 1992 model)
Pais and Hulot (2000). See also Olson and Aurnou (1999)

Some words of caution:

- Those earlier findings were based on 1980 to 2000 finite differences and we know that the secular variation has not been stable over that time period: a "jerk" occurred in 1990 !
- Core flows were computed assuming frozen-flux and tangential geostrophy, and changing assumptions affects the results (see e.g. Amit and Olson, 2004)
- Core flows are also affected by non-uniqueness issues.
- Medium scale core flows are much more energetic than previously thought. How do we deal with contributions from "unknown" small scales ?

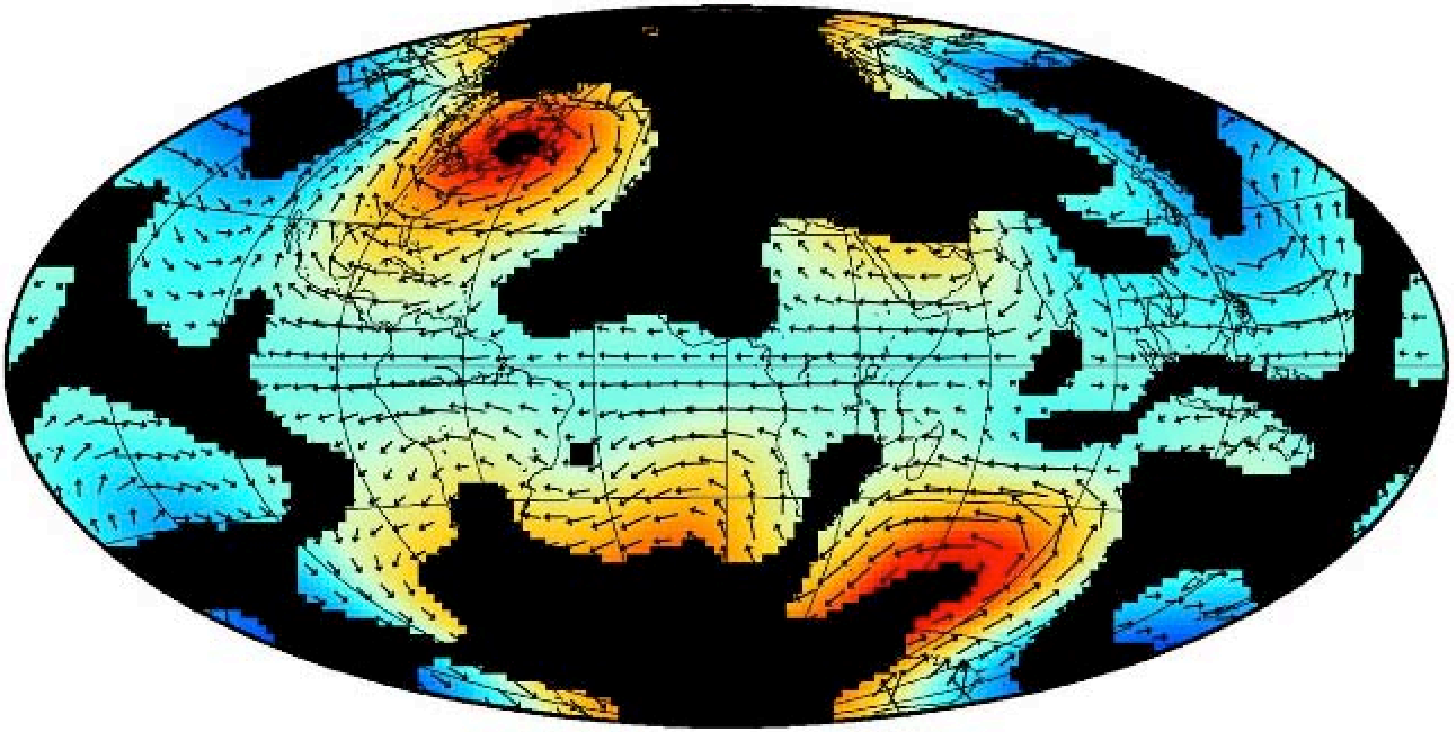


Mandea et al. (2000)



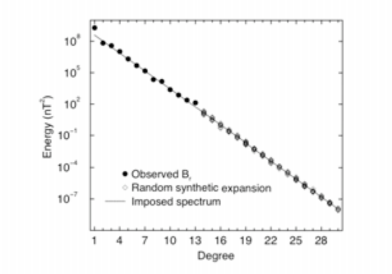
Amit and Olson (2004)

Dealing with non-uniqueness:
Regions where non-uniqueness “hides” the core surface flow
(within the TG and FF approximations)

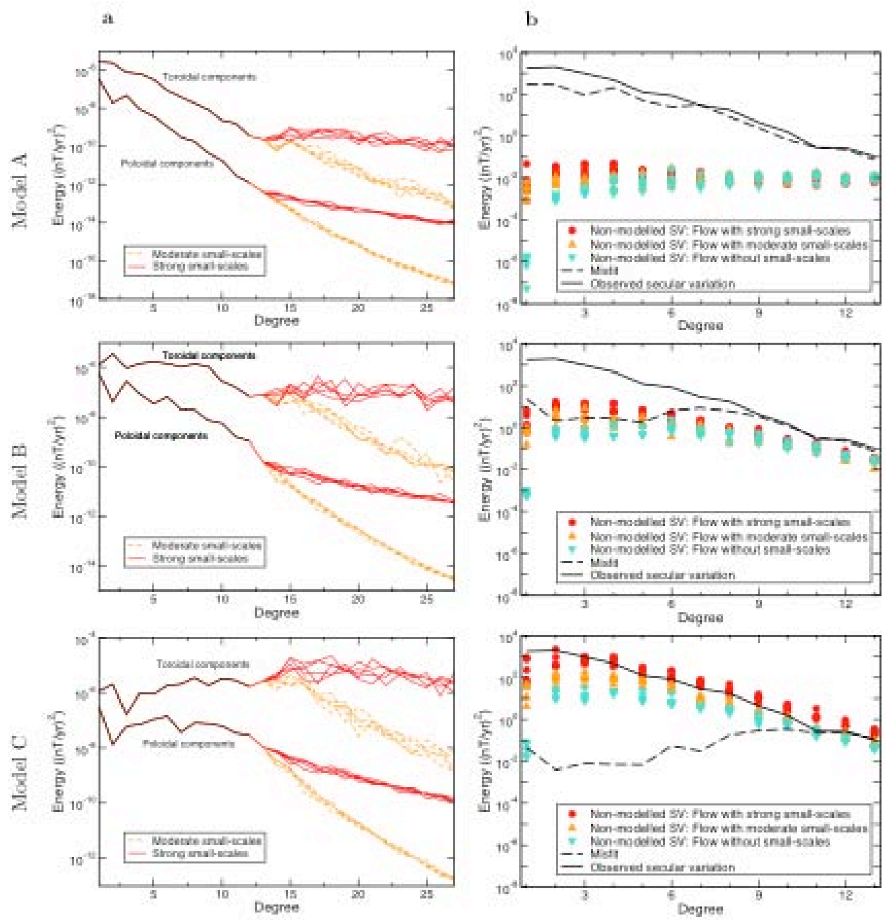


Eymin and Hulot (2005)

Dealing with energetic flows:
Large scale and medium scale flows should not attempt to explain all of the observable small scale secular variation !



Continuation of the MF at small scales



Continuation of the core flow at small scales

Non-modelled SV produced by unknown scales compared to the observed and residual SV

~~**Too much residual SV**~~

Admissible flow:
The residual SV matches
The non-modelled SV

~~**Too much non-modelled SV**~~

Eymin and Hulot (2005)

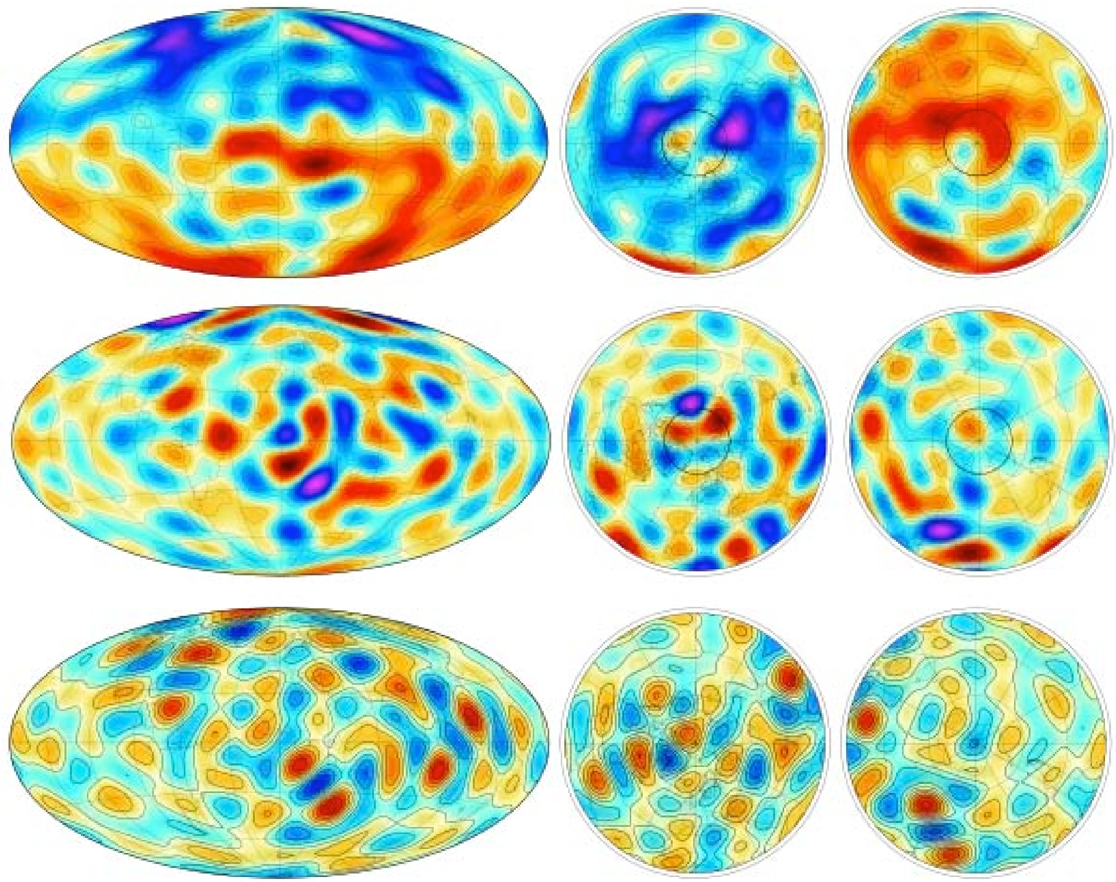
1980 to 2000 average secular variation that is not (and should not be) explained by the admissible flow

Centered on O° | North | South

Core Surface Field 1990

Average Secular Variation 1980 -> 2000

Residual Secular variation 1980 -> 2000



Eymin and Hulot (2005)

But now we can hope to do better and learn more !

- The launches of Oersted (1999), Champ (2000) and SAC-C (2000) missions occurred just after the last known jerk (Mandea et al., 2000).
- 6 years time is enough to provide us with a remarkable model of the secular variation throughout a time period when no jerk seems to have occurred.
- This means two things:
  - A much better estimate of the “instantaneous” secular variation can be computed;
  - Secular acceleration typical of intermediate periods between two jerks can be recovered with unprecedented details.

Time scales for changes of the core field as inferred from the Chaos model (Olsen et al., 2006)

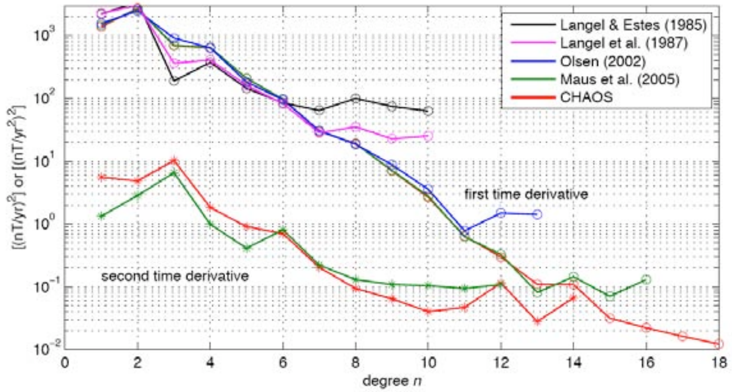
Use

$$\tau_c(n) = \left(\frac{W(n)}{W'(n)}\right)^{1/2}$$

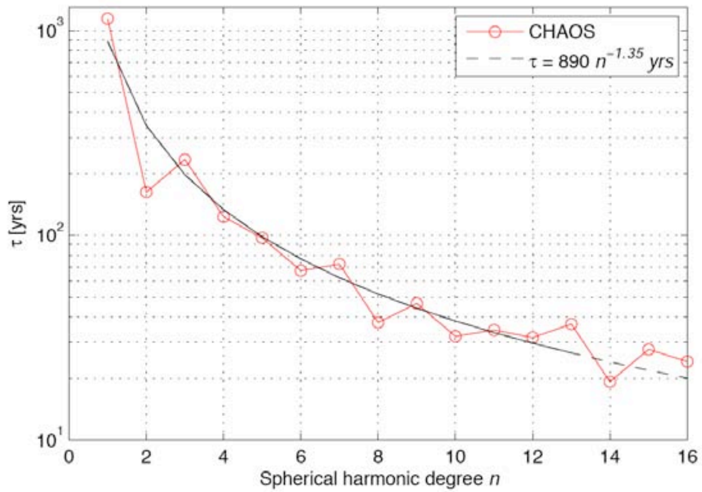
$$W(n) = (n+1)\sum((g_n^m)^2 + (h_n^m)^2)$$

$$W'(n) = (n+1)\sum((\dot{g}_n^m)^2 + (\dot{h}_n^m)^2)$$

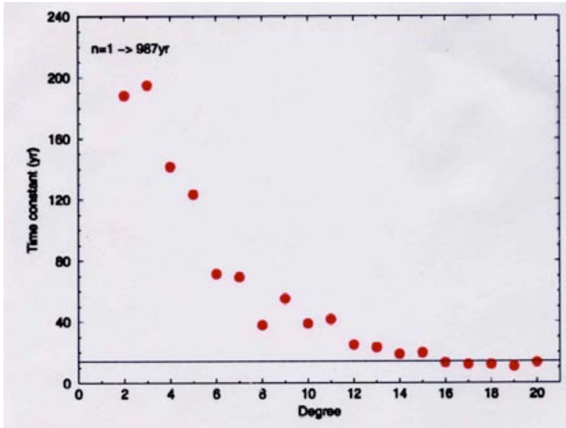
and



to infer

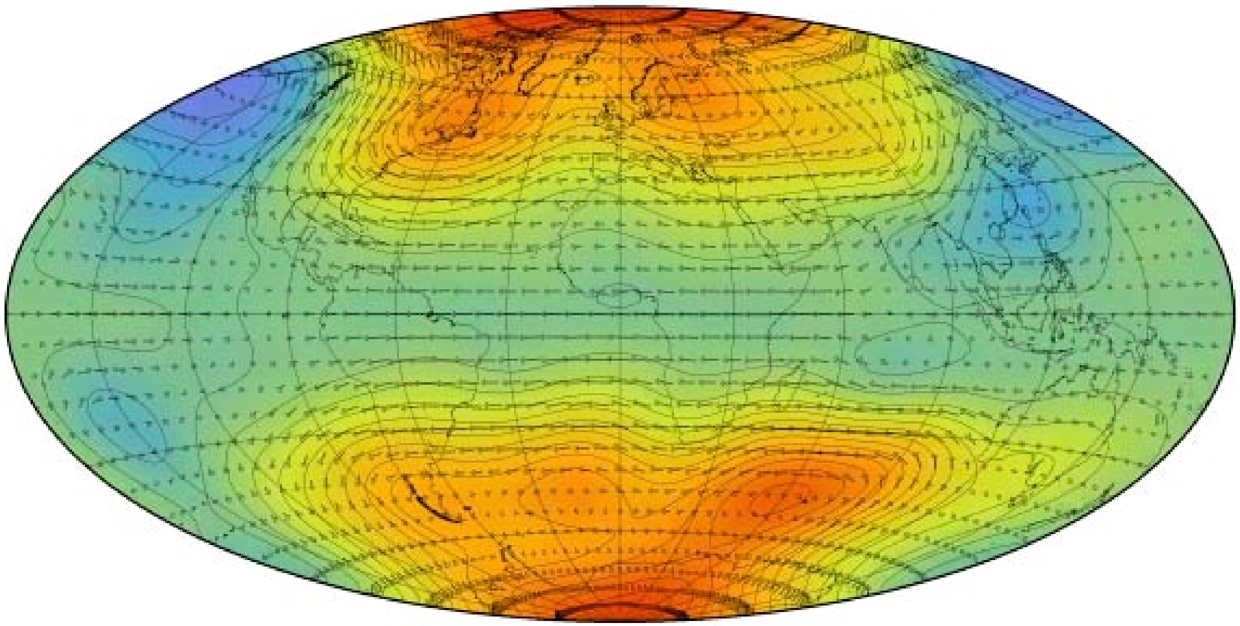


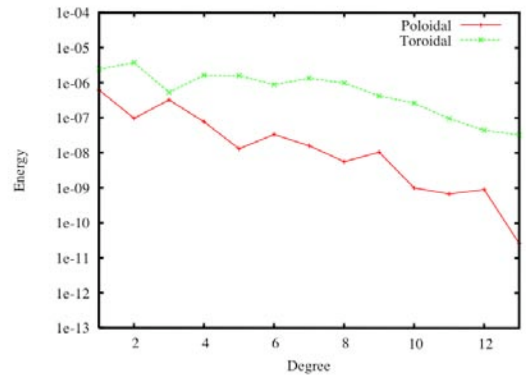
confirming earlier estimates based on Magsat and Oersted:

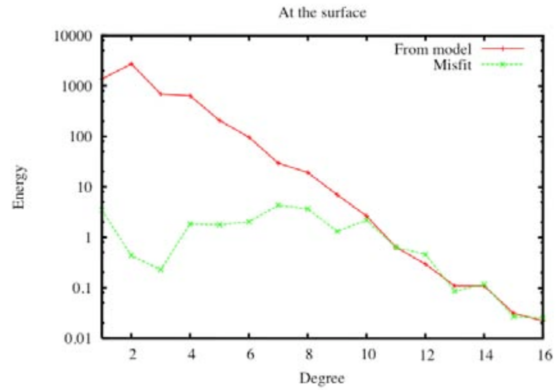


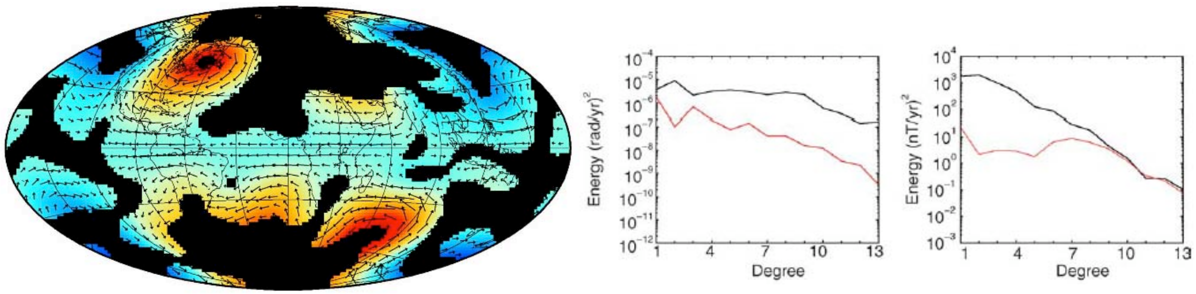
Small scales are indeed renewed within a few decades !

2002.5 admissible core surface flow as inferred from the CHAOS model (within the TG and FF approximations)



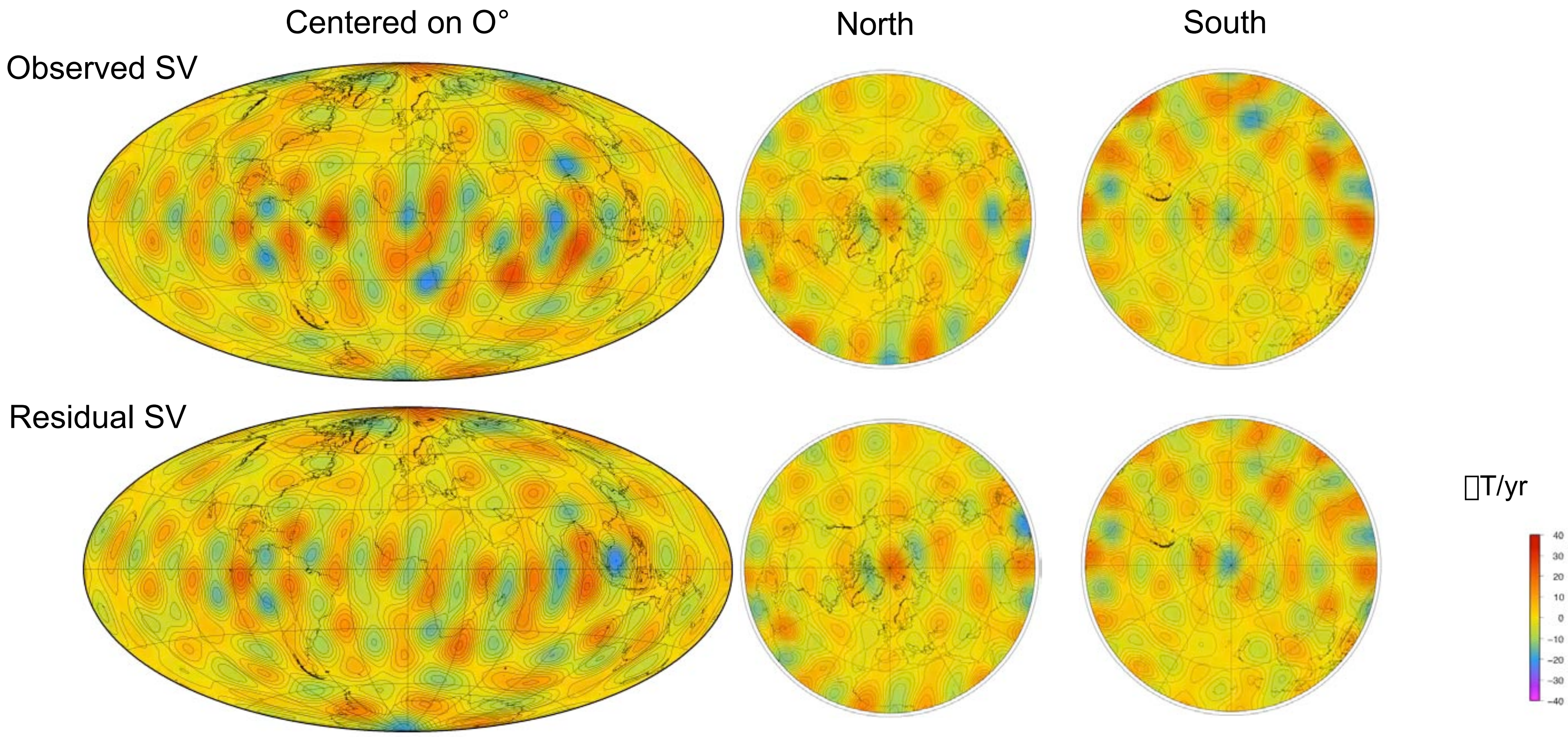






Eymin and Hulot (2005), for comparison

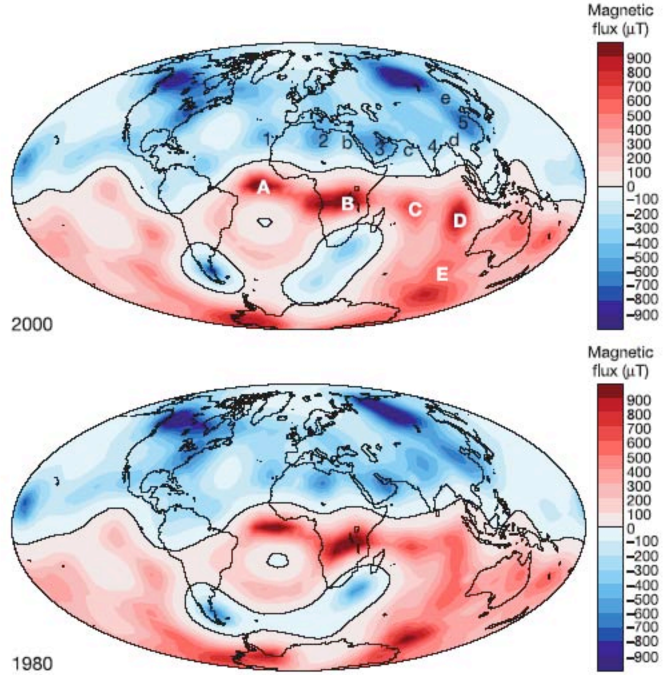
2002.5 secular variation (up to degree 15 at the core surface) that is not (and should not be) explained by the admissible flow



The small scale residual SV is mainly localized at the equator and within the tangent cylinder !

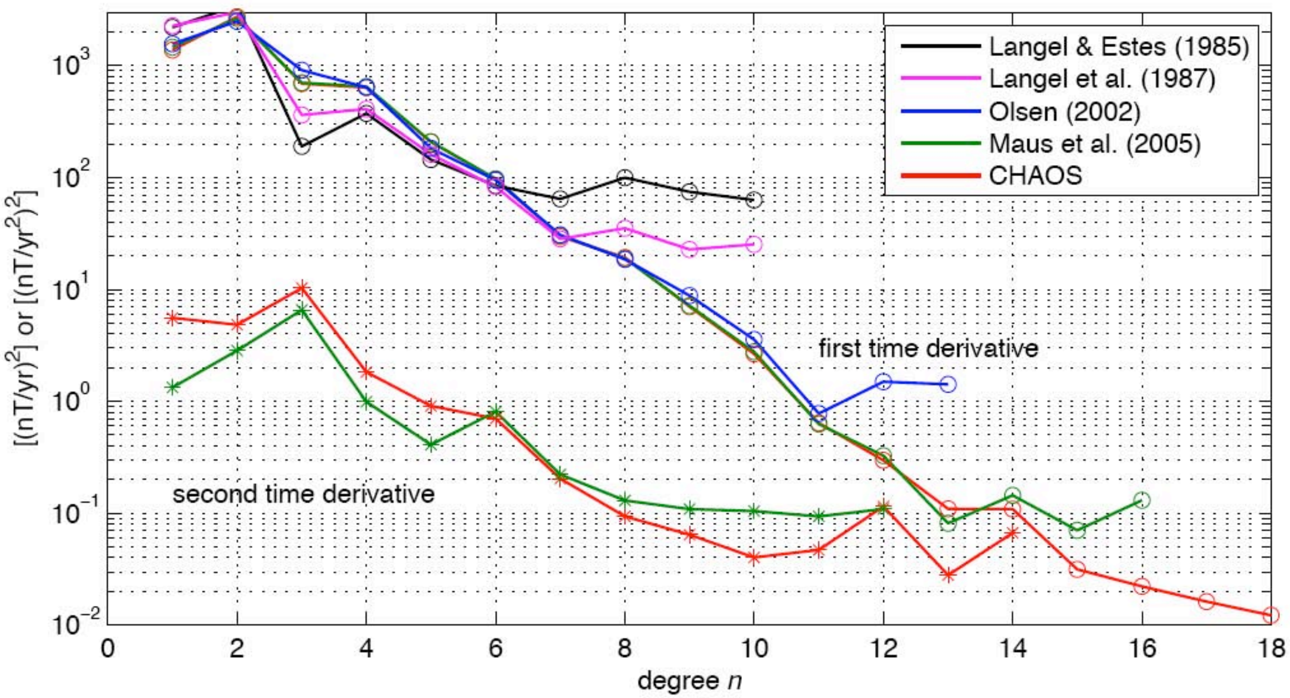
This exciting observation…

- … is in the line of the earlier suggestion that there could be some equatorially trapped waves at the core surface (Jackson, 2003, see also Finlay and Jackson, 2003)



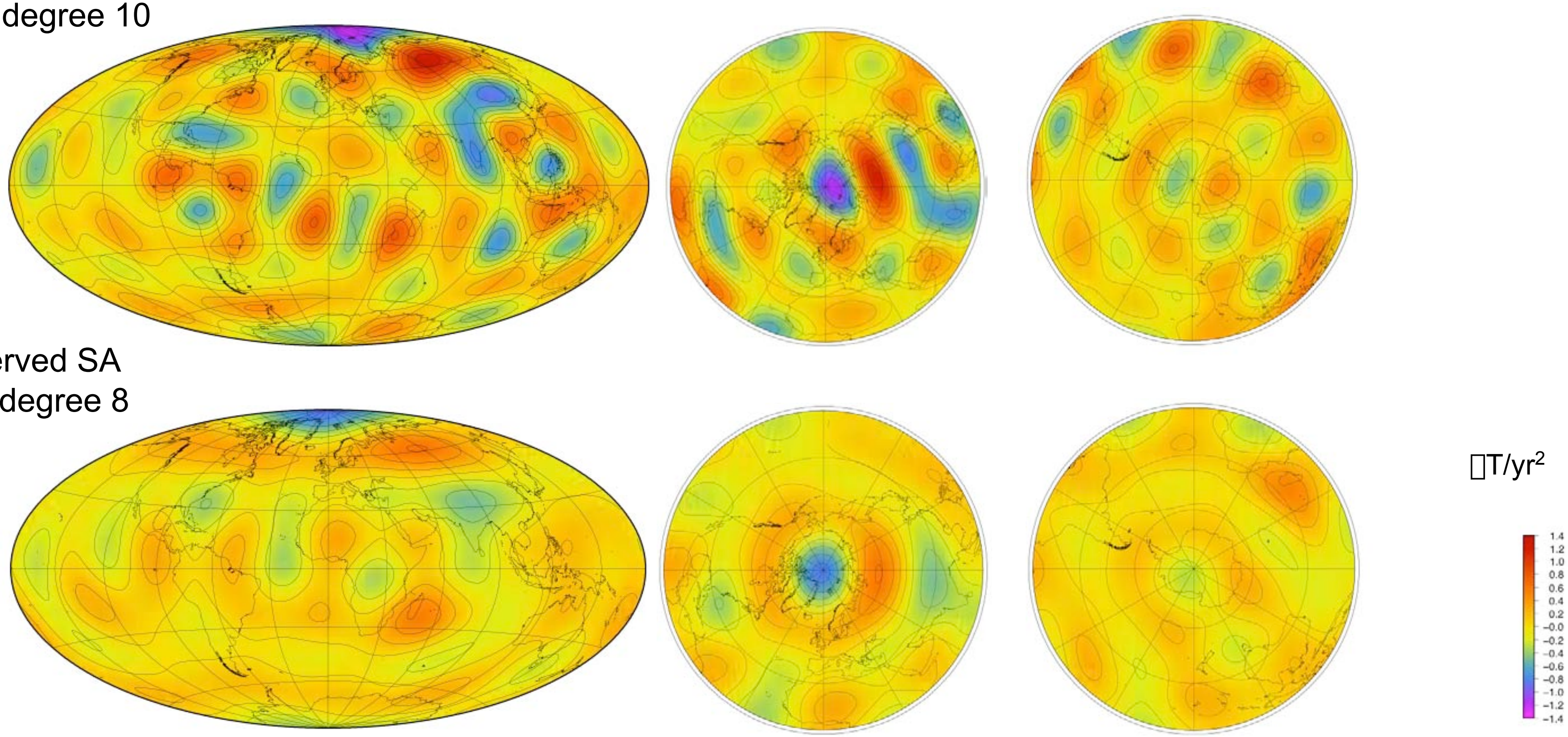
- … shows that large to medium scale flows can explain most of the mid-latitude (and large to medium scale) secular variation,
- … and strongly suggests that additional understanding of core field dynamics (within the tangent cylinder, and at the equator) could indeed be gained by monitoring the evolution of the small scale secular variation, despite the fact we do not have access to the core field itself.

What about Secular Acceleration ?
(CHAOS, Olsen et al. (2006))

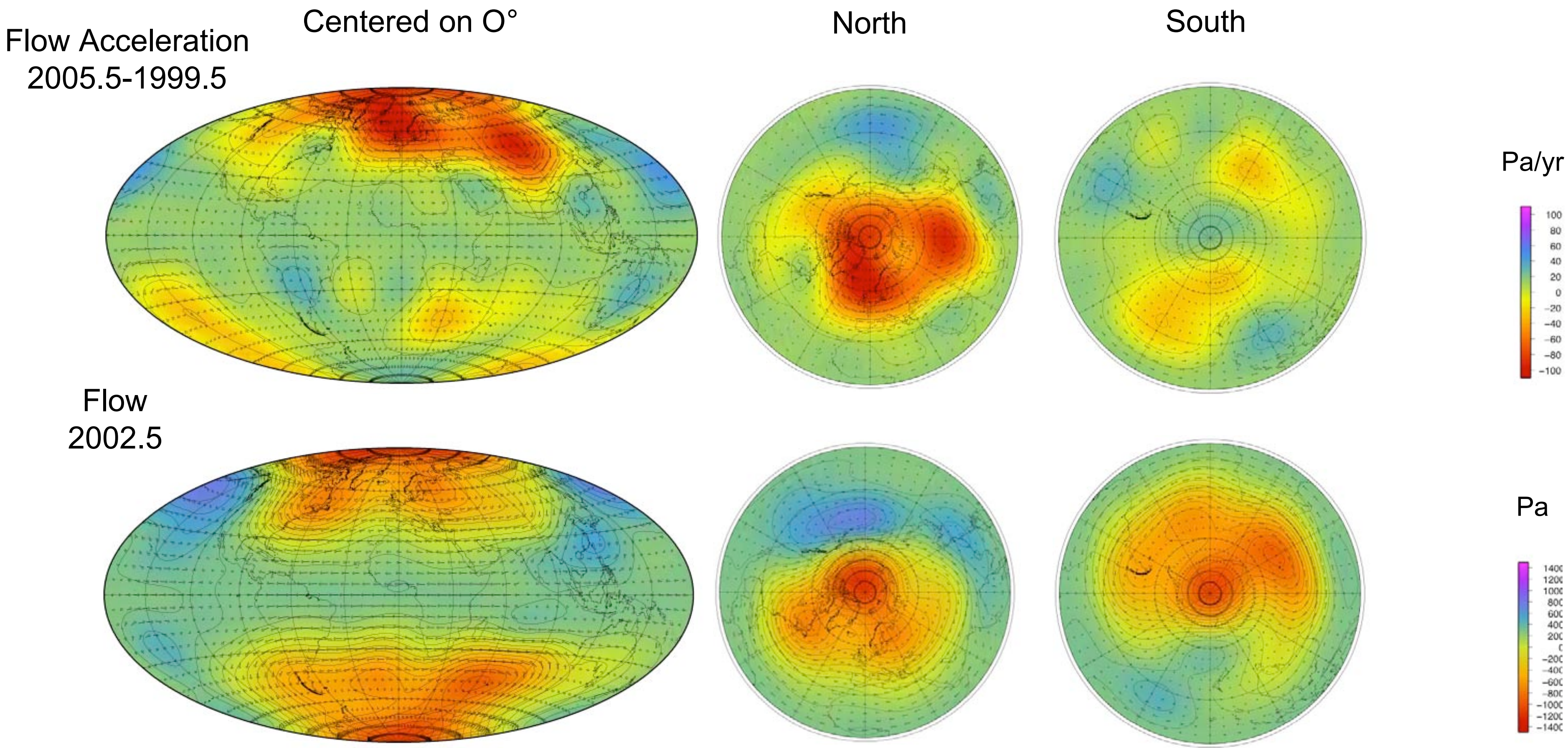


Secular Acceleration seems to be robust up to degree 8, maybe 10

Secular Acceleration (CHAOS, Olsen et al. (2006)) also reflects the asymmetry of core dynamics up to degree 10



To account for this acceleration, the flow seems to need to be accelerated (2005.5-1999.5 flows)



This is not so much a surprise because we need to account for length of day variation. Note however that the flow acceleration does not seem to be purely zonal…

But is this flow acceleration really needed to account for Secular Acceleration ?

- If the Frozen-Flux assumption holds, the radial component of the field at the core surface must satisfy:

$$\frac{\partial B_r}{\partial t} = -\vec{\nabla}_H .(\vec{u} B_r)$$

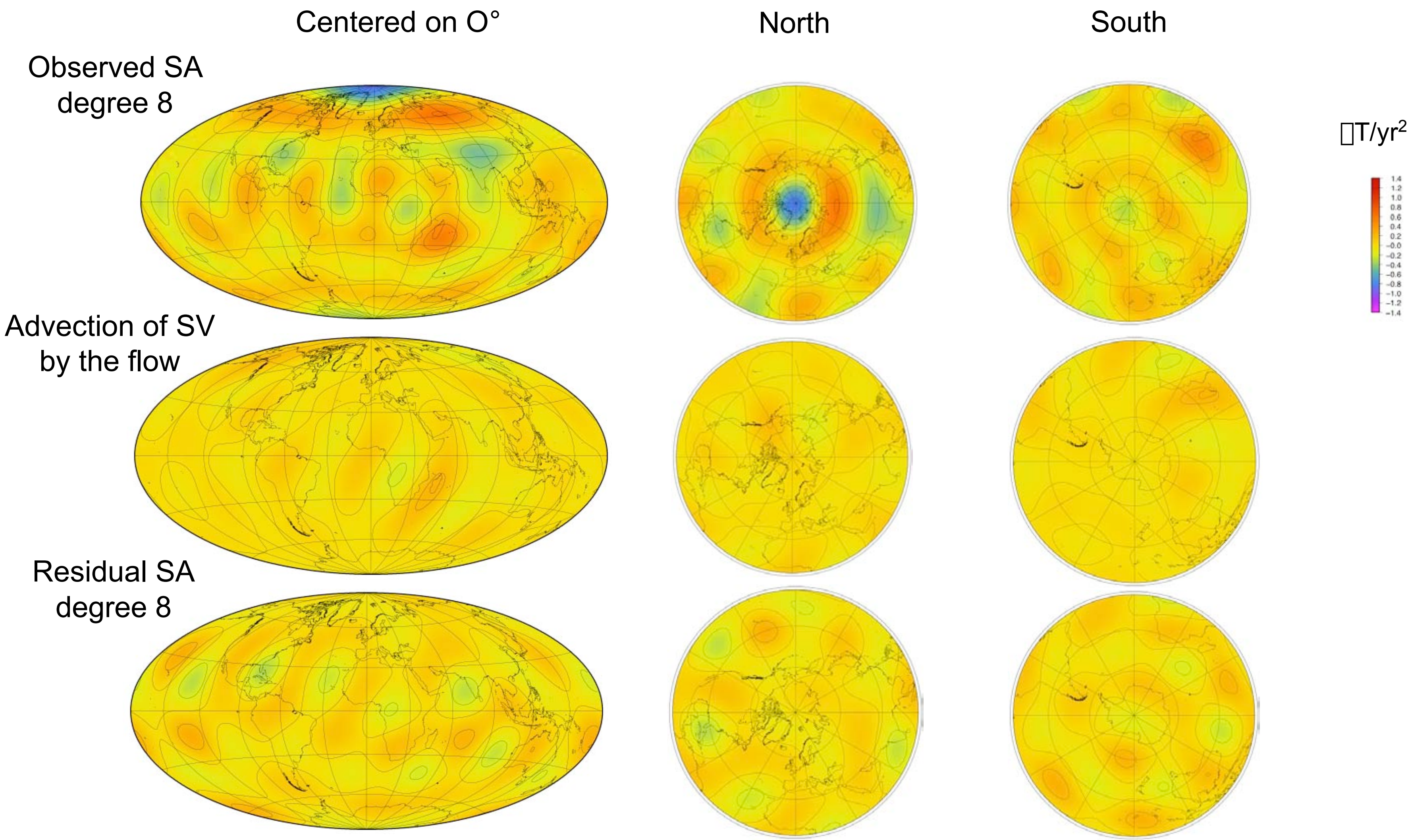
- Taking the time derivative of this then means that the radial component of the Secular Acceleration at the core surface must also satisfy:

$$\frac{\partial^2 B_r}{\partial t^2} = -\vec{\nabla}_H .(\vec{u} \frac{\partial B_r}{\partial t}) - \vec{\nabla}_H .(\frac{\partial \vec{u}}{\partial t} B_r)$$

- Thus, assuming that the Frozen-Flux assumption holds, would mean that secular acceleration is the result of two contributions:
  - advection of the secular variation by the flow,
  - advection of the field by flow acceleration.

- Which is the dominant contributor ?

The flow acceleration really seems to be needed to account for the Secular Acceleration



Note however that it only properly accounts for the degree 8 SA.

Those preliminary analysis of the Secular Acceleration thus suggest that :

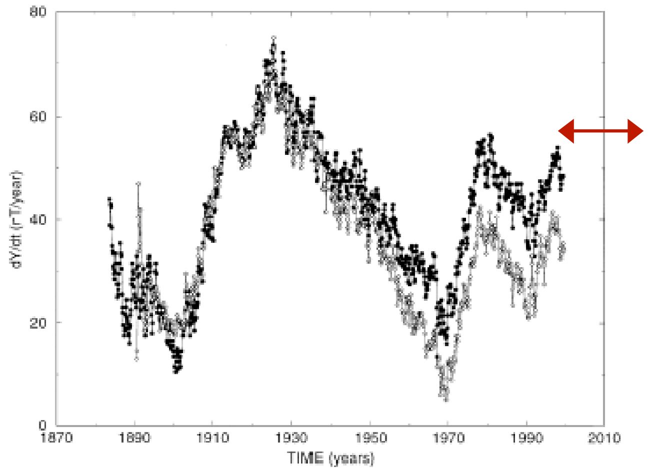
- With current missions, six years of continuous monitoring of the magnetic from space is enough to recover a meaningful description of the secular acceleration up to degree 8, perhaps 10;
- This secular acceleration seems to be mainly due to an acceleration of the large to medium scales of the flow;
- This acceleration does not seem to be restricted to the zonal (and angular momentum carrying) components of the flow.

Note however that :

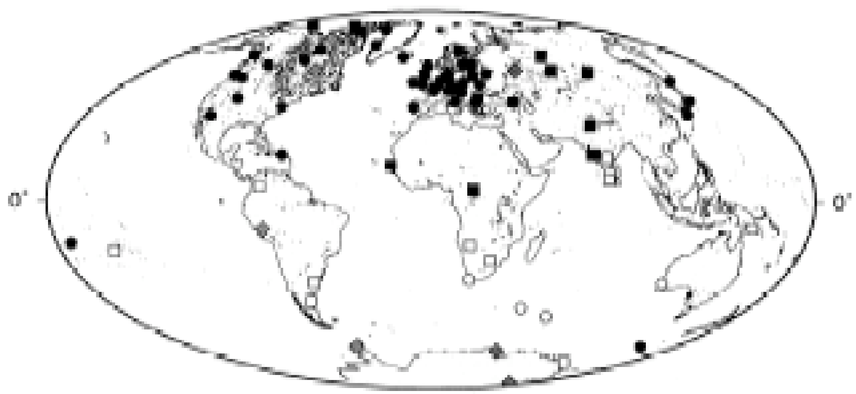
- Non-uniqueness issues need to be better assessed for core flow acceleration;
- Diffusion has been neglected;
- Secular acceleration above degree 8 remains unaccounted for.

This is interesting and could lead to a better understanding of "Jerks"

- Large to medium scale Secular Acceleration is indeed driving the short term (decade time scales) evolution of the largest scales of the field : it is essentially constant between "jerks".
- "Jerks" display a subtle behaviour: those are not quite a change in acceleration, and significant delays are observed between their Northern (early) and Southern (late) occurrence (Alexandrescu et al., 1995, 1996). But it has been recently shown that those peculiarities could be related to distortions due to mantle conductivity (Mandea et al., 1999; Nagao et al., 2003)
- "Jerks" could thus indeed reflect sharp changes in core flow acceleration but involve a subtler process than just the torsionnal oscillation process recently promoted by Bloxham et al. (2002).



Mandea et al. (2000)



Alexandrescu et al. (1996)

Some conclusions

- The core field is changing fast and in an asymmetric manner.
- Thanks to the continuous observation of the magnetic field from space since 1999 (i.e. since the last known geomagnetic « jerk »), we can now also see how the field is currently « accelerating » (which it will likely go on doing in the same way until the next « jerk » occurs).
- Core surface flows accounting for the large to medium-scale (degree 10) field changes can be computed.
- Small-scale changes in the field (above degree 10) cannot straightforwardly be interpreted in terms of core flows. They actually suggest the presence of equatorially trapped waves.
- Field « acceleration » seems to require strong non-zonal flow accelerations and can be used to further investigate the nature and origin of “jerks”.
- Obviously, there is still a lot we can learn from additional even higher quality observations of the magnetic field from space.