The magnetic flux budget of the polar regions

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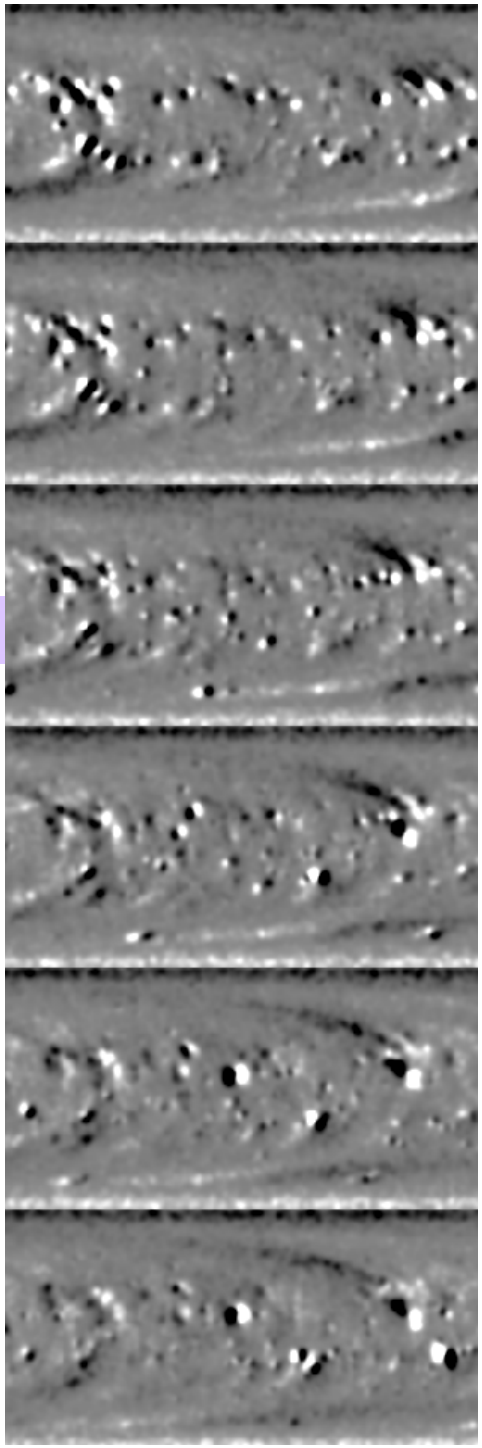


Sources of polar-cap fields

Local sources (mixed-polarity field):

- Proximate: High-latitude ephemeral regions (here: all small spotless bipolar regions).
- Ultimate: Local dynamo source or global dynamo decay?

Distant sources (large-scale field):

- Proximate: All bipolar regions on the solar surface, dominated by largest regions near the equator.
- Ultimate: Global dynamo

Sinks of polar-cap fields

Local sources (mixed-polarity field):

- Subduction
- (Near-)surface fragmentation and dissipation
- Expulsion

Distant sources (large-scale field):

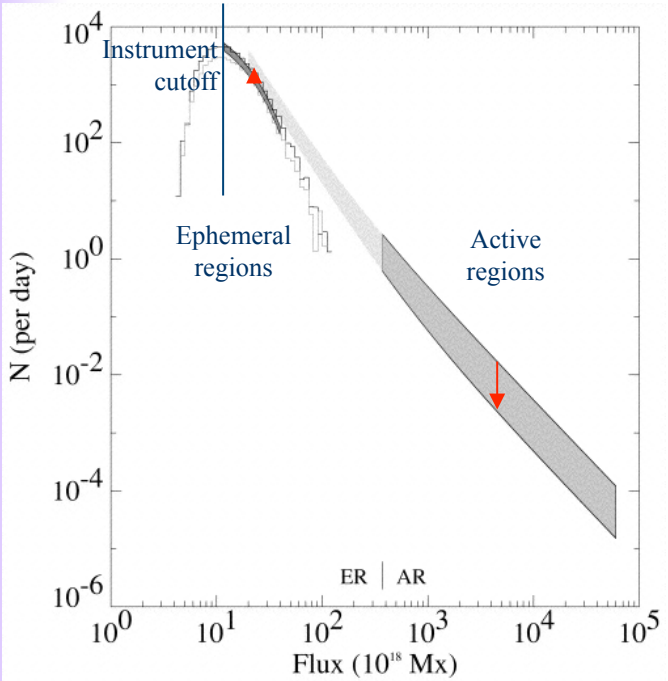
- Subduction
- Interaction with the small-scale field

What do horizontal fields tell us about all this?

"Local" sources: where/how do ephemeral regions form?

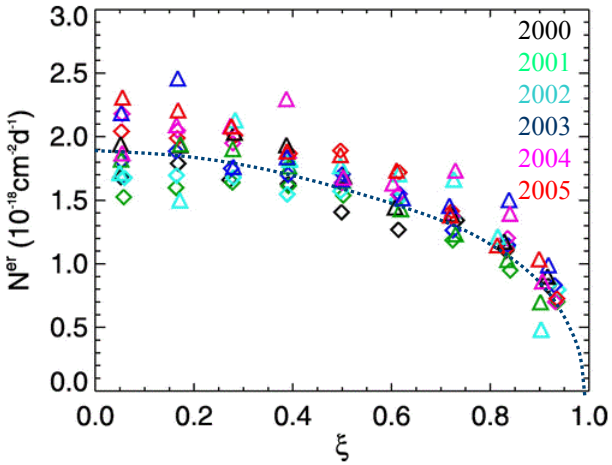
- Ephemeral regions
  - form a *continuous extension* of the AR frequency-flux spectrum, but *vary much less* (and perhaps in anti-phase) with ARs.
  - display a *butterfly pattern* that broadens with decreasing flux.
  - have an *increasingly random orientation* relative to the E-W direction with decreasing size.
  - are *less frequent in environments with larger flux imbalance* (fewer in "unipolar" regions - and thus indirectly fewer under coronal holes). Effect not yet measured for polar regions.

N.B. Stellar observations show that the least active stars have at most internetwork-level emissions.



Composite distribution function of bipoles emerging on the Sun per day, per flux interval of 10^{18} Mx. The distribution for active regions (defined as regions larger than 2.5 deg^2) taken from the literature (K. Harvey, 1994) varies by about a factor of 8 through a typical cycle; the extremes of that variation bound the dark shaded area on the right. The much smaller variation for the smallest ephemeral regions—shown by the darkest shading—is likely weakly in antiphase with the sunspot cycle; full histograms are shown for 1997 October (black) and 2000 August (gray). The turnover below 10^{18} Mx likely reflects the detection threshold of MDI. The lightly shaded area between the smallest ephemeral regions and the active regions is an approximation that still awaits confirmation. Figure from Hagenaar et al. 2003

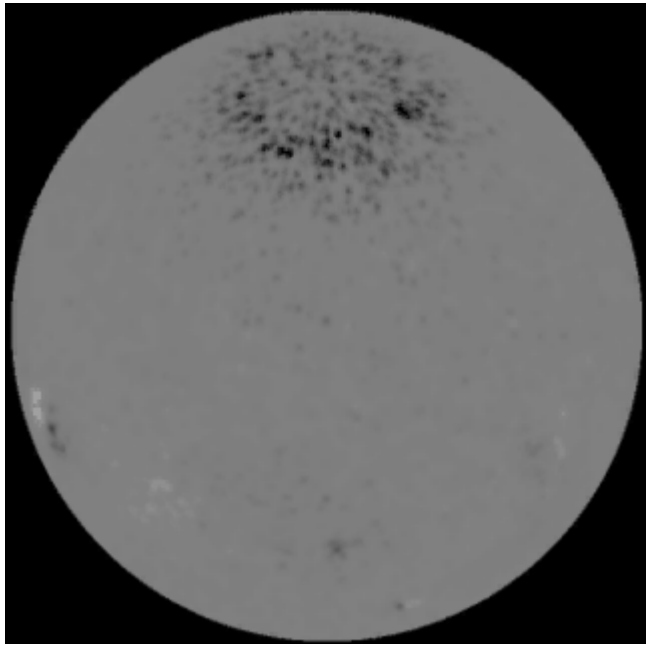
Top: Emergence frequency N_{er} of ephemeral regions, per unit surface, per day, as a function of the flux imbalance ξ in a region. *Bottom*: Total absolute flux $\sum \Phi$ emerging in those regions. Diamonds represent quiet Sun outside coronal holes and triangles represent quiet Sun inside coronal holes. The squares and triangles do not show a difference. Colors represent different data sets. *Black*: 2000; *green*: 2001; *light blue*: 2002; *dark blue*: 2003; *pink*: 2004; *red*: 2005.



From Hagenaar et al. (2008; ApJ 678, 541)

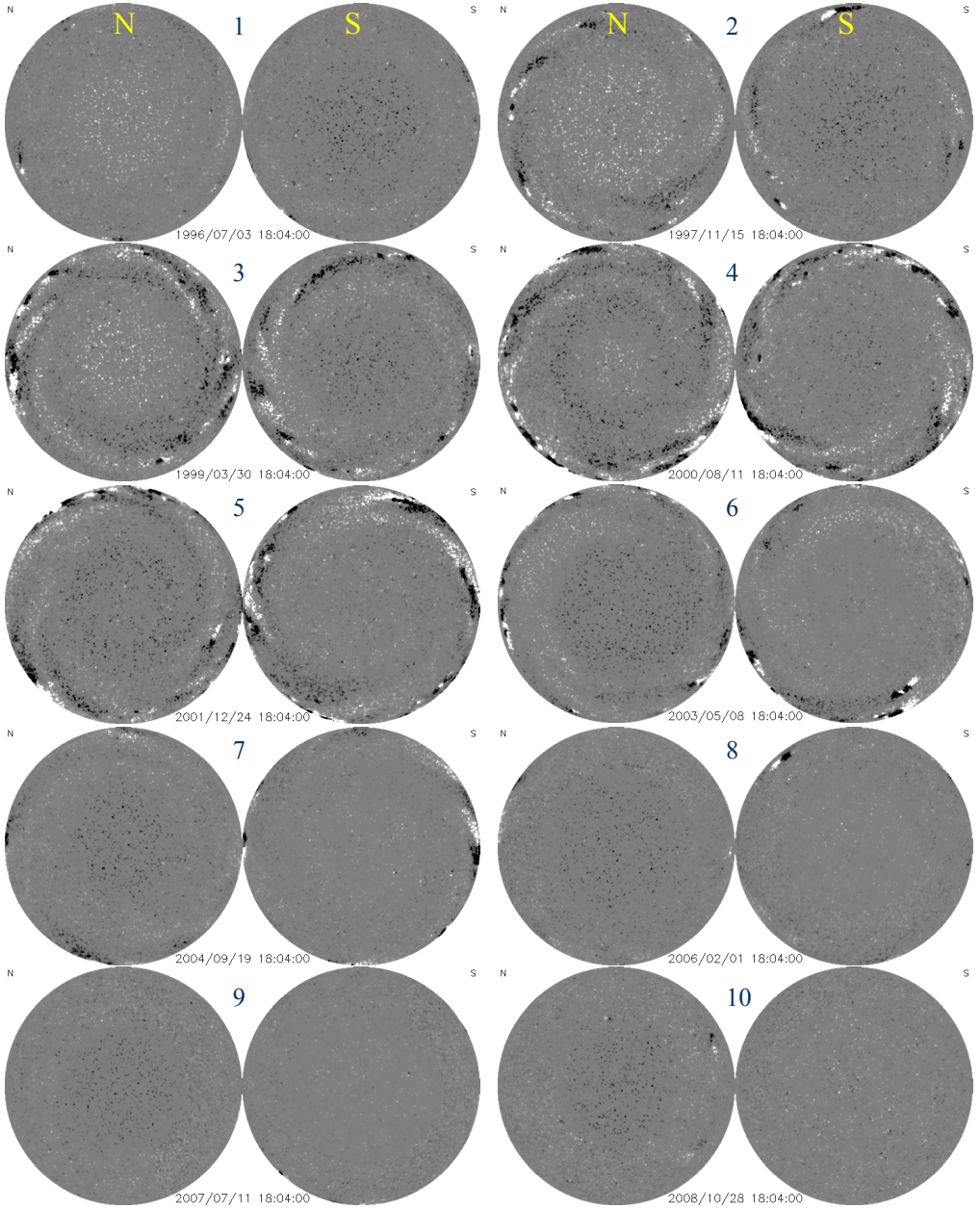
Simulations of activity: surface-flux transport

Simulated “Sun” from 40°N



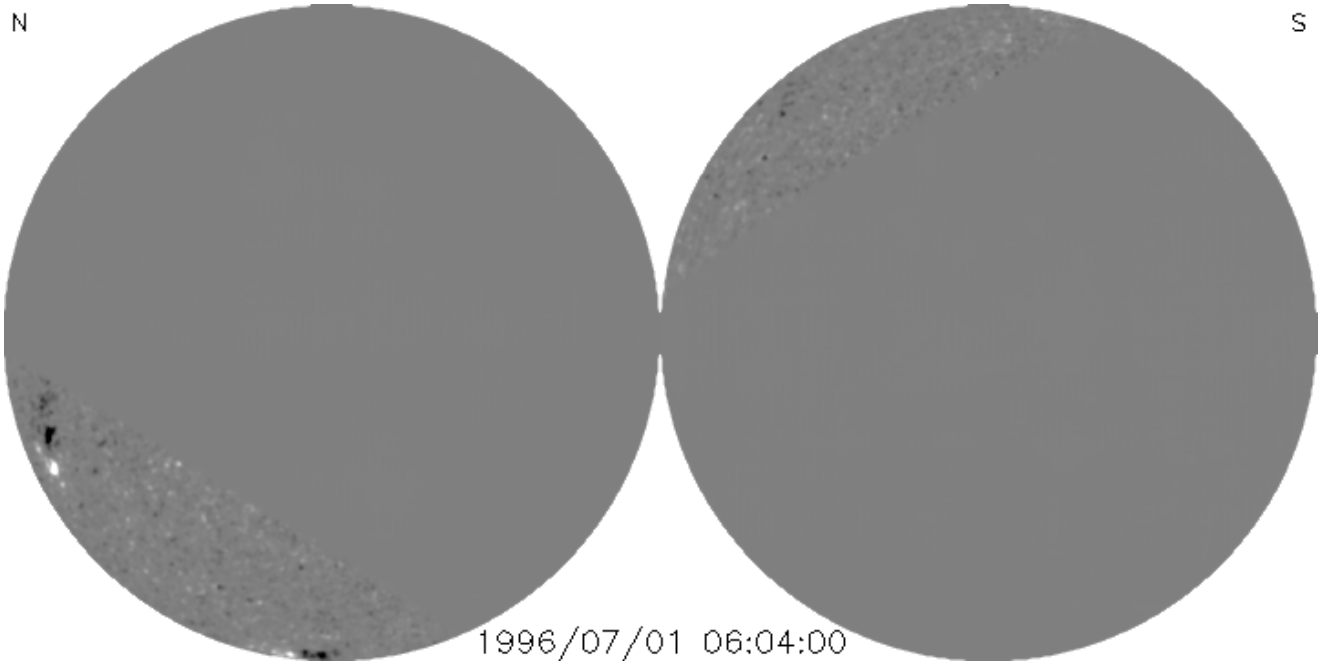
Polar fields in an assimilation-simulation model

- Much of the time, polar fields consist of strong-field "unipolar" network field, and horizontal internetwork field.
- Large-scale polar fields build up as a result of large-scale surface flux transport.
- Role of ephemeral regions and 3D transport remain to be determined.
- Shown are polar views from a movie on the next page …



Polar fields in an assimilation-simulation model

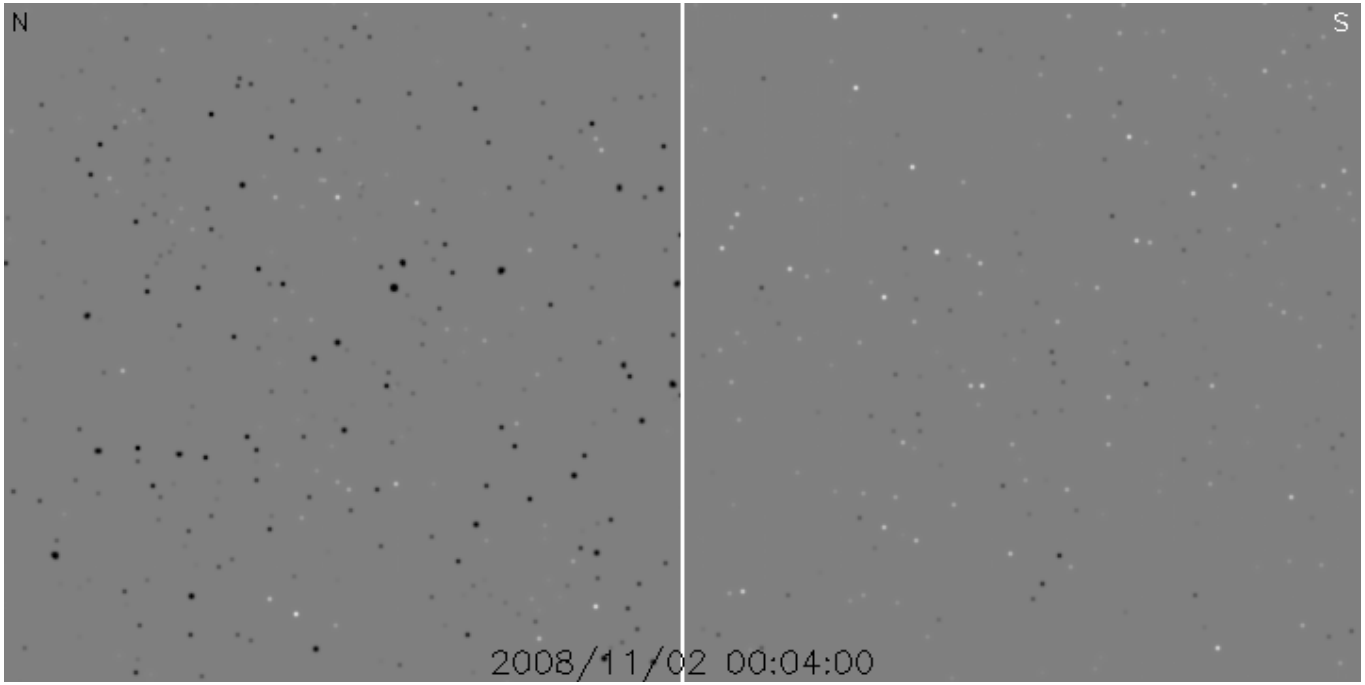
- Movie showing 12 years (@12h steps) of hybrid SOHO/MDI and assimilation flux-dispersal model:



See http://www.lmsal.com/forecast for ongoing daily assimilation.

Polar fields in an assimilation-simulation model

- Movie showing 30d (@6h) of hybrid SOHO/MDI and assimilation flux-dispersal model for polar regions (within 10 degrees of pole). *This run does not incorporate the Hagenaar et al. (2008) findings.*



Movie at 1” pixels; gray scale saturation at 1 kG.

Modeling surface flux dispersal

The diffusion approximation:

If field is always normal to the surface, the MHD induction equation yields a diffusion equation for a signed scalar, subject to:

- Flux emergence
  - From AR to ER; butterfly pattern; tilts; clustering; ….
- Diffusion by the (super-)granular random walk
  - Magnetoconvective coupling; nonlinear behavior
- Meridional advection
  - Weak flow, close to detection limit
- Differential rotation

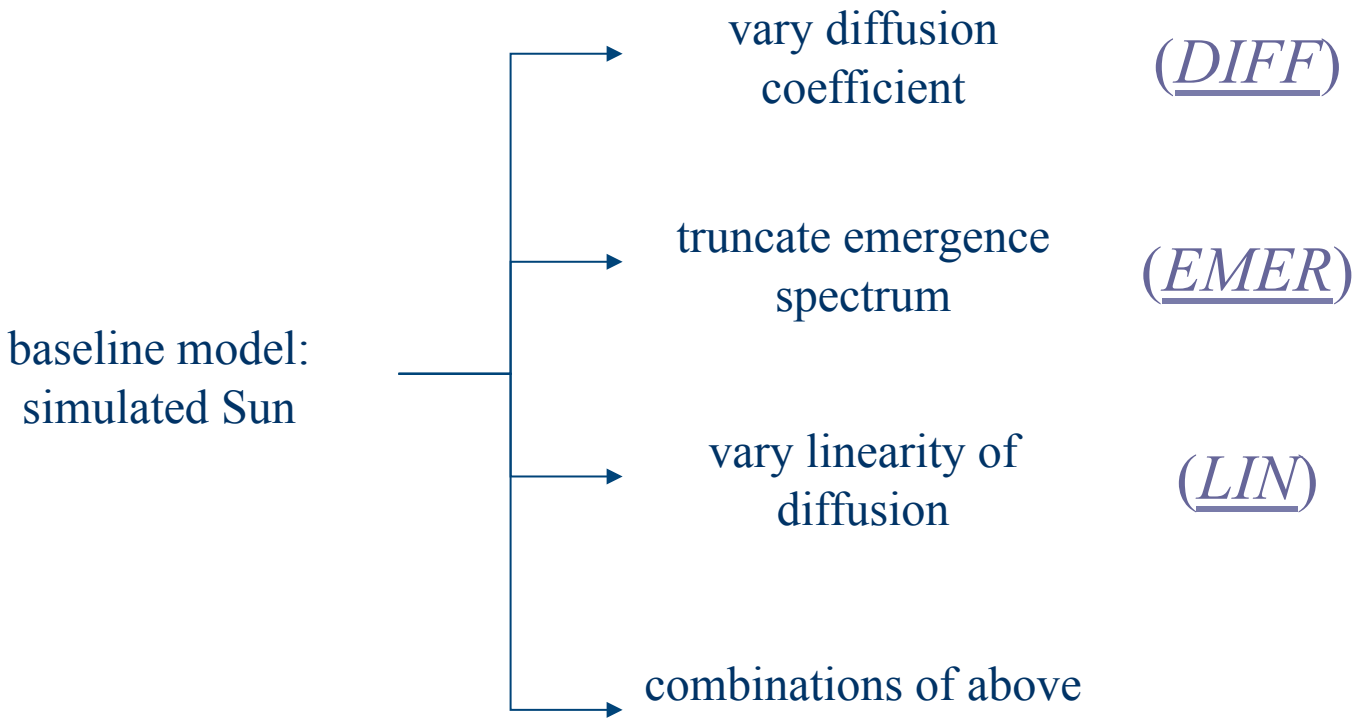
Shape polar field behavior

Shapes surface patterns

Yields a fair quantitative approximation of flux behavior on large scales and for long time scales. The role of 'intranetwork field' is unclear…

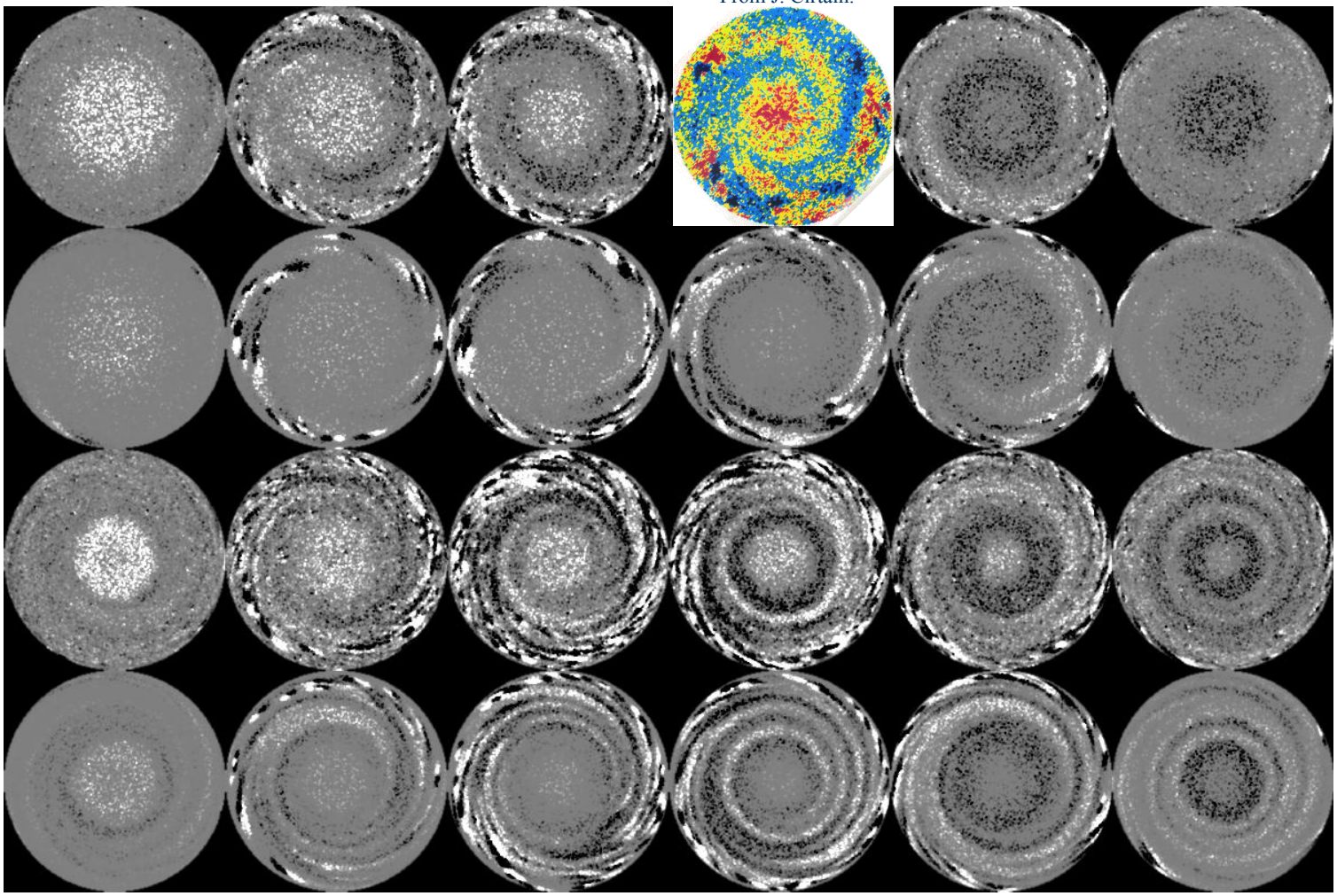
Sensitivity of polar fields to component processes

A few sample experiments:



Sensitivity of polar fields to component processes
- polar view -

From J. Cirtain.



baseline

EMER

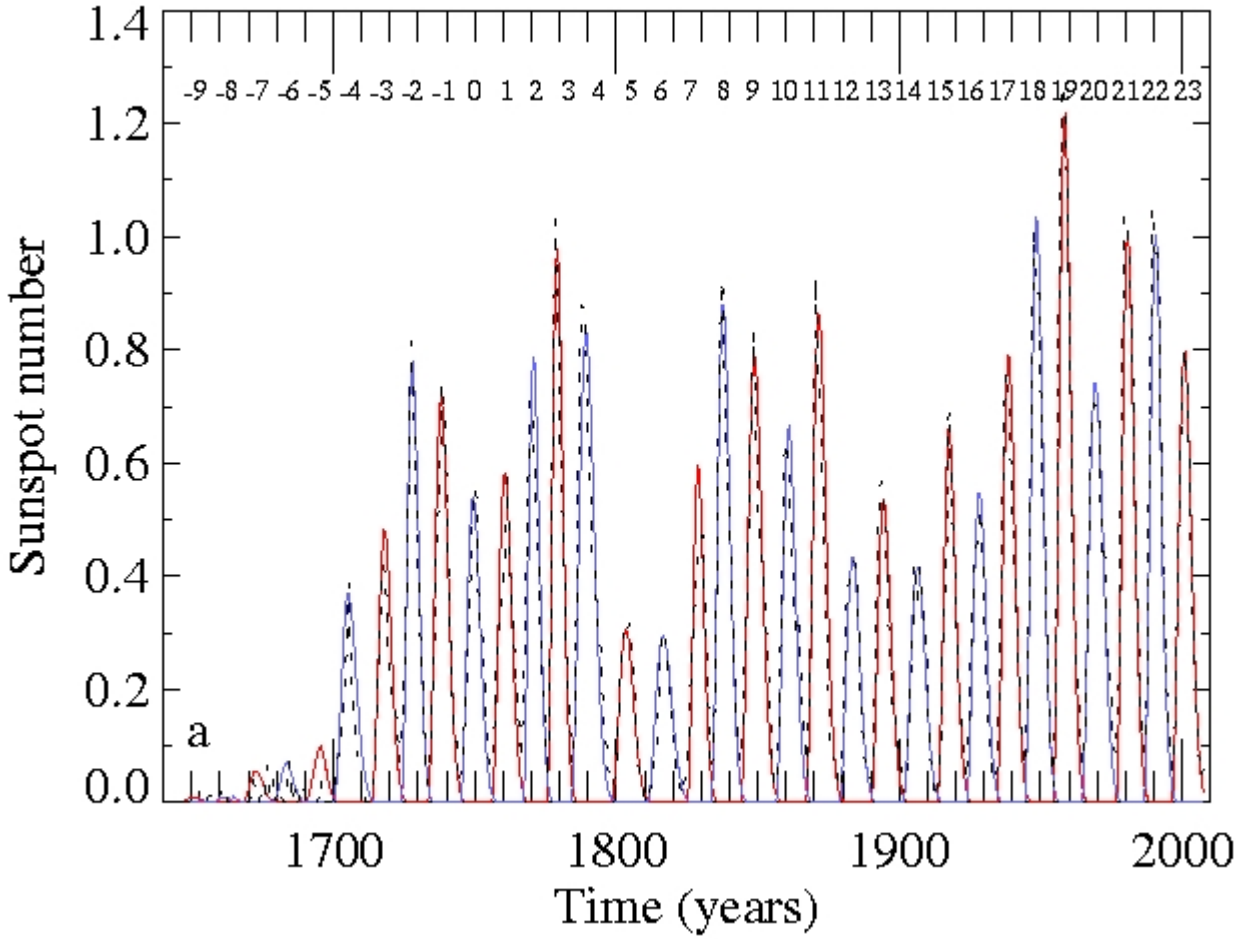
DIFF

EMER DIFF

cycle phase ⟶

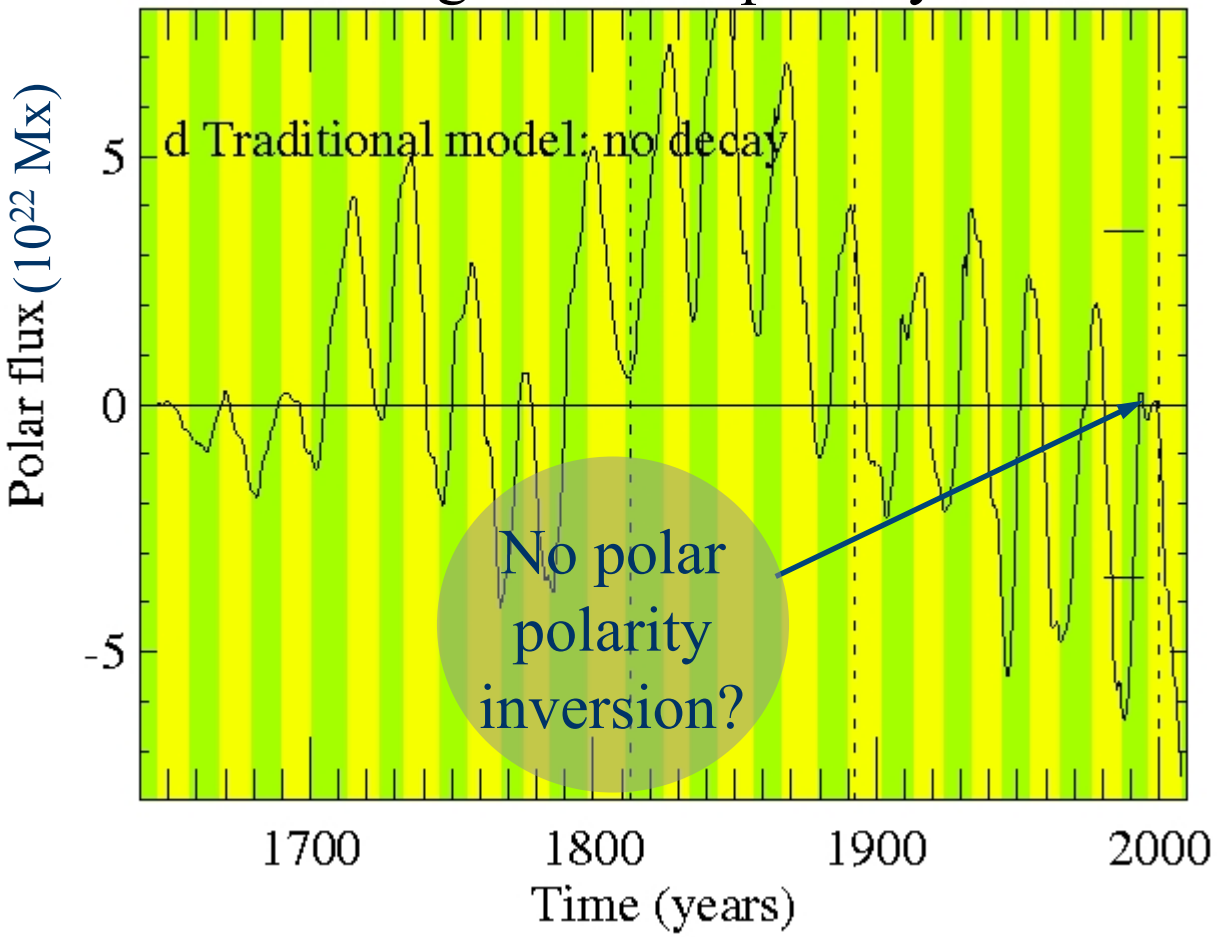
Sunspot cycles: history and approximation

Successive cycles often differ strongly:



Polar-cap (>60°) absolute flux

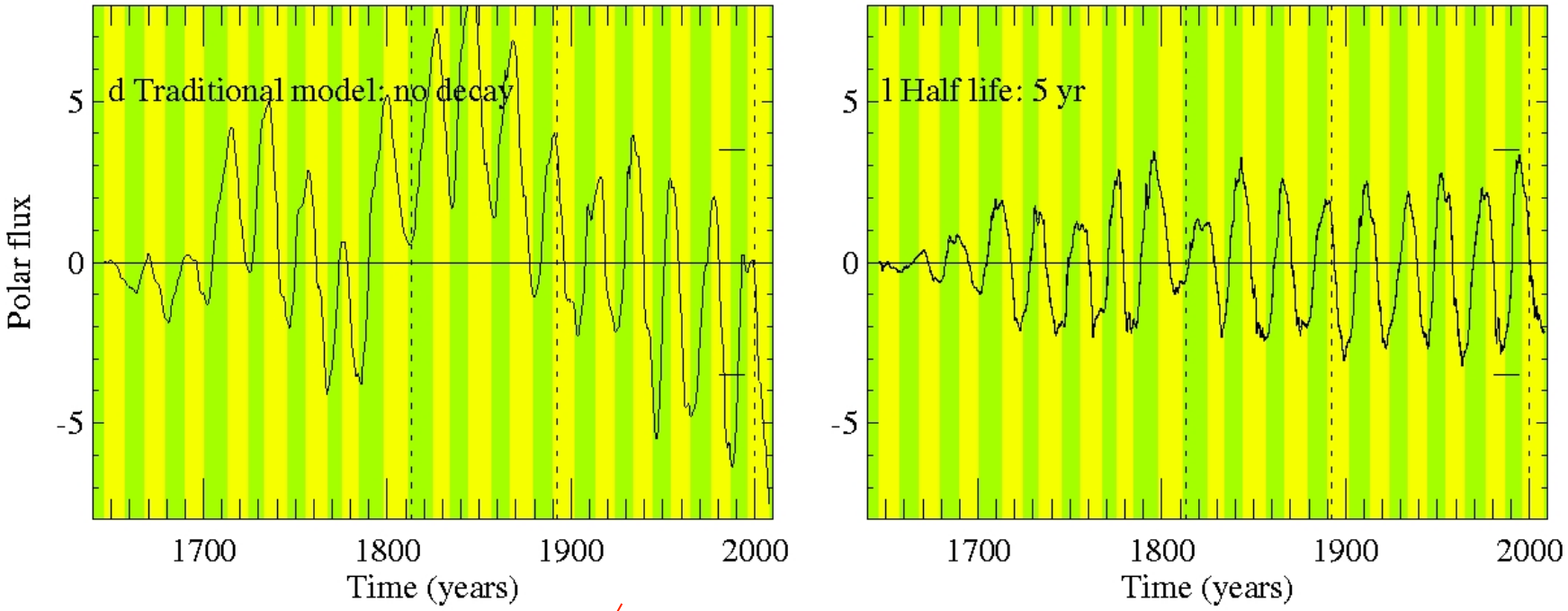
And the polar-cap flux "capacitor" does not simply alternate in strength or even polarity:

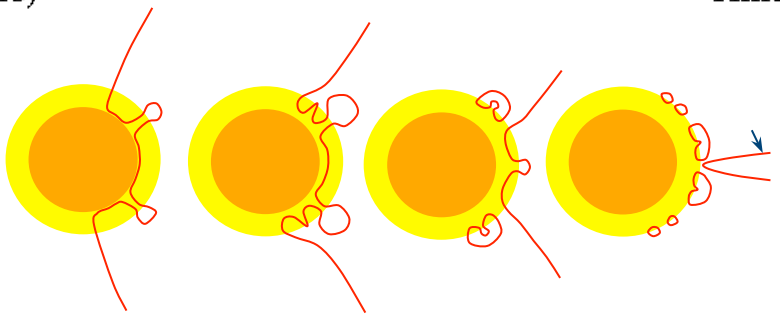


What if flux "decayed" by, e.g., 3D transport?

The polar-cap flux behavior signals something is missing from our understanding:

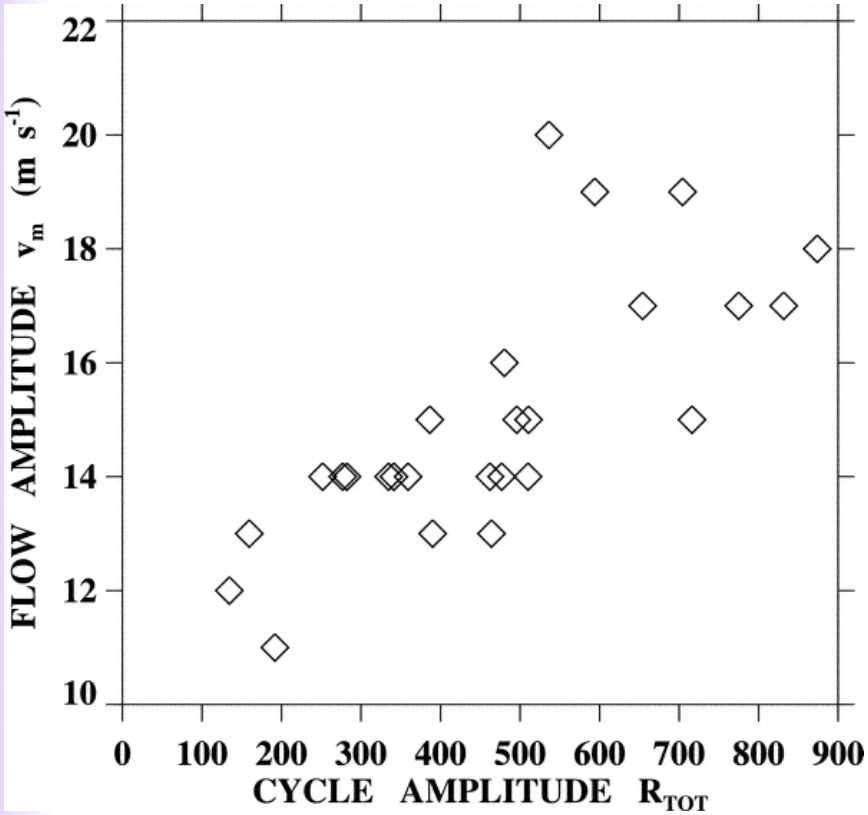
[Schrijver et al. 2002 (ApJ 577, 1006)]

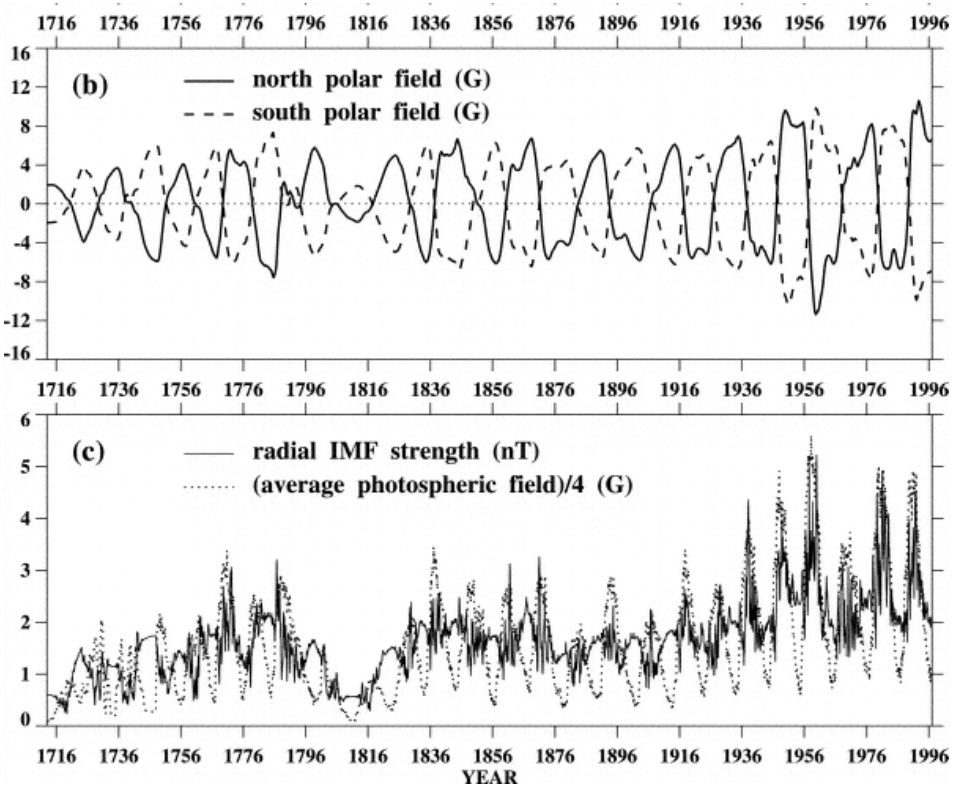




Alternative: modulation of flux transport

Changing meridional advection *[Wang et al. 2002 (ApJL 577, 53)]*, can cause cycle strength and advected polar flux to be nearly the same from cycle to cycle:





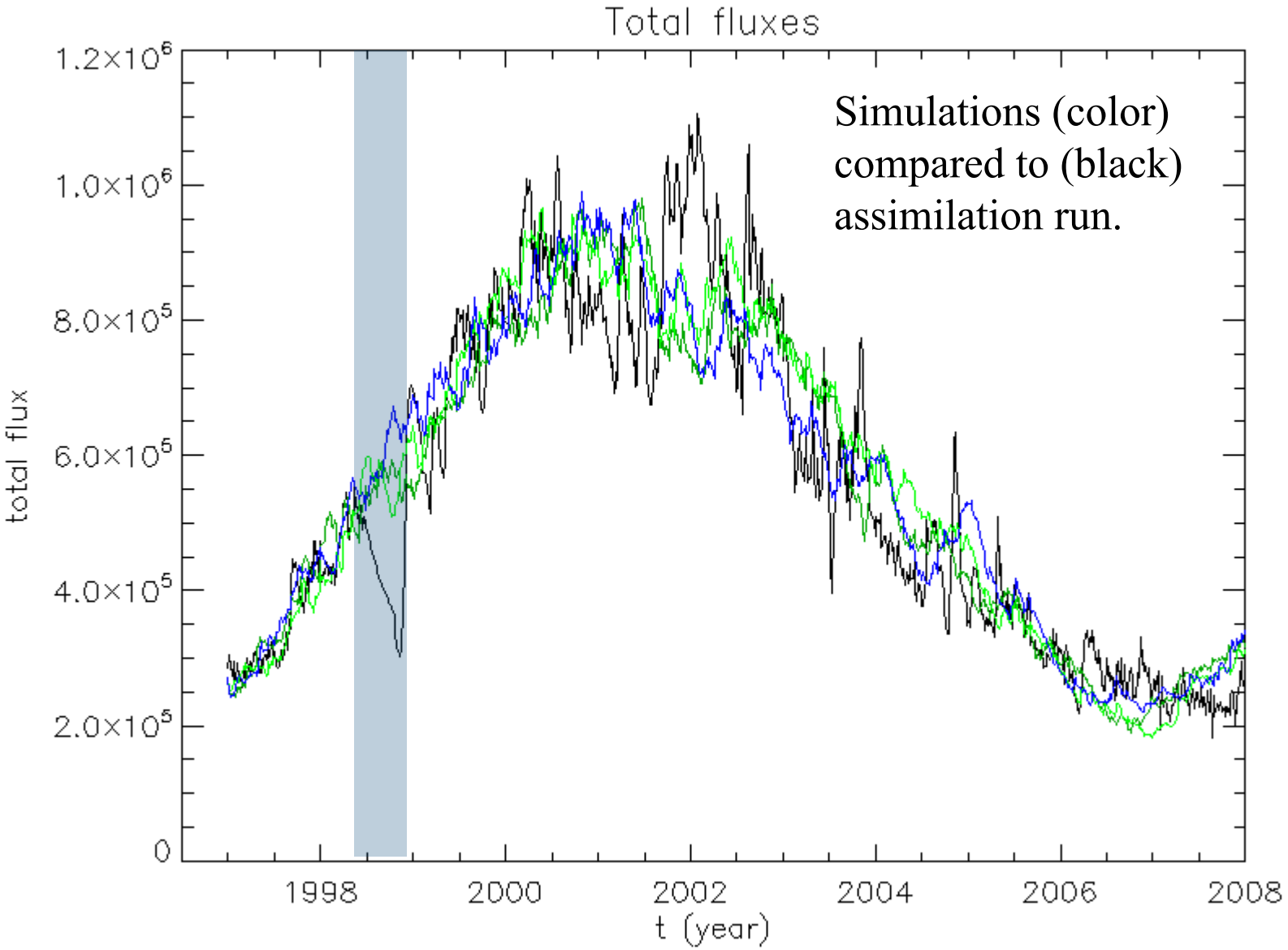
Detailed modeling of cycle 23

The flux dispersal model can be combined with observational data:

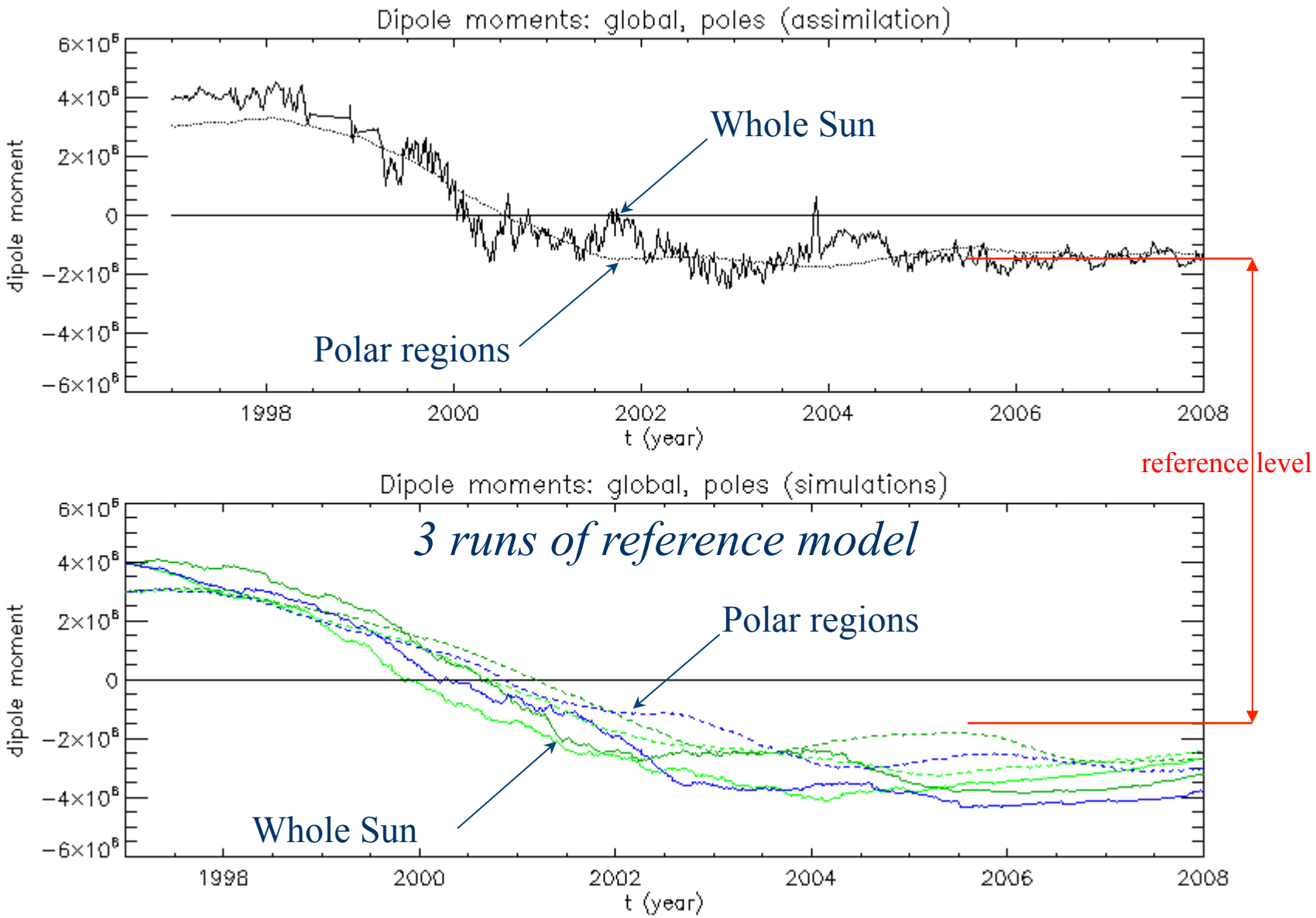
- Direct insertion of magnetic fluxes from SOHO/MDI or SOLIS;
  - Use data only within ~60 degrees from disk center
- Initial configuration: from ‘best-fit’ run since 1643

N.B. In this model the high-latitude field results from advection of flux from the assimilation zone between ±60 degrees in latitude.

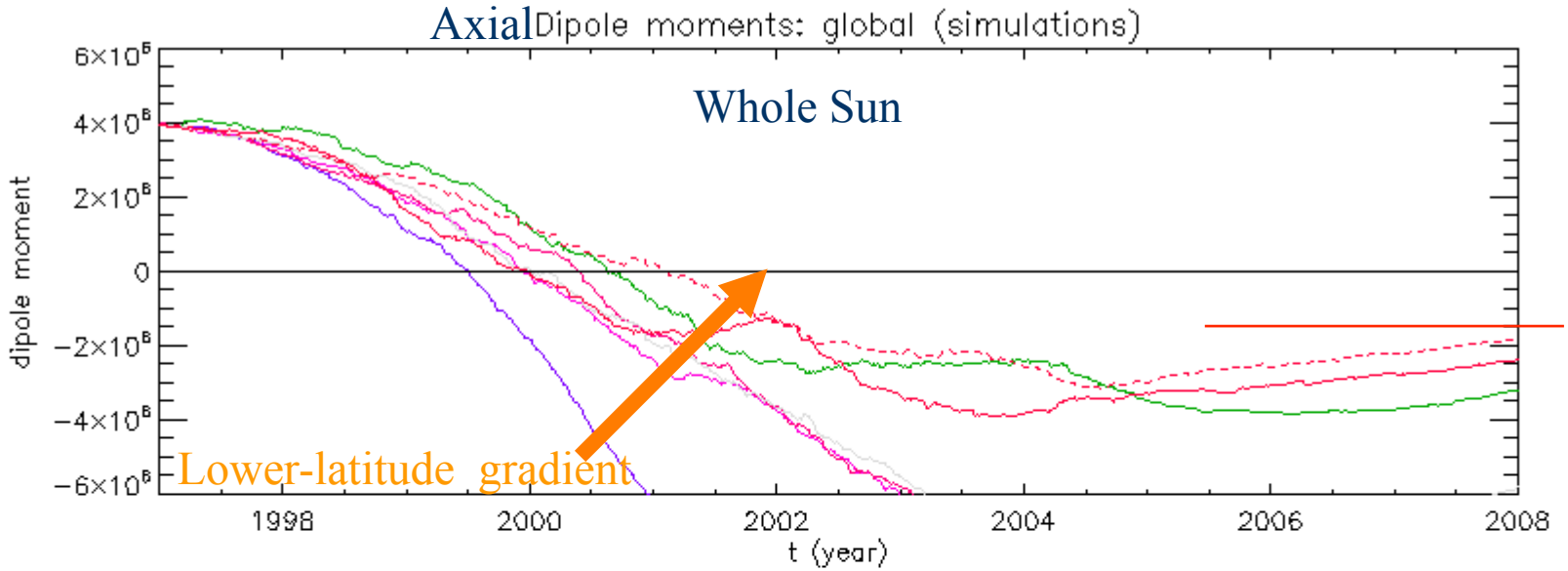
Detailed modeling of cycle 23



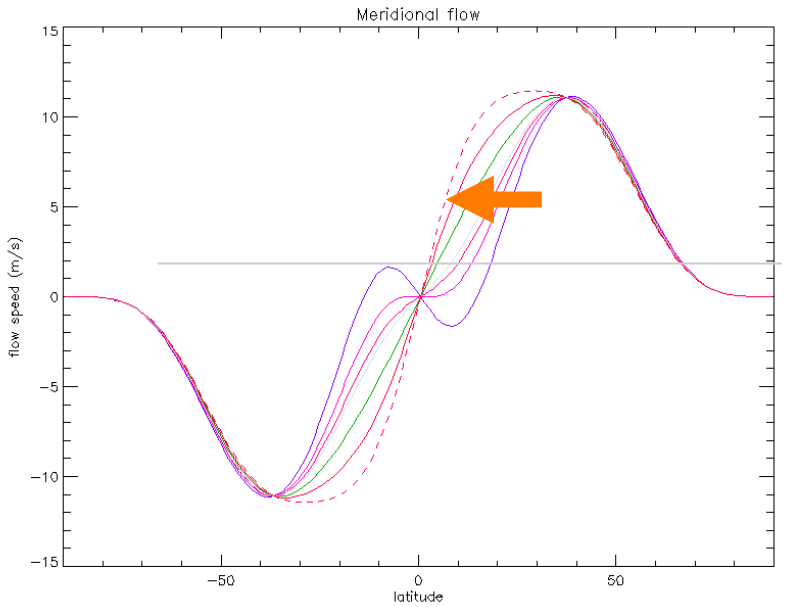
Axial dipole moments: obs. and model



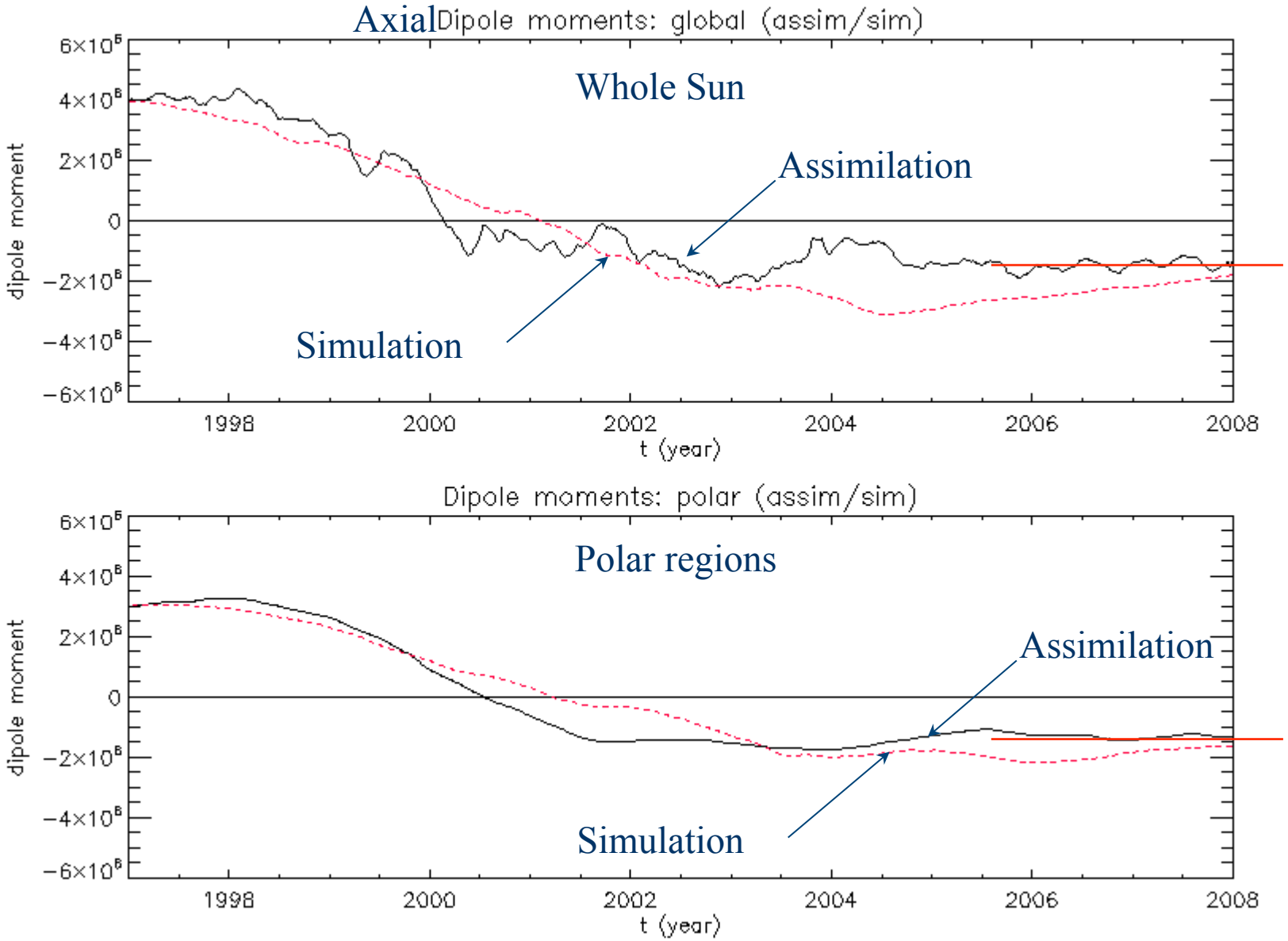
Axial dipole moments and meridional flow



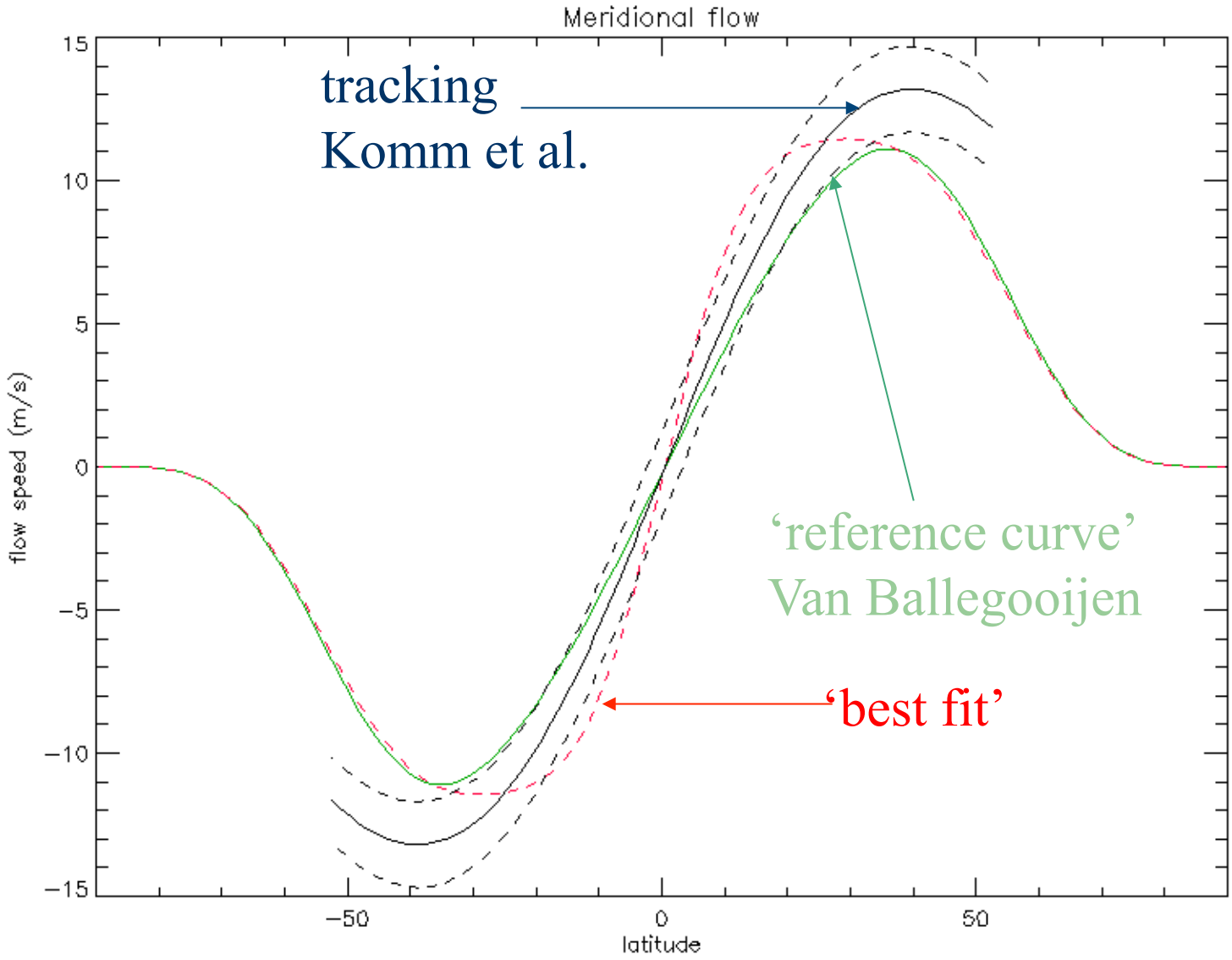
A steeper/shallower meridional flow profile near the equator weakens/strengthens the polar caps and delays/hastens polarity reversal.



Detailed modeling of cycle 23



‘Best-fit’ meridional flow profile



Conclusions:

- The *surface flux dispersal model reproduces large-scale properties of the solar photospheric field to within current uncertainties*. The most stringent test is based on a comparison with decade-long MDI records.
- Modeling based on historical records suggest *something is missing from our surface flux transport models: 3D diffusive transport* appears unavoidable. *Modulation of meridional flow* has been observed, but not directly over multiple cycles. Perhaps tracers like limb faculae (Sheeley and Warren 2006) or historical filament observations can be used to infer any meridional flow changes.
- Modeling of the current cycle suggests *changes in average strength or profile of the meridional circulation* from cycle to cycle, but the magnitude may be close to observational uncertainties.

Understanding the polar flux budget

- To understand the net polar-cap flux requires
  - long-term (>11 y), continuous (<1 min.), highly-sensitive (<1 Mx/cm^2) measurements of
    - the evolving full-sphere vector-magnetic field, and
    - the evolving meridional advection, in comparison with
    - a high-fidelity 3-D flux-transport model;
  - and a high-fidelity, high-resolution convective-MHD model of the Sun.
- To understand mixed-polarity component of the (polar) quiet Sun requires
  - detailed study of statistical properties of the ensemble of ephemeral regions, as function of
    - cycle phase and
    - environment (flux balance, latitude, …);
  - and a high-fidelity, high-resolution convective-MHD model of the Sun.

Issues for a science definition exercise:

- Is there really a significant and important problem with the polar flux budget that we must (and can) address at high latitudes, or do observations of lower latitudes suffice to learn what the Sun can tell us?
- Are the (high-latitude) surface phenomena telling enough about the deep-seated field?
- How would we differentiate local from global dynamo action, and why are high latitudes important to answering that question?
- High-fidelity modeling of field transport is important for definition of the mission and critical for the interpretation of the results.
- Polar-field reversal is a multi-year process, starting in cycle-rise phase.
- Telemetry will be an important limitation: minute-cadence, high-resolution magnetograms appear to be needed, exceeding telemetry available by >10x -100x[TBD] for field measurements only.
- Measurements depend on resolution – impact of elliptical orbits on science return TBD.
- "Calibration" dependence on latitude (on Sun and in orbit) will need to be a high priority [can probably be addressed now as function of longitude].