SOLAR CYCLE PREDICTION

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Session I: The Global Magnetic Field of the Sun and the Solar Cycle

Previous lectures:
- The solar cycle over the centuries (Chatzistergos)
- MHD dynamo theory and solar cycle models (Charbonneau)

What is left is to

3. connect these 2 topics:
   Interpreting long-term variations on the basis of MHD dynamo theory
2. Explore possibilities of forecasting
   2c physical precursors
   2b precursor based on cycle overlap
   2a time series methods
1. Discuss importance/applications: space climate

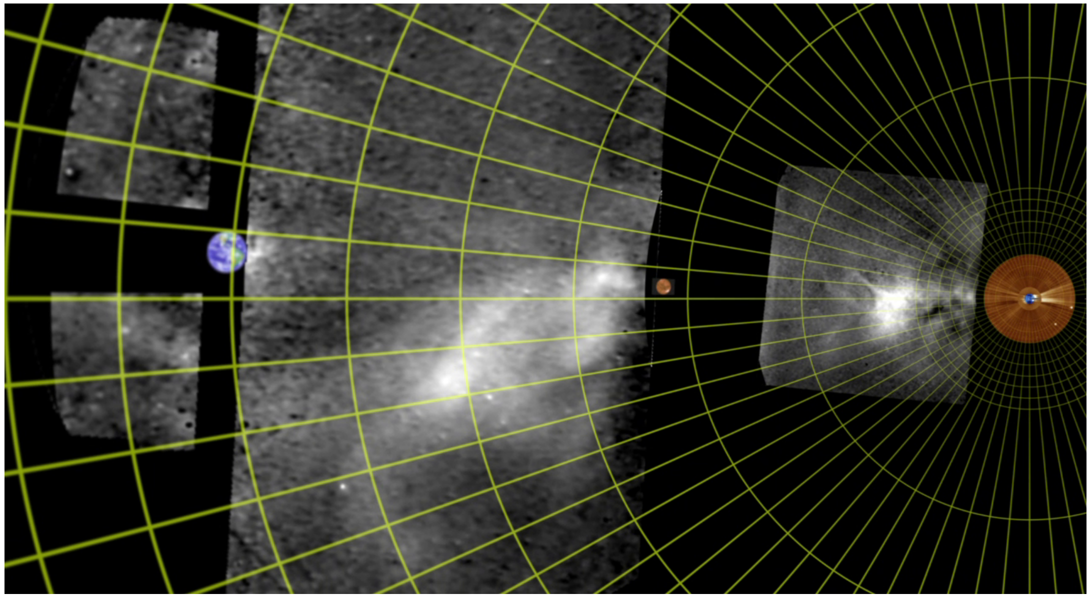
First lecture : 1 and 2
Second lecture: 3

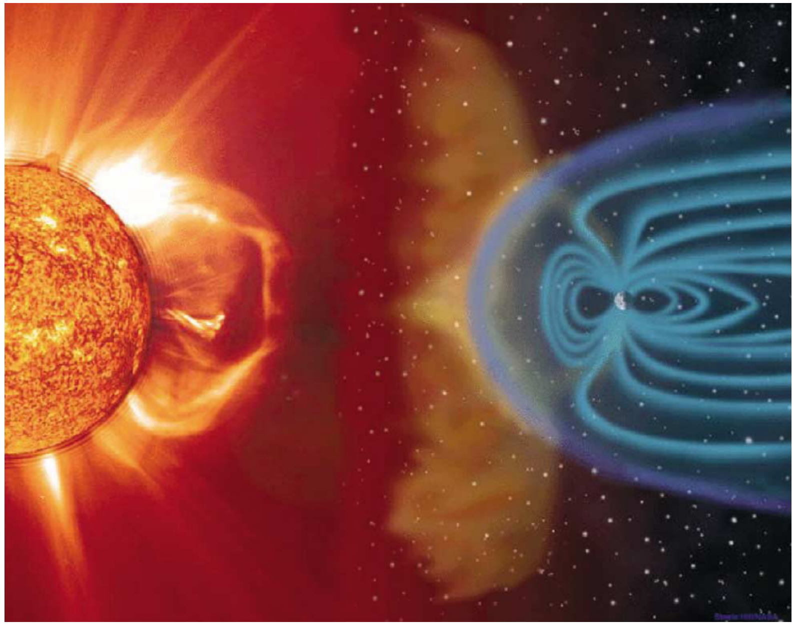
1. SPACE CLIMATE: ORIGIN AND IMPORTANCE

Space weather: the incessant forcing exerted by the solar wind plasma flow and, in particular, by solar magnetic activity on the space environment of Earth and other bodies in the solar system.

This forcing perturbs the Earth's magnetic sphere of influence (geospace) on timescales of hours and days

⇒ detrimental (potentially catastrophic) to terrestrial infrastructure and human assets in orbit.





WHERE DOES SPACE BEGIN?

The Kármán line

—introduced by Kármán (1956) in a conference paper

(no, you don't need "Q1" to be famous...)

Aerodynamic lift: $F_L = C_L A \rho v^2/2$

$C_L \sim 1$: lift coefficient A: wing area

$\Rightarrow$ Set $F_L = mg$ to get a minimal speed for an airplane v_{lift}.

Orbital speed: $v_{\text{circ}} = \sqrt{\dfrac{GM}{R+h}}$

The Kármán line is located where $v_{\text{lift}} = v_{\text{circ}}$. Depends on vehicle.

For a Boeing 747: 61 km For a Bell X-2 (Kármán's original choice): 84 km

Definitions:

Fédération aéronautique internationale (FAI) technical definition: 100 km

USAF: 80 km ($\sim$top of mesosphere)

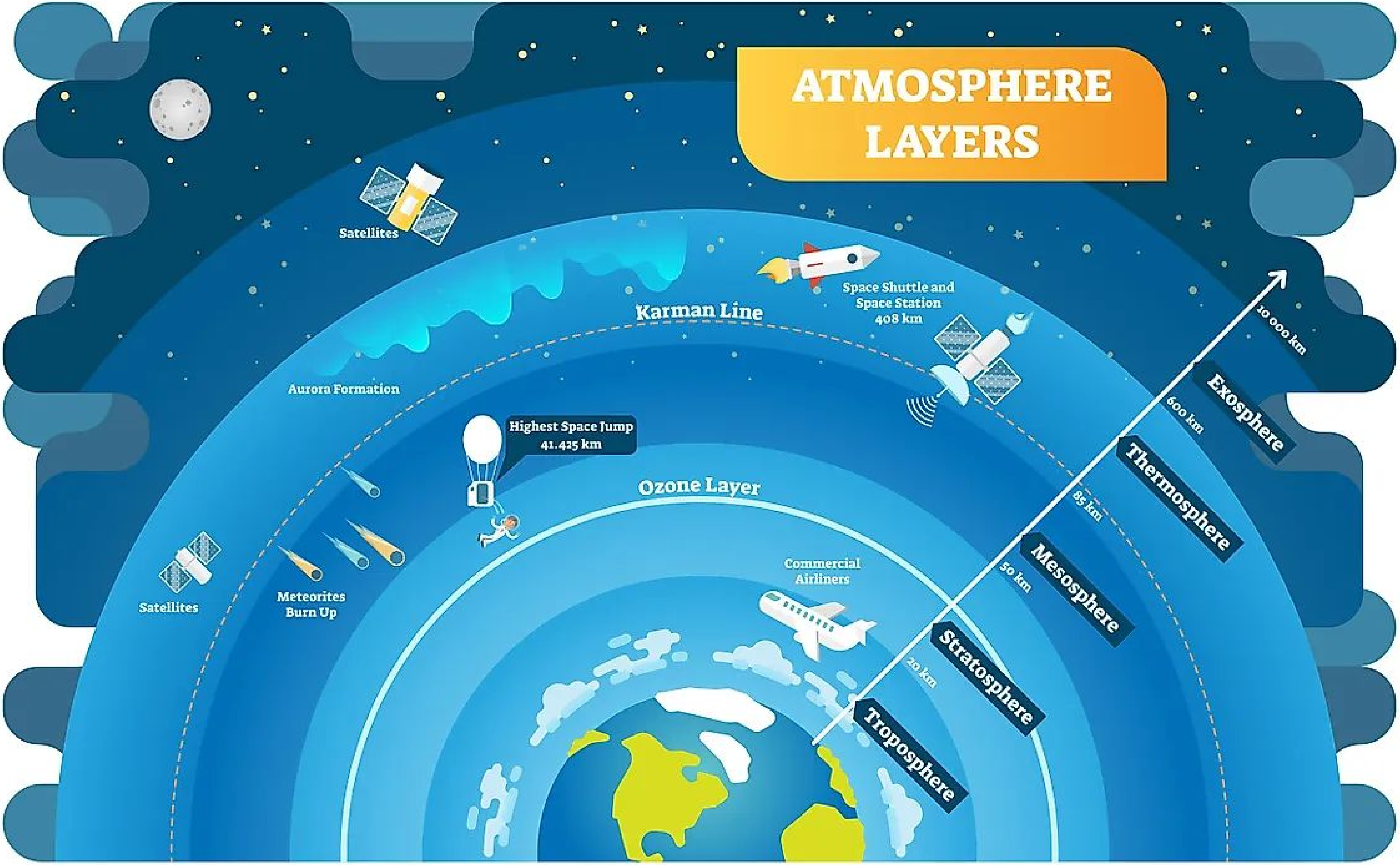
Currently there is a tendency toward lowering the limit to 80 km:

– NASA switched from FAI to USAF definition in 2005.

– McDowell (2018): circular orbits sustained from 125 km only; but elliptical orbits with perigees down to 70-80 km can be sustained for several periods.

– Pressure from private aerospace manufacturers offering suborbital flights (Blue Origin, Virgin Galactic...)

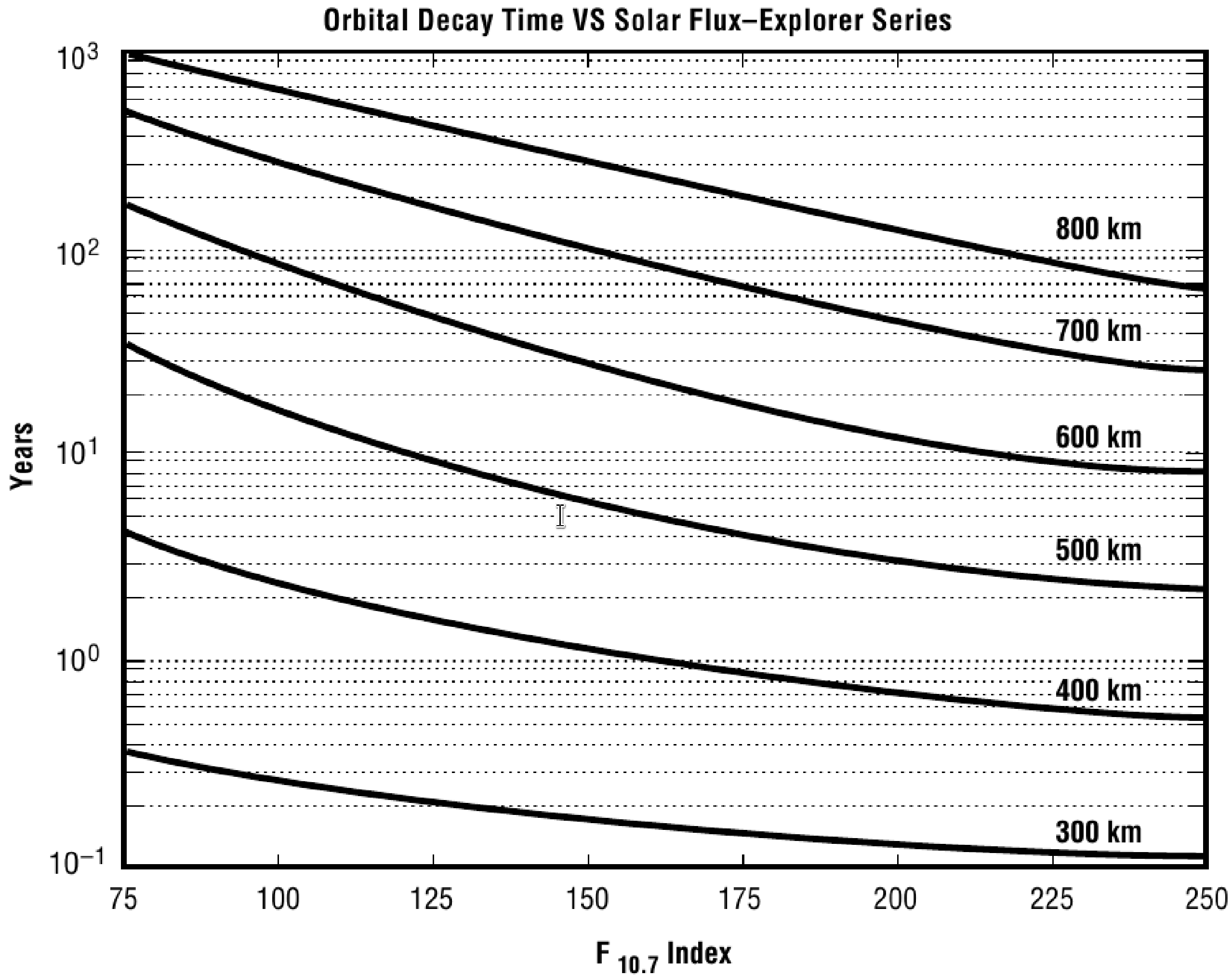
No legal validity; international law does not define space or the upper boundary of national airspace.



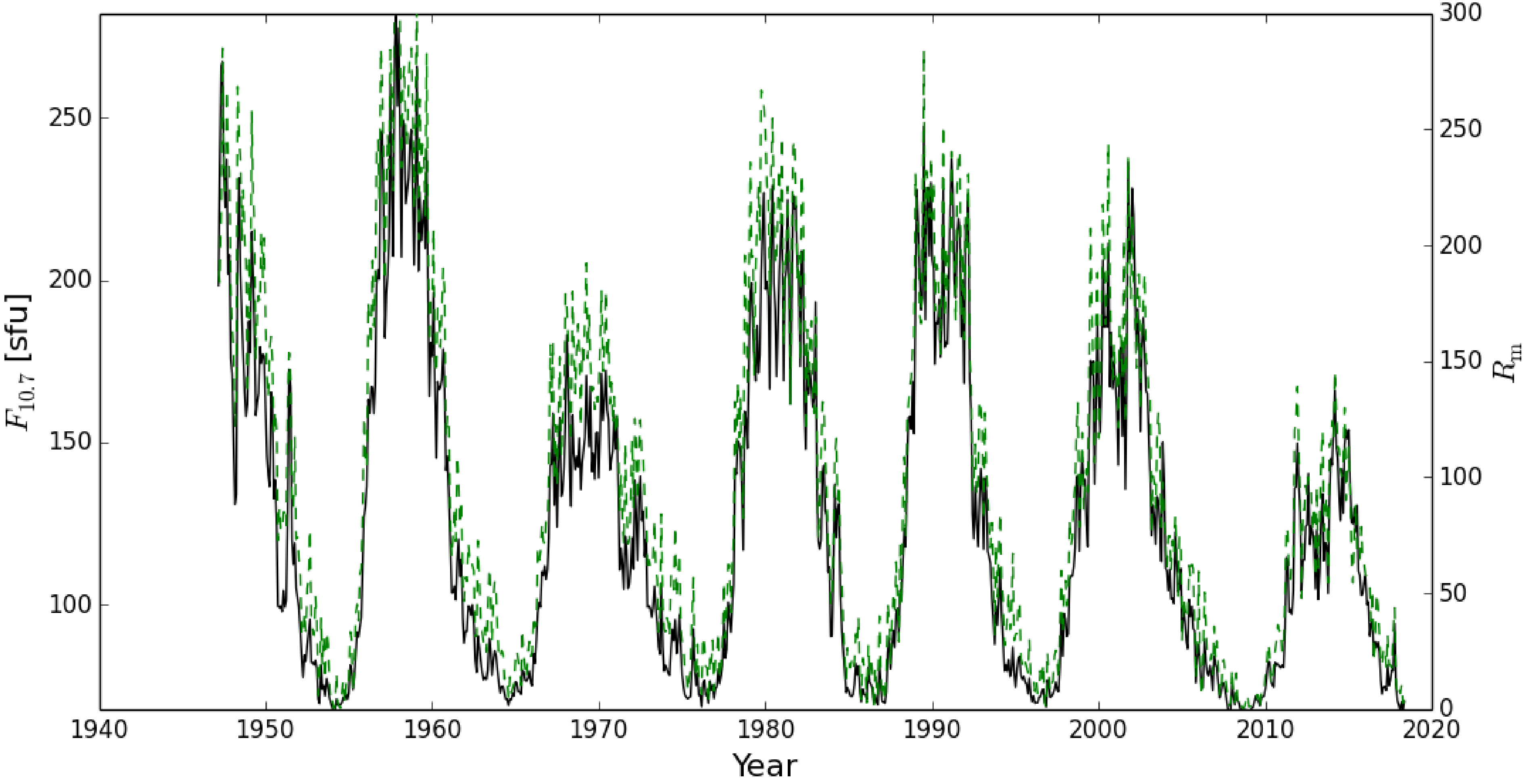
ATMOSPHERE LAYERS
Satellites
Karman Line
Space Shuttle and Space Station 408 km
Aurora Formation
Highest Space Jump 41.425 km
Ozone Layer
Satellites
Meteorites Burn Up
Commercial Airliners
10 000 km
Exosphere
600 km
Thermosphere
85 km
Mesosphere
50 km
Stratosphere
20 km
Troposphere

⇒ the upper atmosphere is “in space”!

⇒ significant aerodynamic drag on satellites ⇒ orbital decay:



Vaughan (1997)

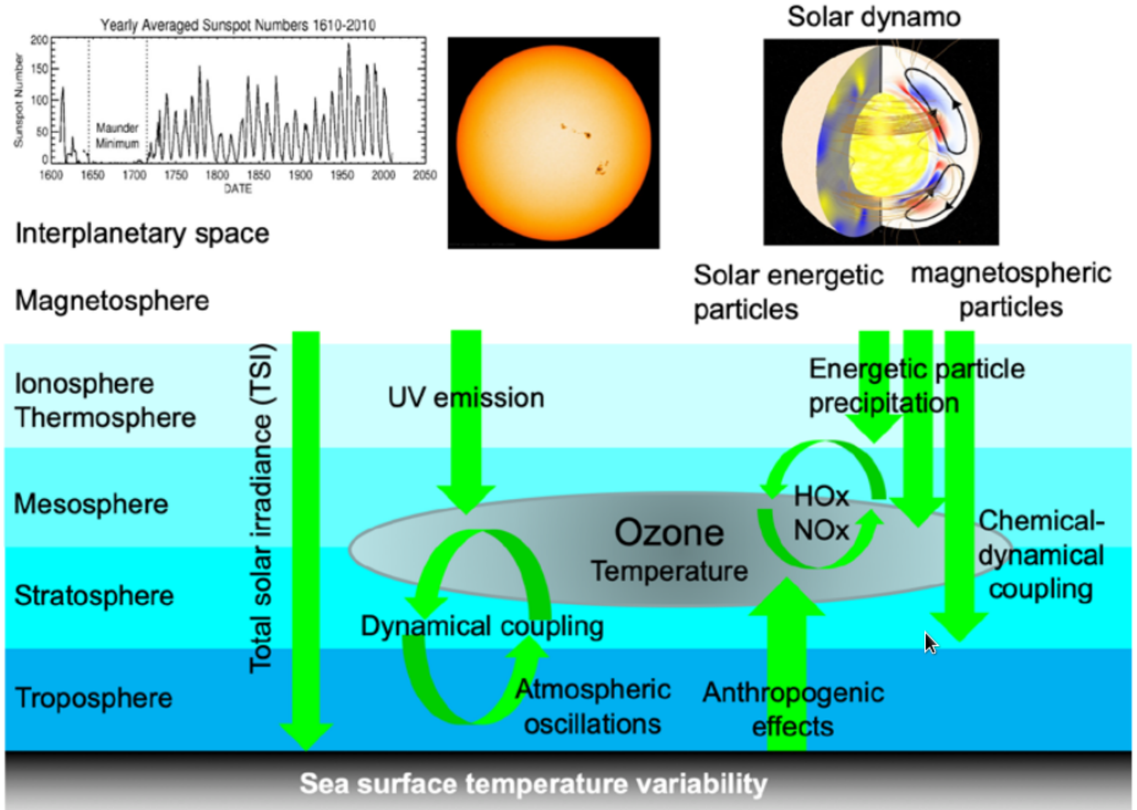


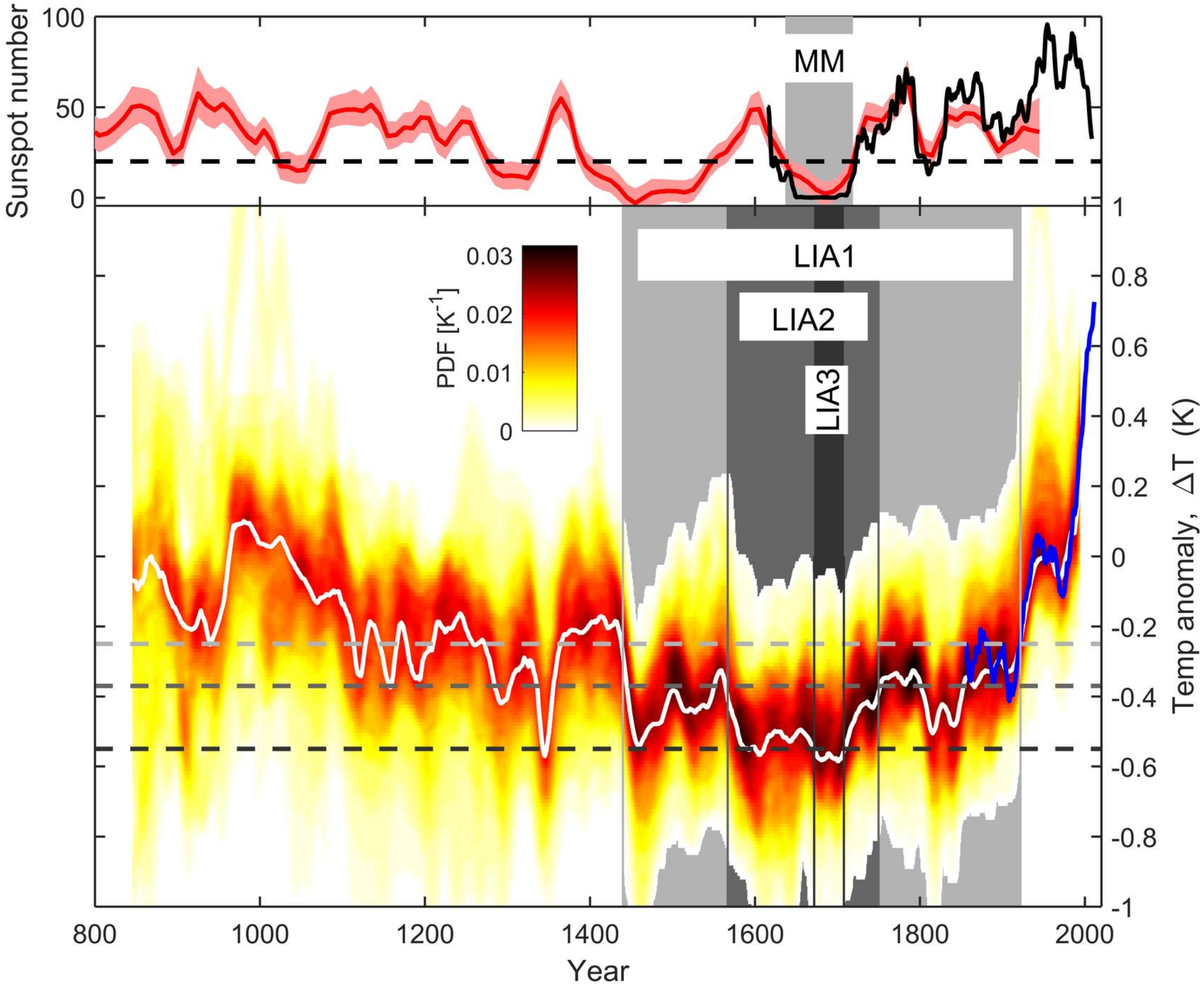
⇒ e.g., ISS orbit ($h = 420$ km) decays by 2 km/month ⇒ orbital boosting is needed.
Space climate related variation in fuel requirement several tons/year, $\sim 10^8$ \$!

Space climate: Long-term variation in the occurrence frequencies of space weather events and other space weather conditions, due to the Sun's variability over timescales of decades, centuries and millennia.

Ability to predict space climate is important for

– planning of future space missions
– incorporation of realistic solar forcing variations in models of climate change
– ...



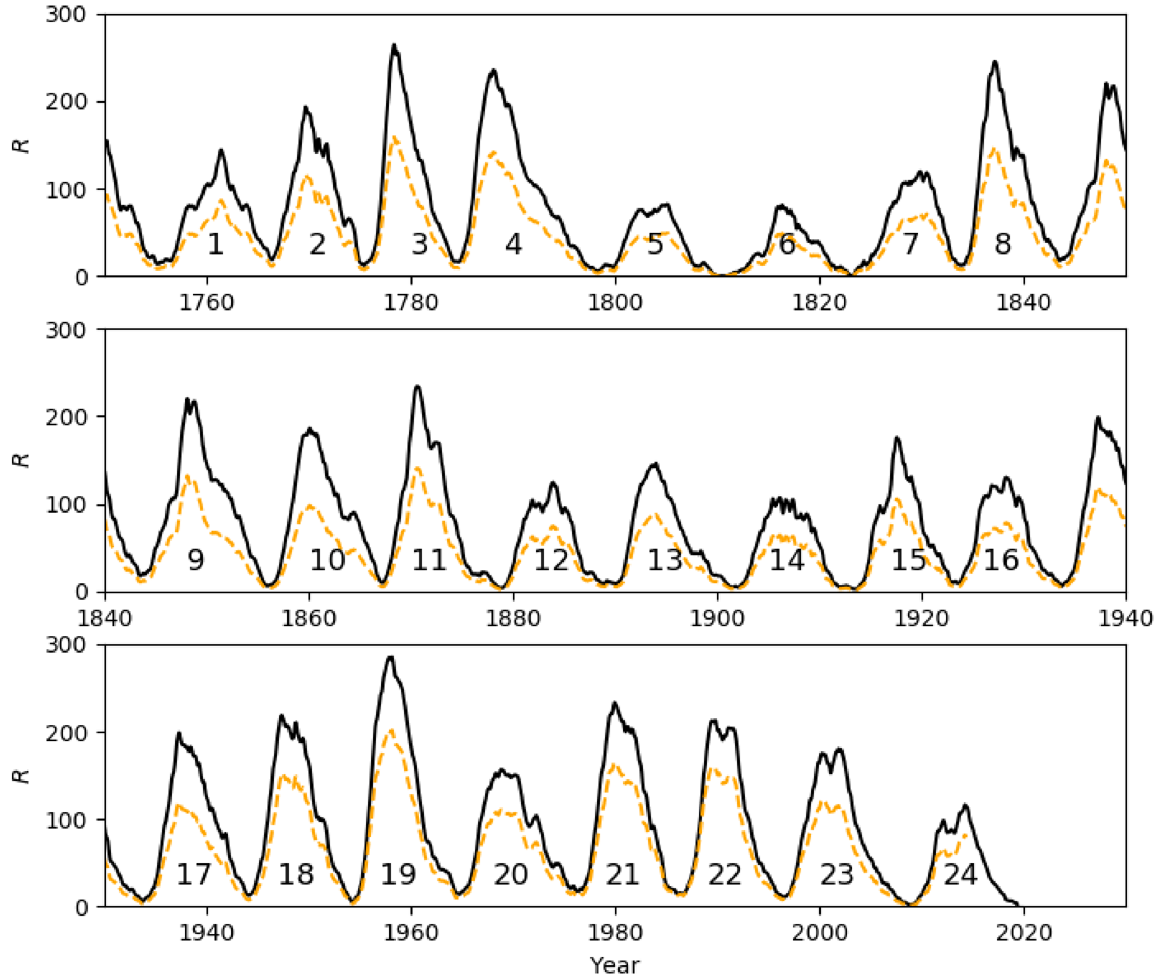


Owens et al. 2017

The level of solar activity is most commonly characterized by the sunspot number (SSN).

SSN has many varieties:

group SSN (GSN); relative SSN (R); international SSN (S_N); revised S_N; pseudo-SSN etc.



The variation of SSN is dominated by the Schwabe cycle:

Length:

11.0 ± 1.2 yr (9.0–13.6 yr)

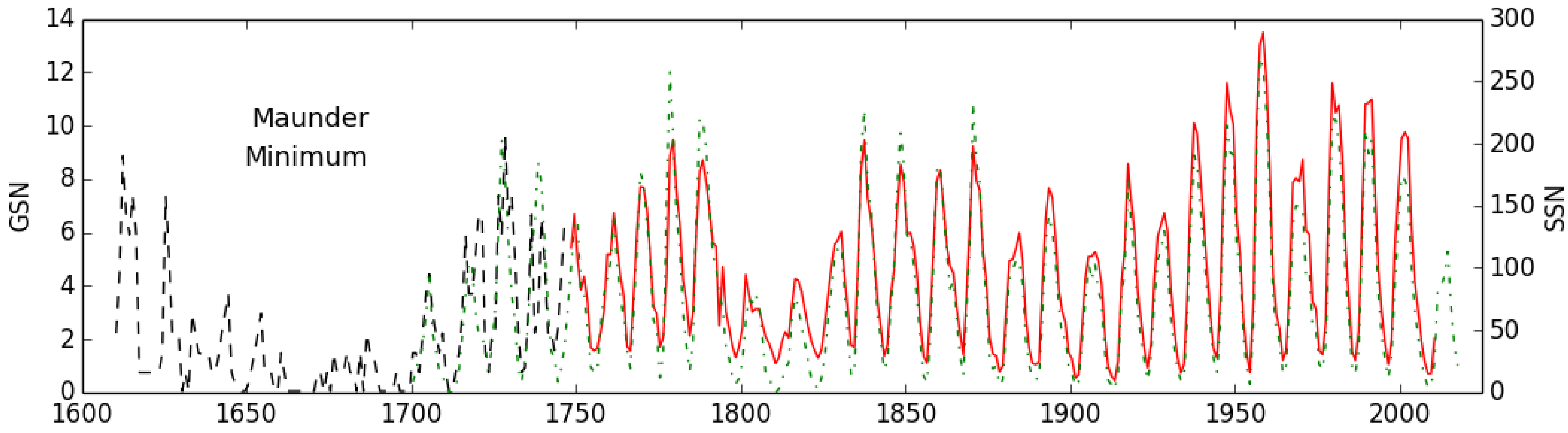
Amplitude: 179 ± 57 (81–285)

Cycle 25 started Dec 2019.

ARs are the sources of major space weather events

⇒ the long-term variation of SSN determines space climate:

long-term [decadal or longer] variations in solar activity
and associated variations of conditions in interplanetary and geospace



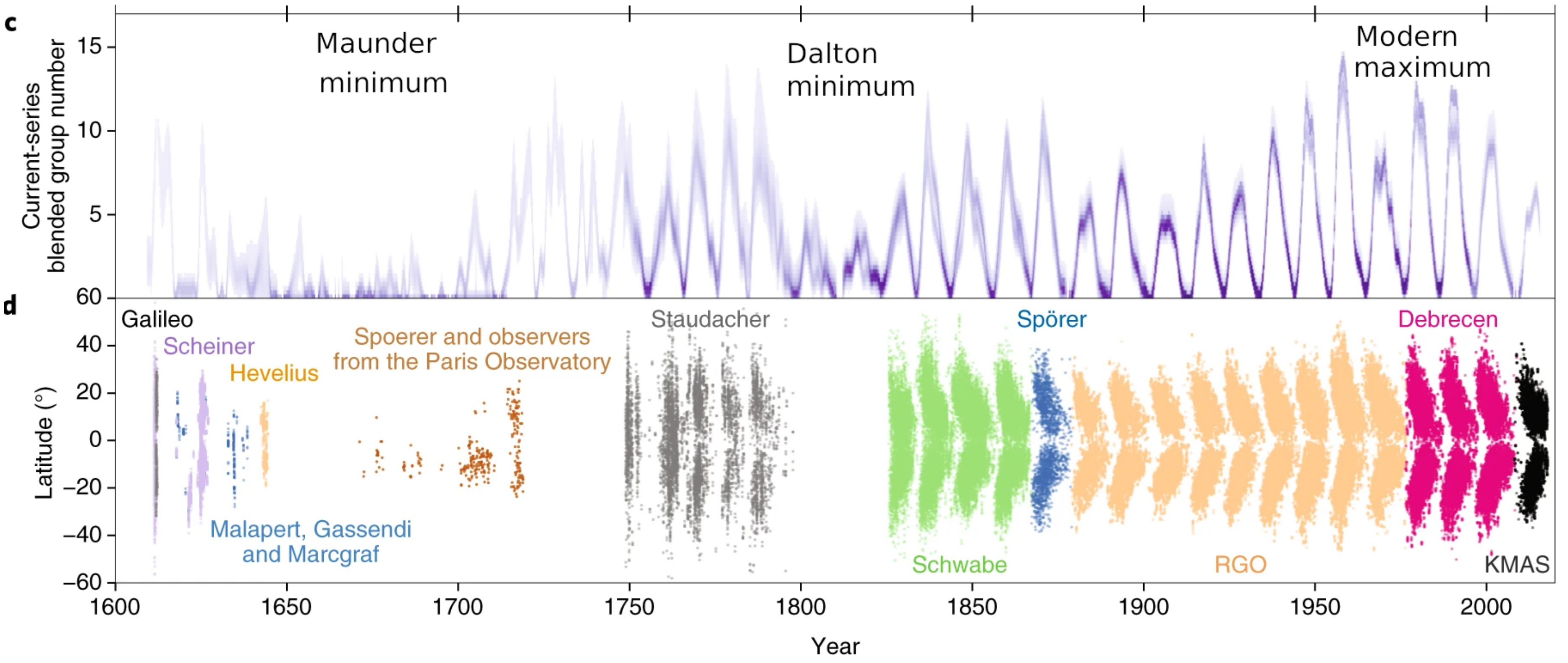
Petrovay (2020)

Red solid: annual means of reconstructed group sunspot numbers (Chatzistergos 2017).

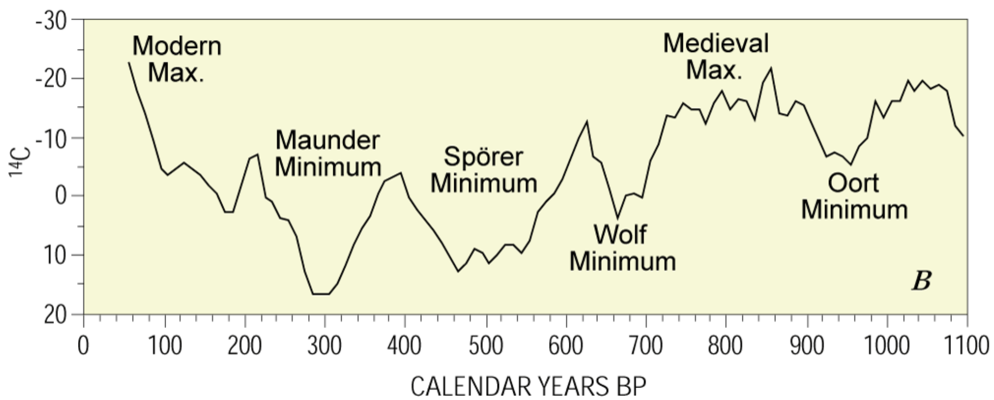
Green dash-dots: revised annual sunspot numbers. Black dashed: pre-1749 values from

Svalgaard et al. (2016), multiplied with 0.85 [for better alignment with the other curves]

A more candid representation, after Muñoz-Jaramillo et al. (2019):

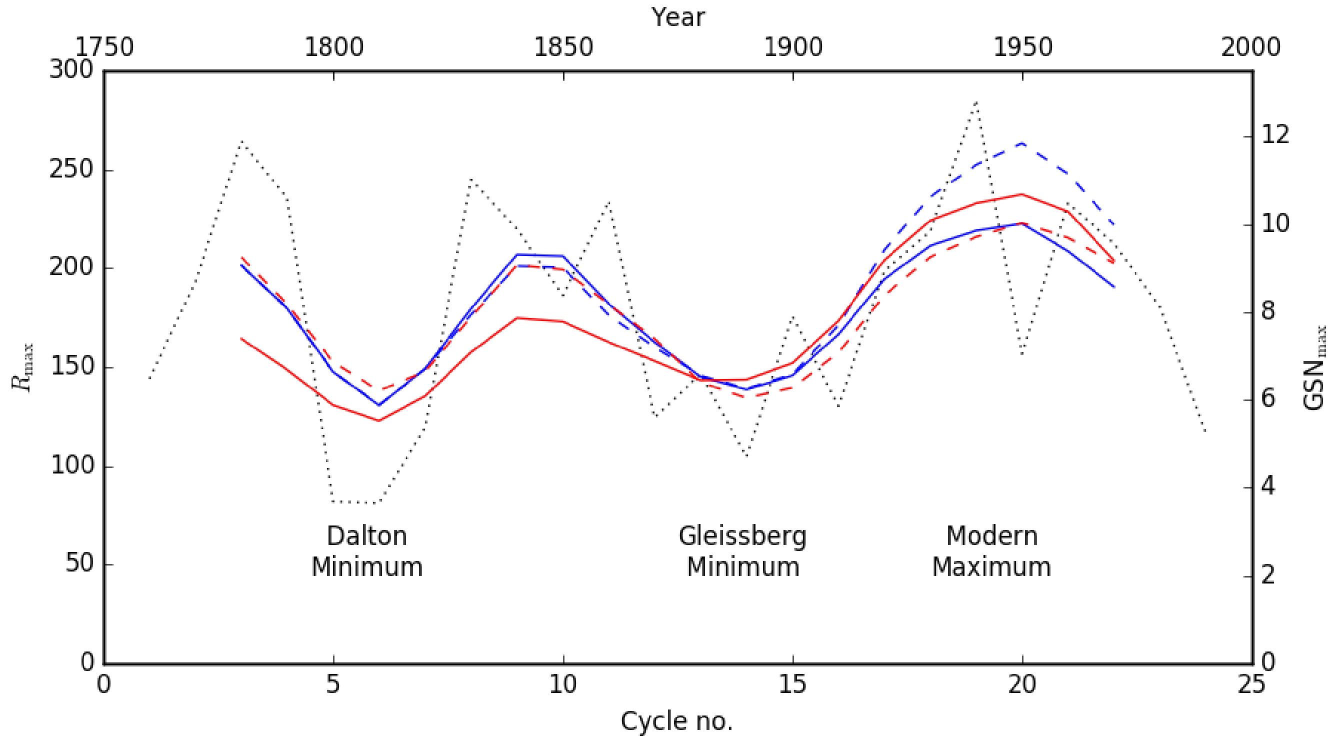


Extension backwards in time
by terrestrial proxies
(cosmogenic radionuclides):



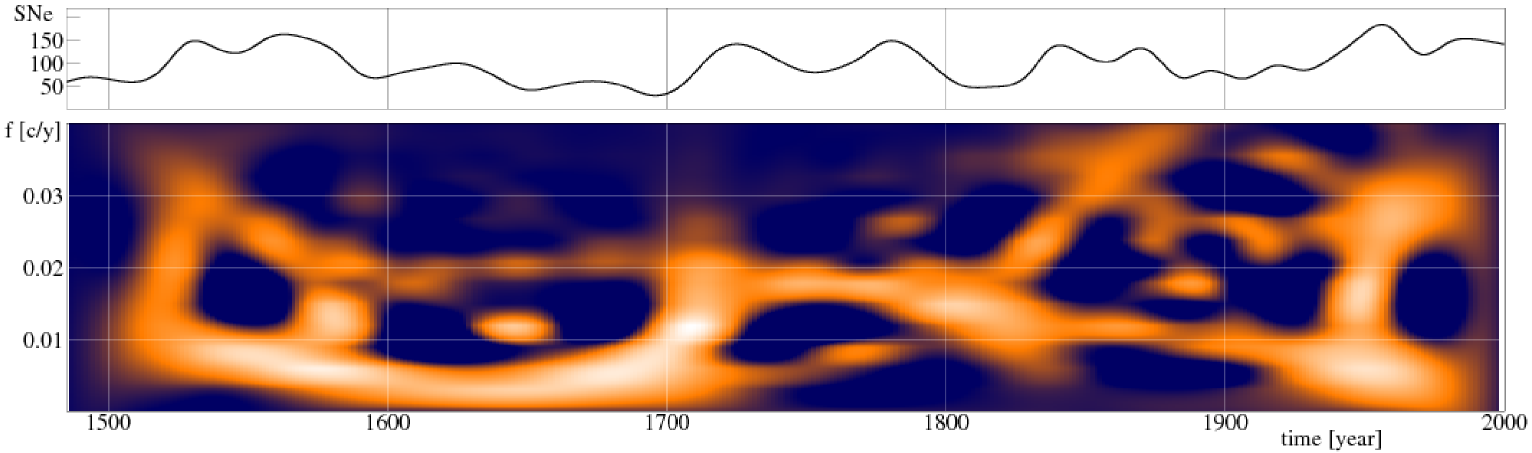
2a CYCLE PREDICTION: TIME SERIES METHODS

Linear time series methods = looking for periodicities in the data
(Nonlinear time series methods: chaotic behaviour, modelled by AI / ML / NN)



Long term variations: "12221" sliding average (Petrovay 2020)

Gleissberg cycle : Its “period” kept increasing in the past 300 years, from 50 years to 130. Its minima: “semi-grand minima”.



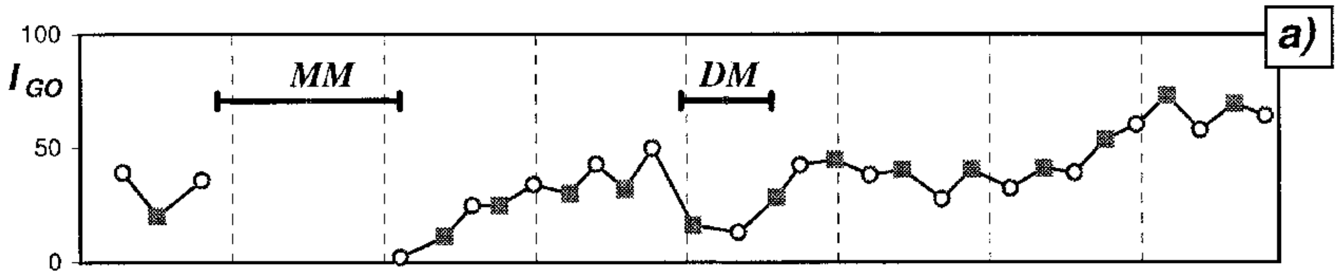
(Kolláth & Oláh 2008)

Gnevyshev–Ohl rule: odd-numbered cycles stronger than previous even-numbered

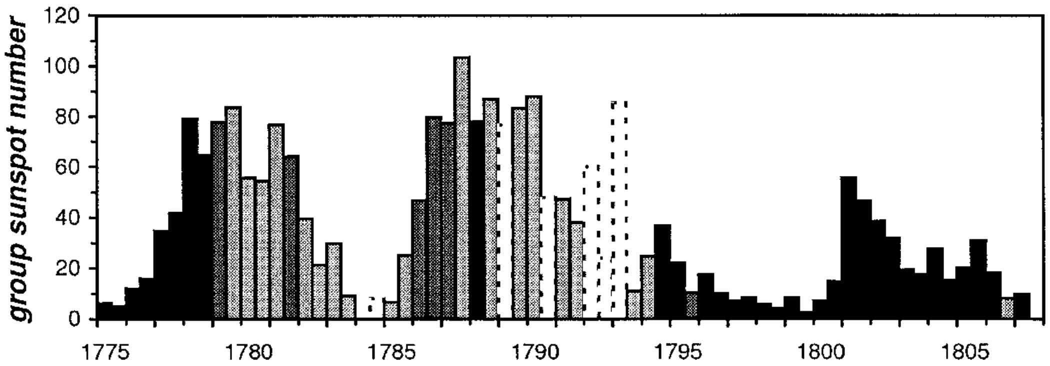
($\int R\,dt$ greater) (Gnevyshev & Ohl 1948)

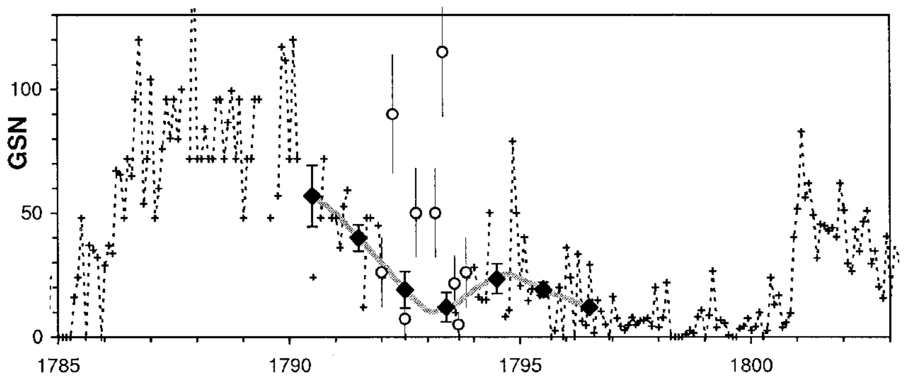
Valid for rel. sunspot numbers since cycle 10; invalid for cycle pairs 4–5 and 8–9.

Strictly valid for group sunspot no. except pair 8–9 (start of Dalton-minimum):
a phase jump occurs here.



⇒ A "lost" solar cycle between 1793–1800? (Usoskin et al. 2002)

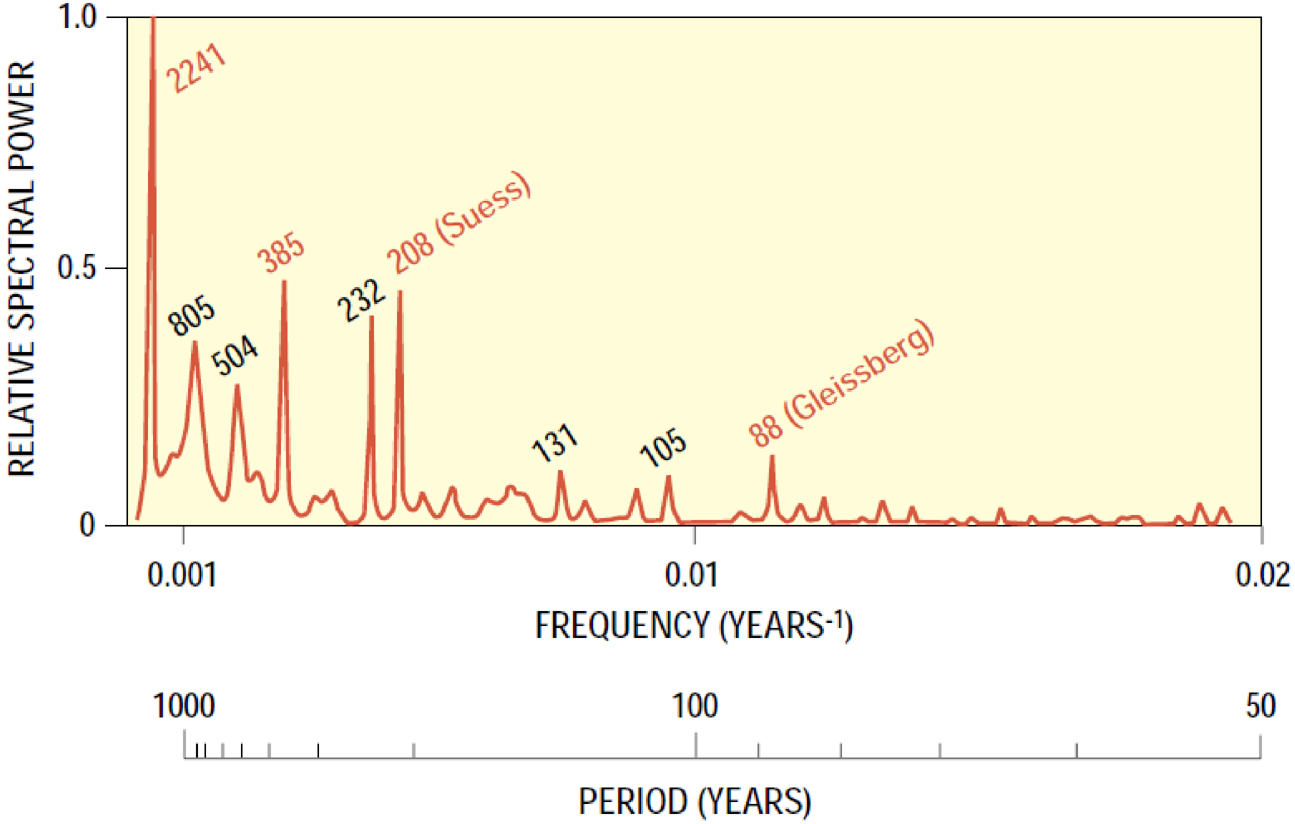




Supersecular cycles based on cosmogenic proxies:

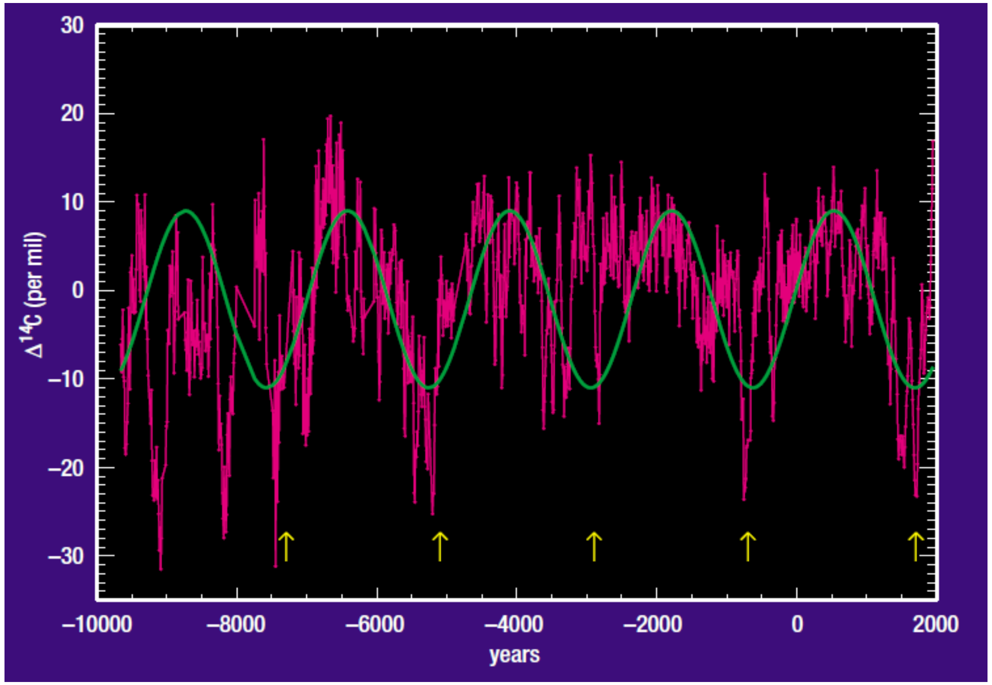
intermittent character (they only appear episodically)
their minima/maxima: grand minima/maxima

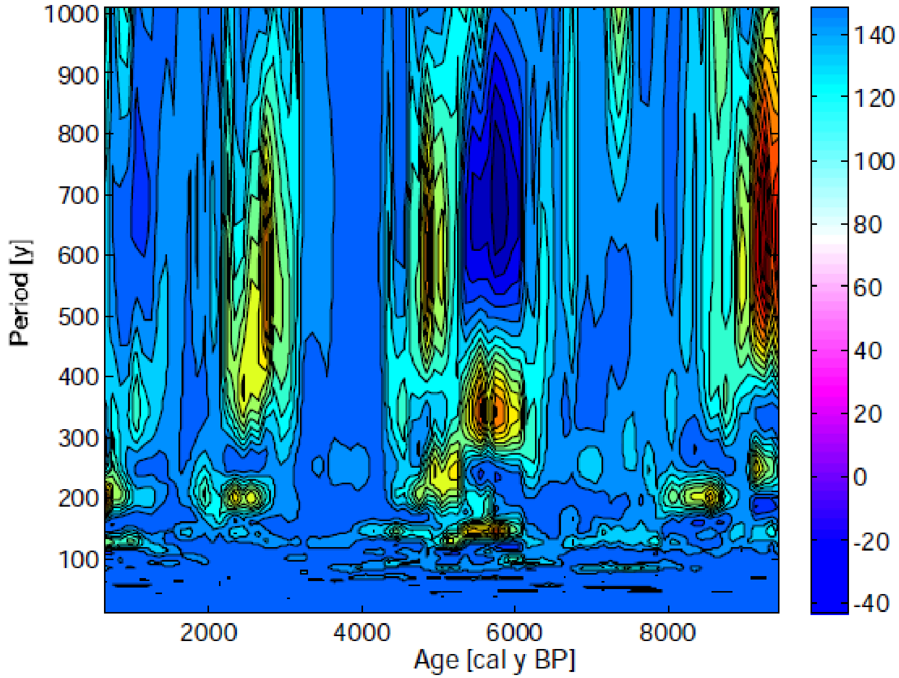
- De Vries- (or Suess-) cycle: ~ 210 yr
- $\sim 600–700$ yr cycle; cycles around 150, 350 yr?



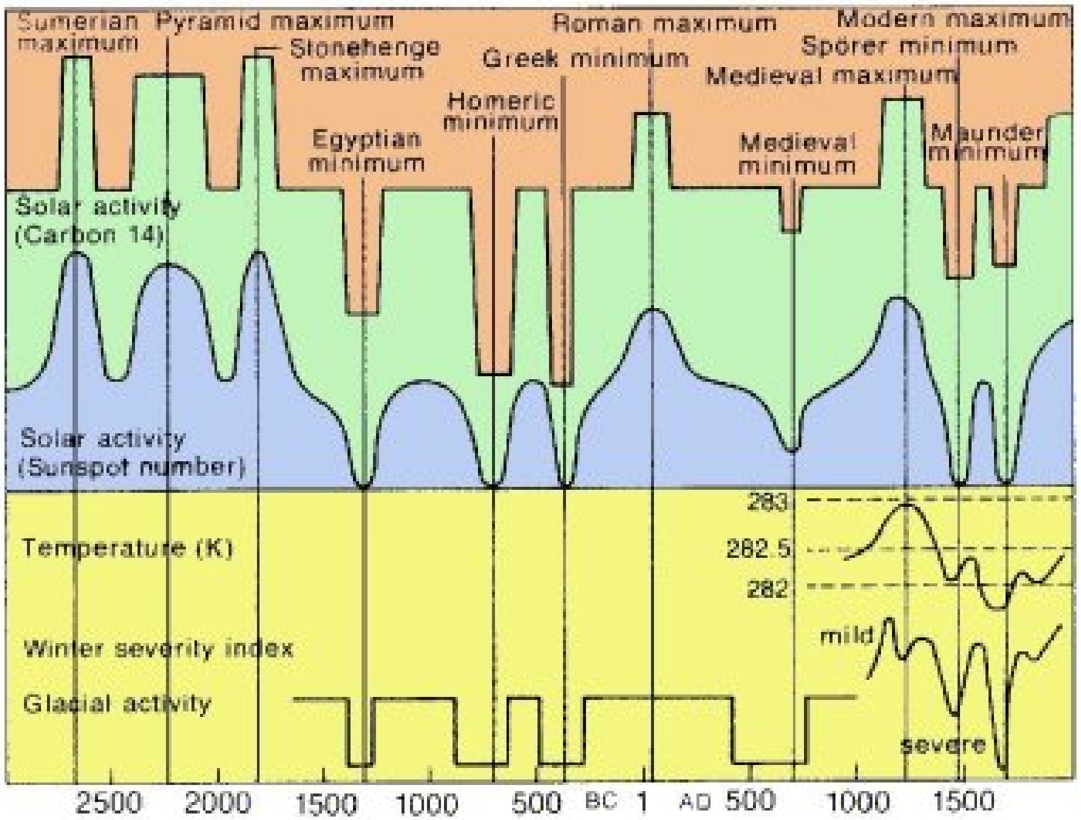
Supermodulation (aka Hallstatt cycle): ~ 2300–2500 yr:

modulates the occurrence of grand minima.

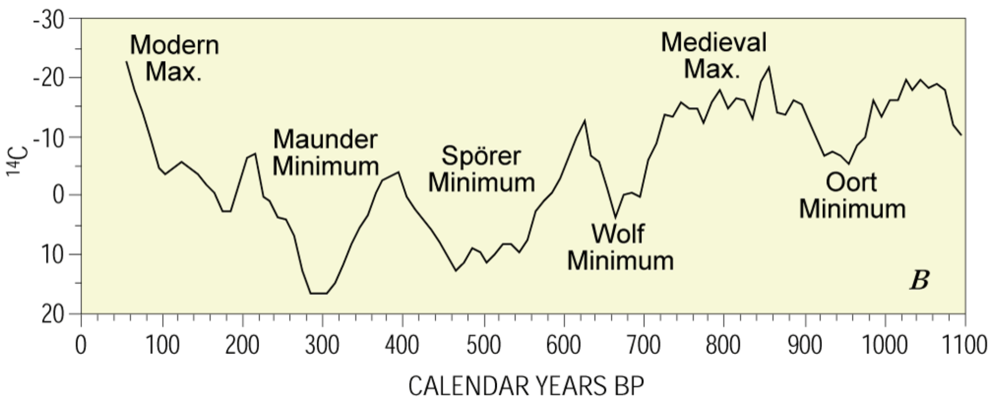




Grand minima appear in ~ 1000-year intervals around the minima of the Hallstatt cycle, recurring according to the supersecular cyclicities (McCracken & Beer 2008)



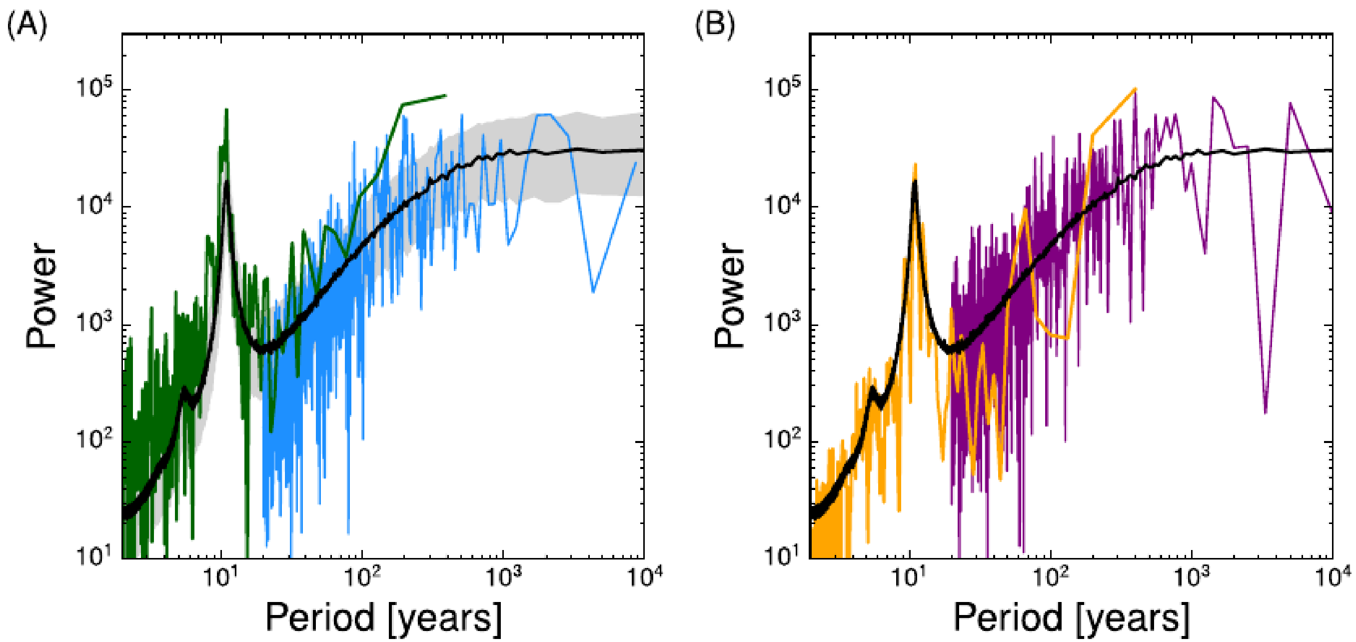
The Spörer episode:



Interpretation in terms of dynamo models

Weiss & Tobias (2016): a simple dynamo model with nonlinear coupling between dipolar and quadrupolar modes displays supersecular cycles and supermodulation.

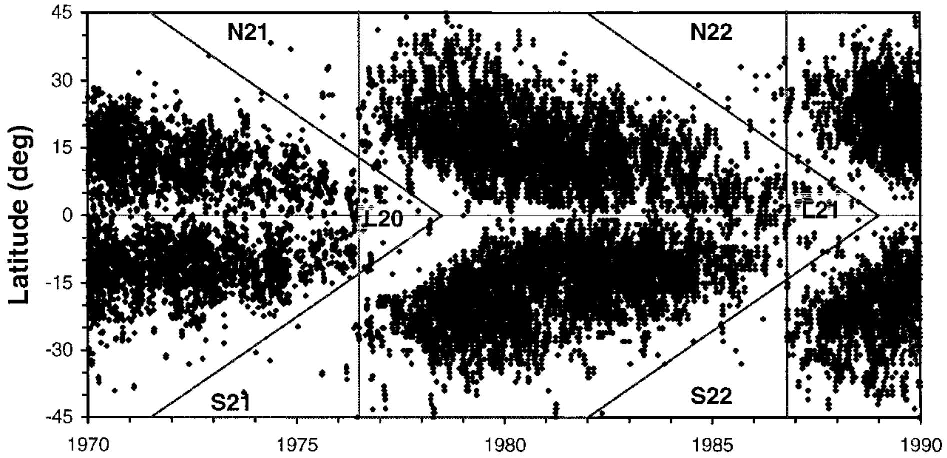
Cameron & Schüssler (2017): weakly nonlinear, truncated dynamos with stochastic forcing → a noisy limit cycle, consistent with solar observations without intrinsic periodicities:



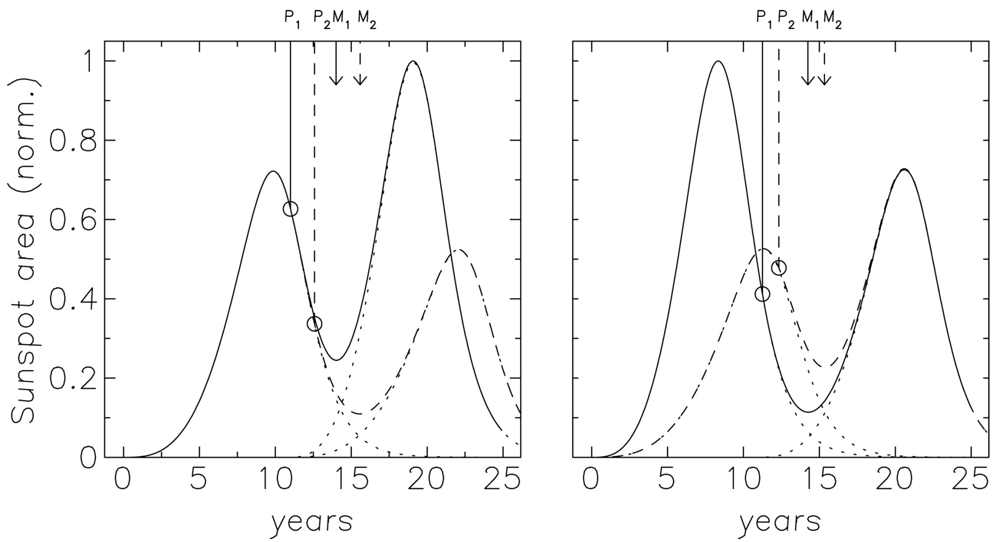
Precursor approach: instead of a homogeneous time series, consider a discrete chain of individual solar cycles.

Precursors may be due to
- temporal overlap
- interdependence between members of the chain (physical precursor)

2b CYCLE PREDICTION: PRECURSORS BASED ON CYCLE OVERLAP

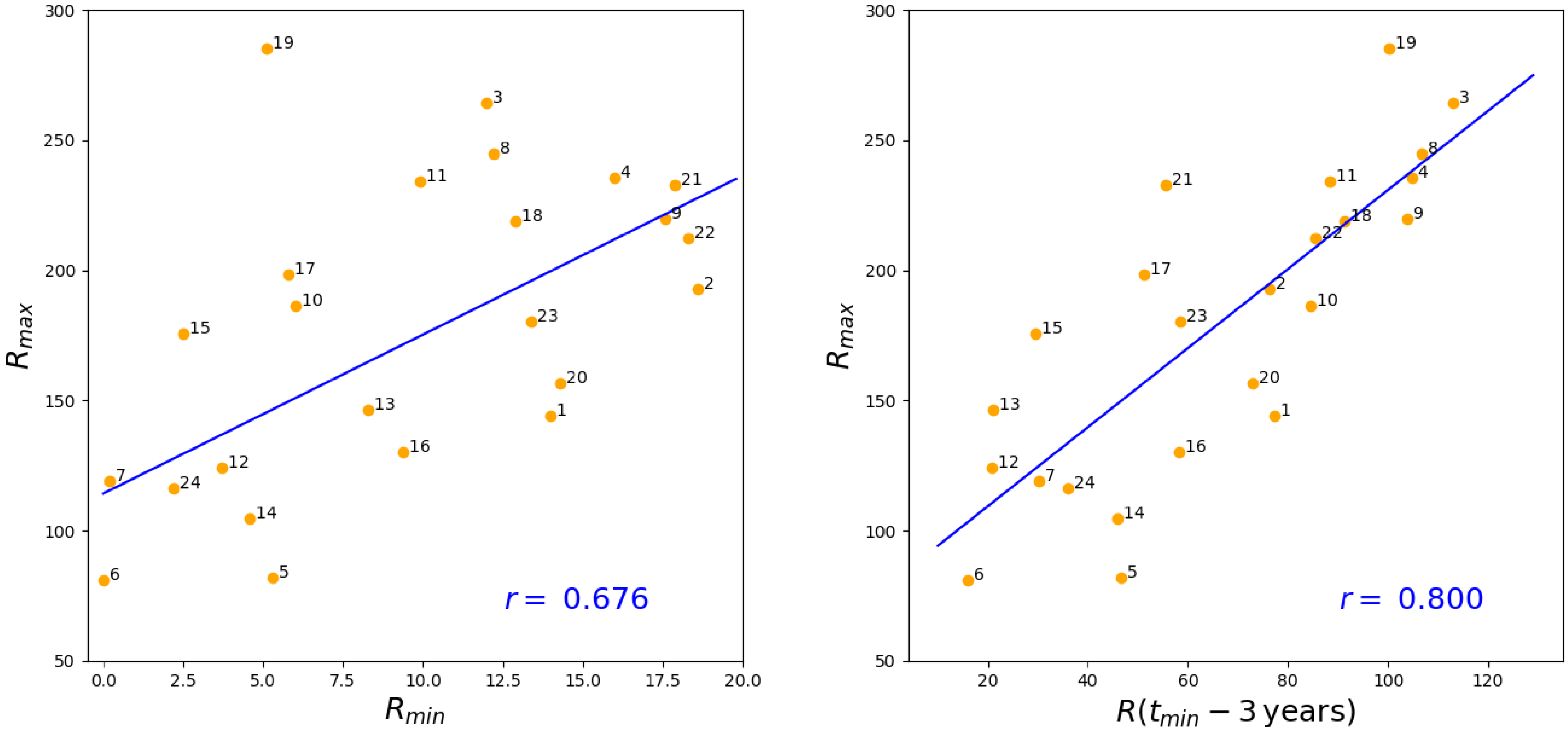


Usoskin et al. (2002)

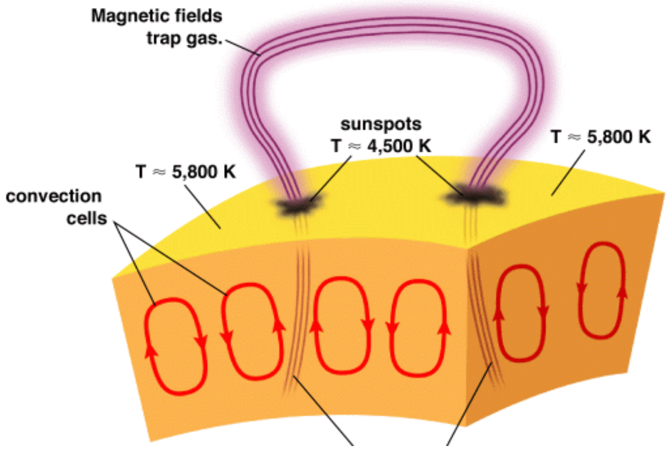


Cameron & Schüssler (2007)

Cycles overlap + stronger cycles rise steeper ⇒ "minimax" method:

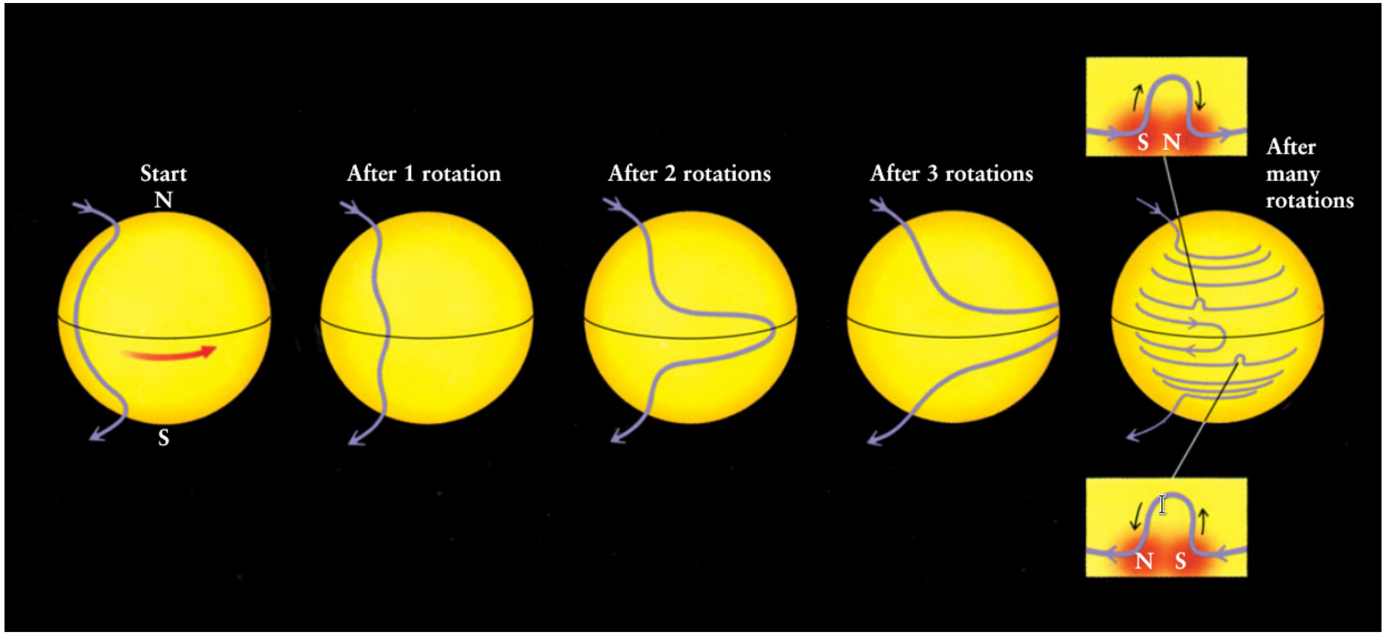


2c CYCLE PREDICTION: PHYSICAL PRECURSORS



ARs are typically bipolar and East–West oriented ⇒ the underlying field is azimuthal (toroidal).

Toriodal field is generated by differential rotation winding up an initial poloidal (dipole-like) field:



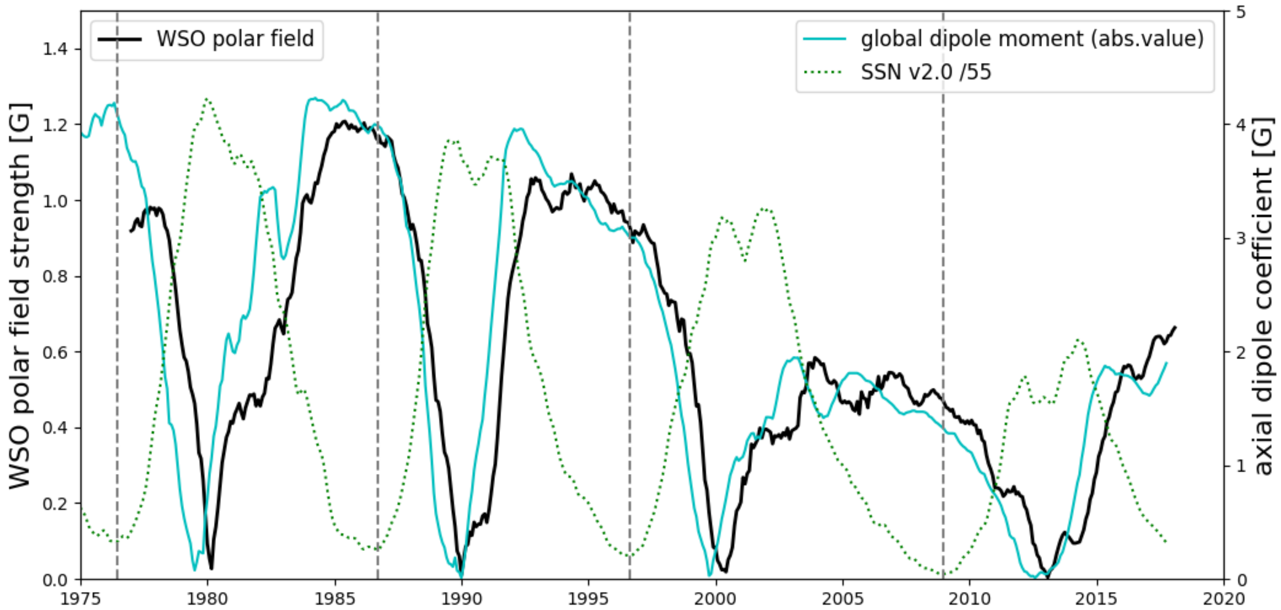
cartoon from Freedman & Kauffman 2008

THE POLAR PRECURSOR

So we expect:

toroidal flux ~ amplitude of global dipole at start of cycle (Schatten et al. 1978).

But magnetograms of the global solar magnetic field only cover the last 4 cycles:



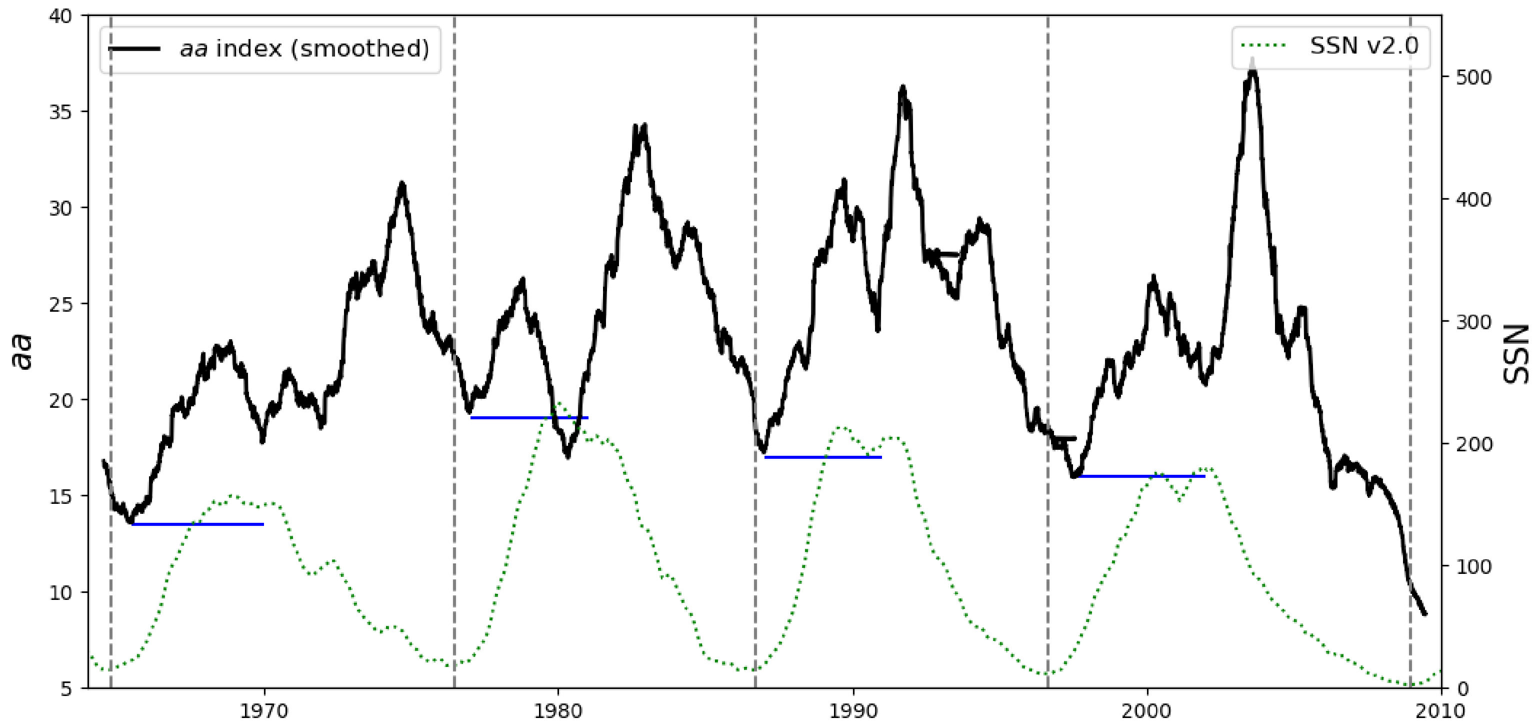
NB Dipole moment: $$D(t) = \frac{3}{4\pi} \iint B(\theta, \phi, t) \cos\theta \sin\theta \, d\theta \, d\phi$$

Proxies:

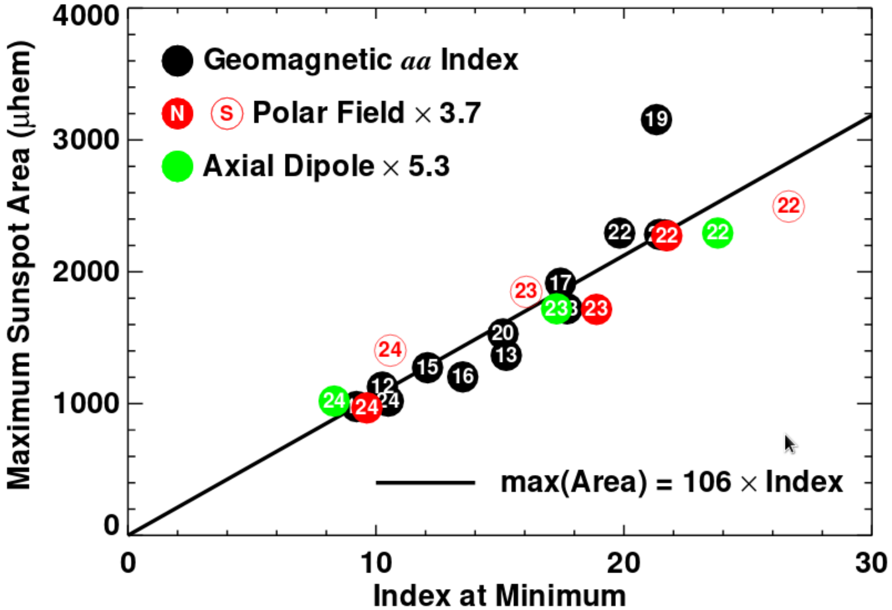
– facular records (Mt.Wilson, Kodaikanal, Pulkovo, Mitaka), since 1837

– dipole–octupole index from H_α maps, since 1915 (Makarov et al. 2001)

– geomagnetic aa iindex at solar minimum, since 1868:



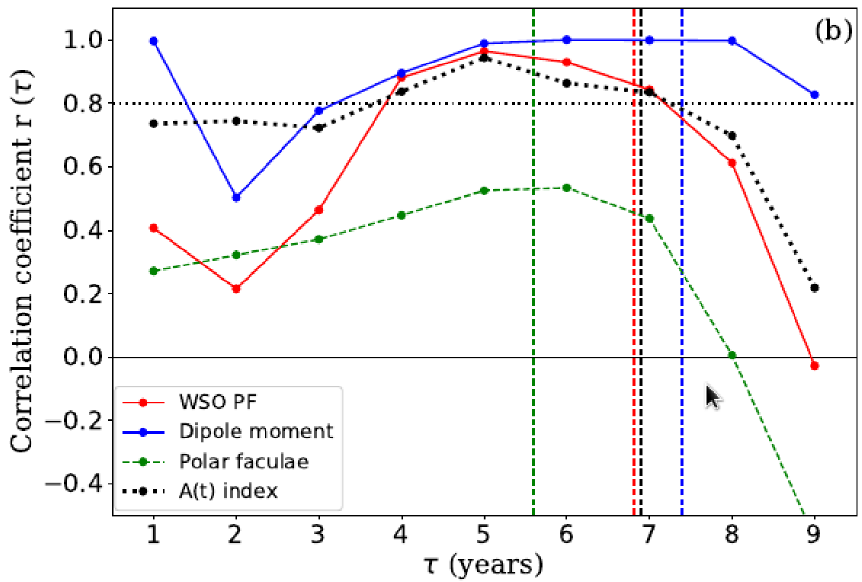
⇒ The polar precursor works:



Hathaway & Upton (2016)

But what is its temporal range? From minimum to maximum it's only 3-4 years.

Our recent study (Kumar et al. 2021): this can be extended to 7 years by evaluating it 4 years after polar field reversal:

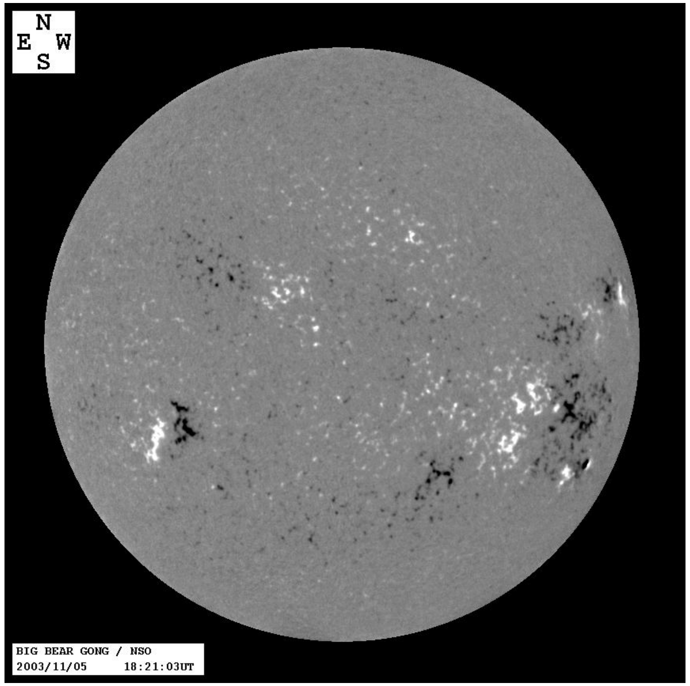


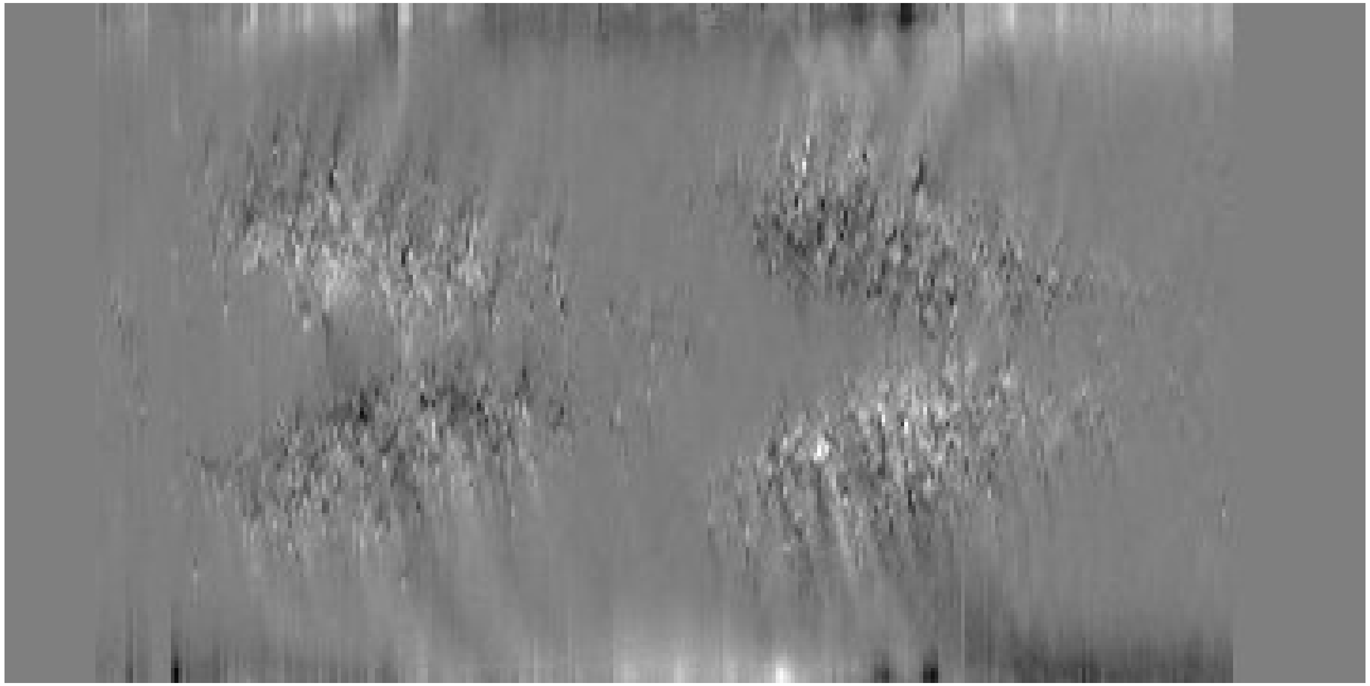
3. MODEL-BASED METHODS

SURFACE FLUX TRANSPORT (SFT)

Can we predict the precursor / understand the evolution of the solar dipole moment?

Magnetogram and magnetic butterfly diagram $\Rightarrow$ Hale rules + Joy's law:





Surface transport of emerged flux by turbulent and large-scale flows:

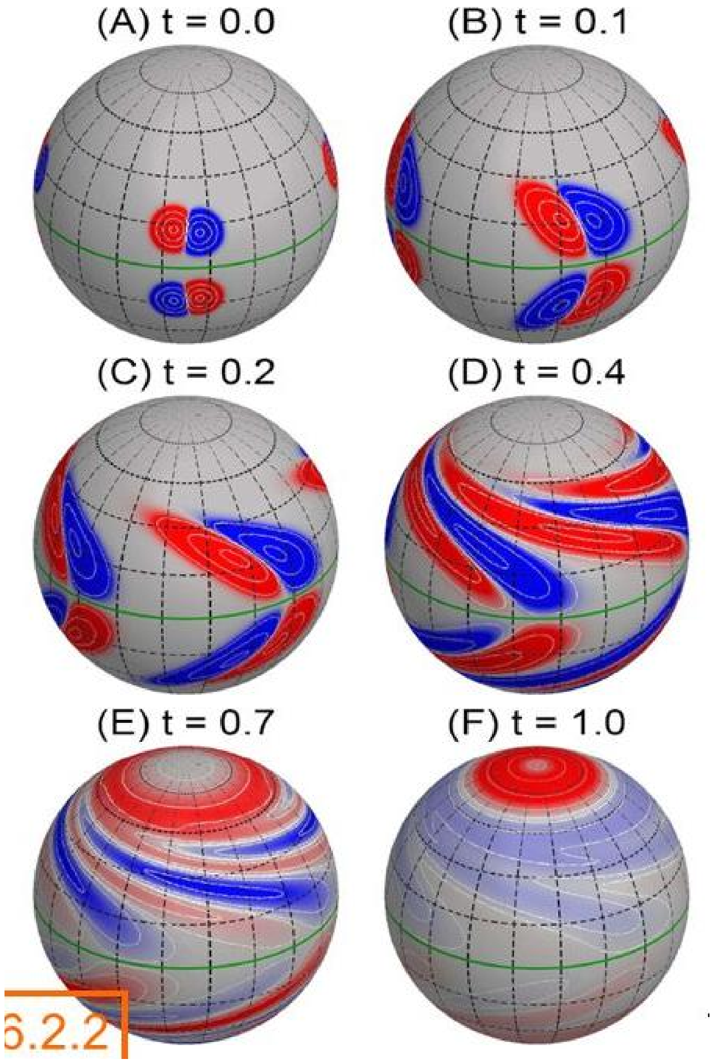
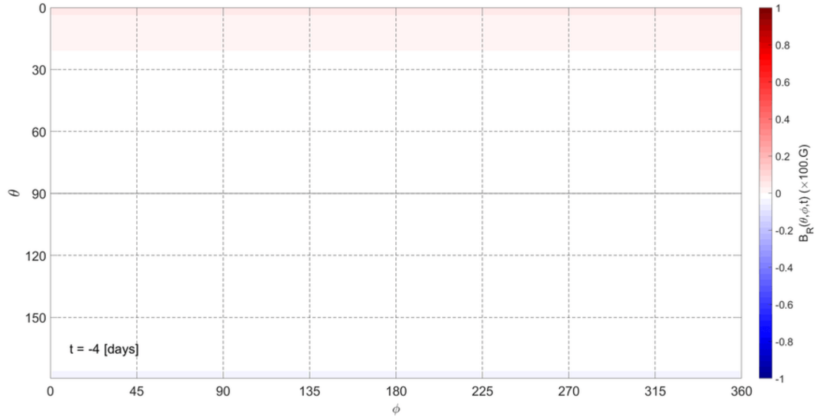
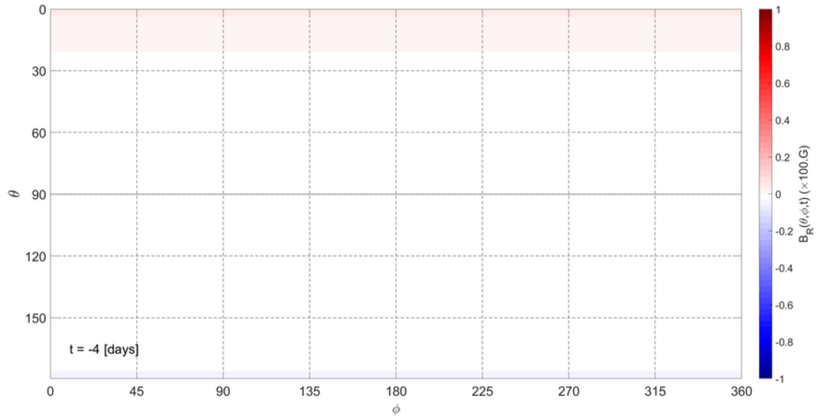


figure ©Paul Charbonneau





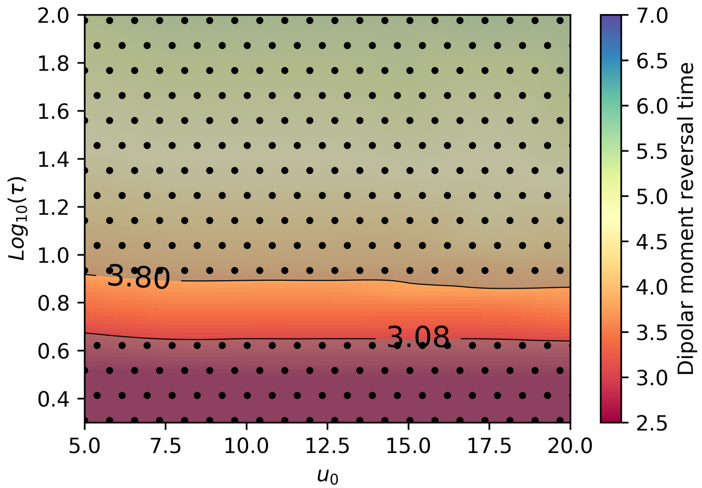
animations ©Melinda Nagy

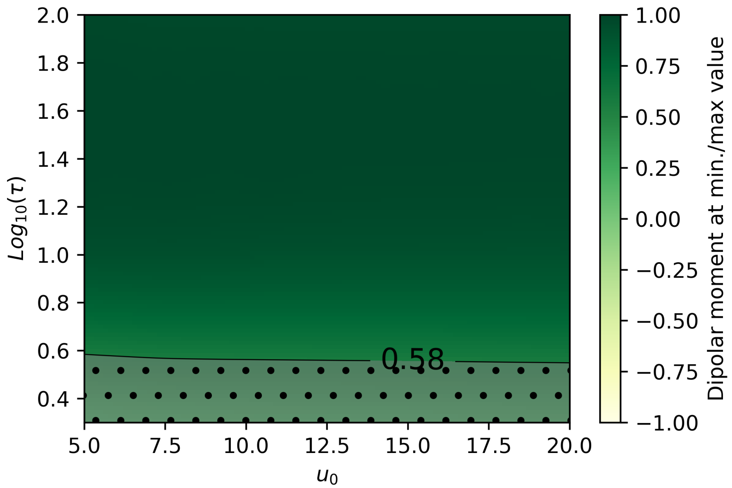
Polar field builds up from poleward transport of *unbalanced* trailing polarity AR fields, described by surface flux transport (SFT) models.

SFT equation:
$$\frac{\partial B}{\partial t} = \underbrace{-\Omega(\lambda)\frac{\partial B}{\partial \phi}}_{\text{diff.rot.}} - \underbrace{\mathbf{u}\cdot\nabla B}_{\text{merid.flow}} + \underbrace{\eta\nabla^2 B}_{\text{turb.diffusion}} - \underbrace{B/\tau}_{\text{decay due to 3D}} + \underbrace{S(\lambda,\phi,t)}_{\text{AR source}}$$

Btw. recent evidence for the need of a decay term:

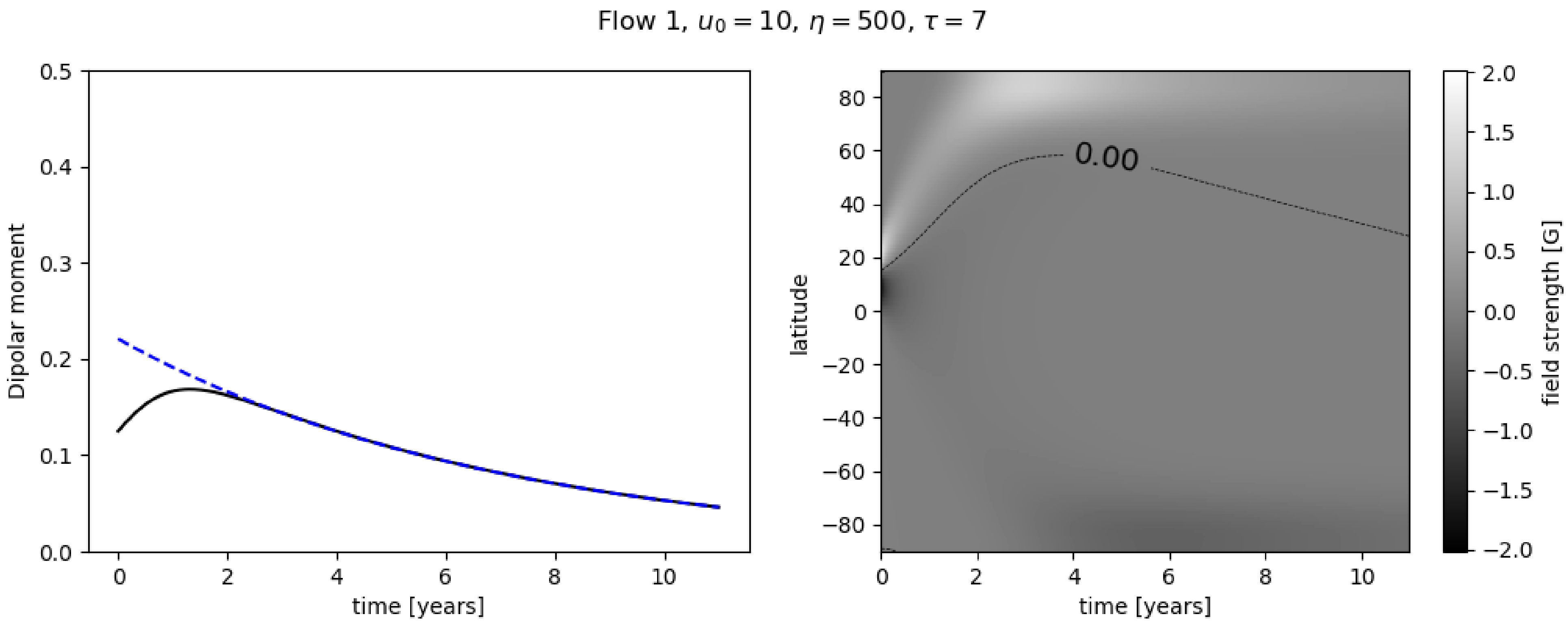
Virtanen et al. (2017), Whitbread et al. (2019), Petrovay & Talafha (2019)





Petrovay & Talafha 2019

Consider a single AR source:

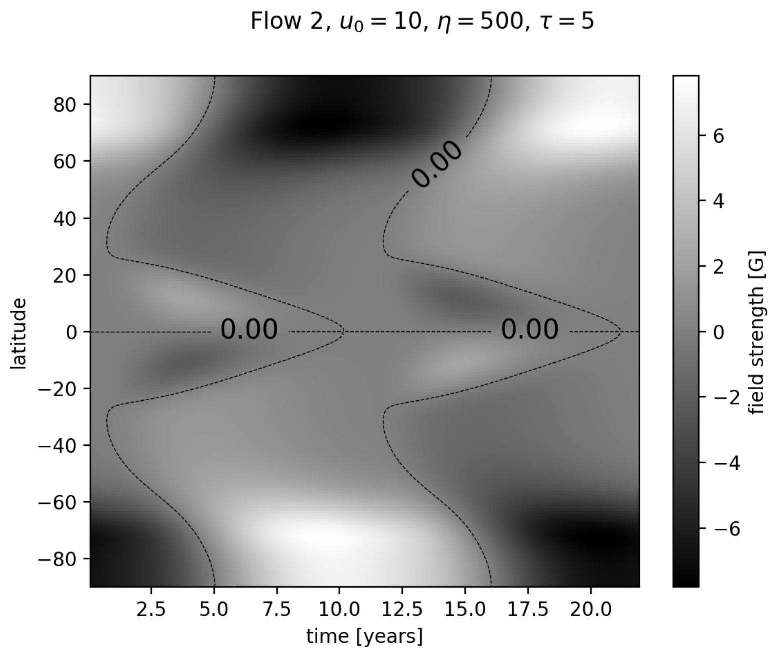


Petrovay et al. 2020

The SFT equation is linear ⇒ solutions can be superposed ⇒

⇒ polar fields are built up from the contribution of many individual AR:

ARs are responsible for the reversal of the polar field and for the buildup of new, opposite polarity polar field late in the cycle.



Polar fields serve as the seed for the toroidal field in the next cycle ⇒ amplitude of next cycle may be determined well before the minimum by considering the dipole contributions of individual AR. (Wang & Sheeley 1991)

A bipolar AR with tilt α contributes

$$\boxed{\delta D_i = \frac{3}{4\pi R^2}\Phi\, d\ \sin\alpha\ \cos\lambda}$$

$\Rightarrow$ Variations in number, Φ, λ and tilt of AR lead to intercycle variations.

Variations in AR dipole contribution may be due to

(1) systematic nonlinear feedback (e.g. tilt quenching)

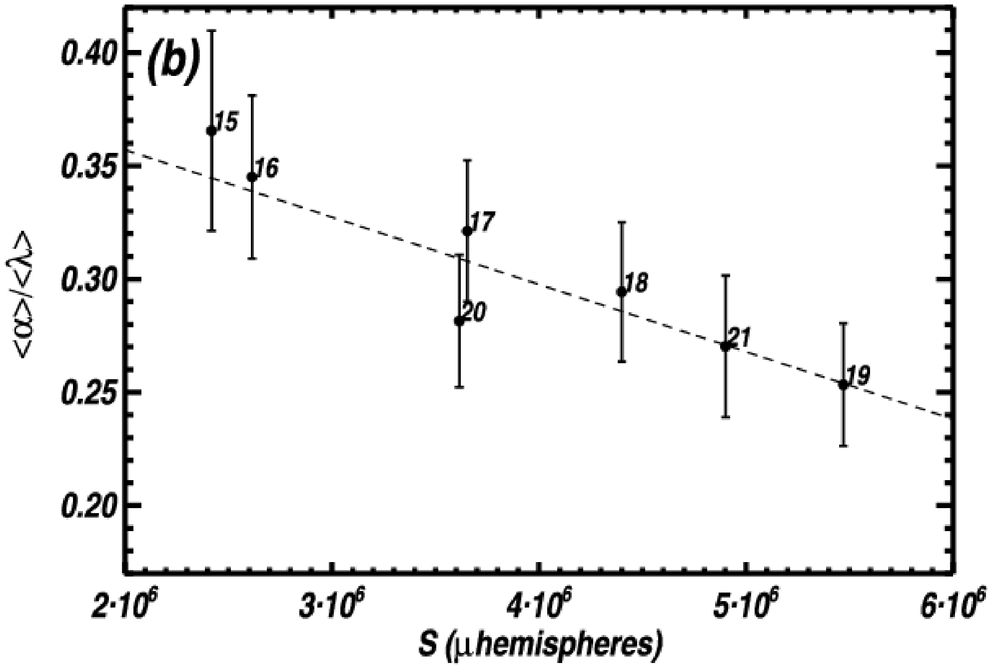
(2) random fluctuations

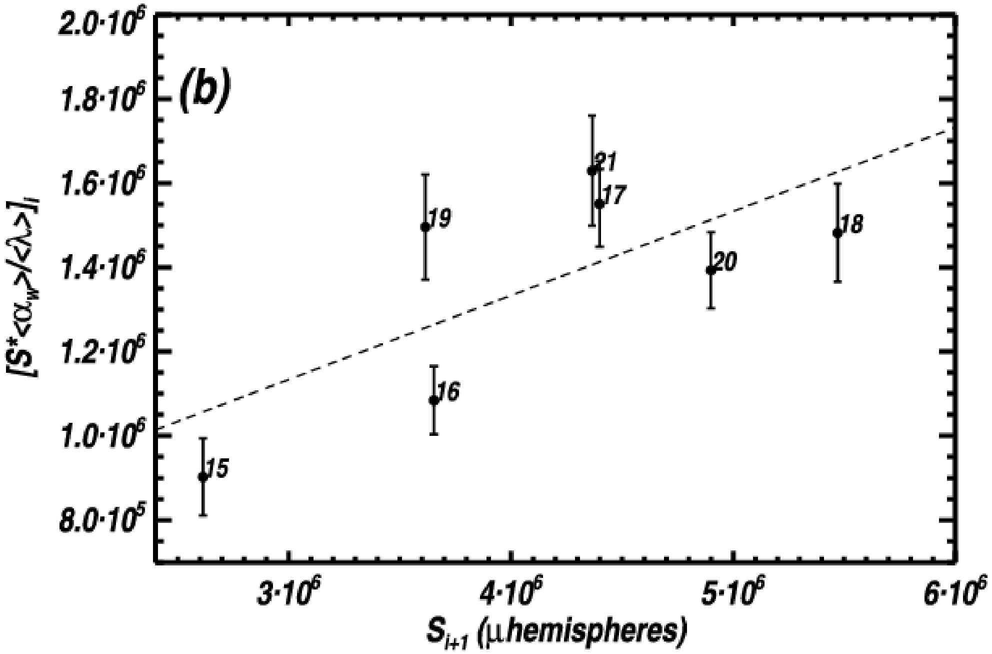
TILT QUENCHING — TILT PRECURSOR

Dasi-Espuig et al (2010):

(a) Stronger cycles – lower tilt.

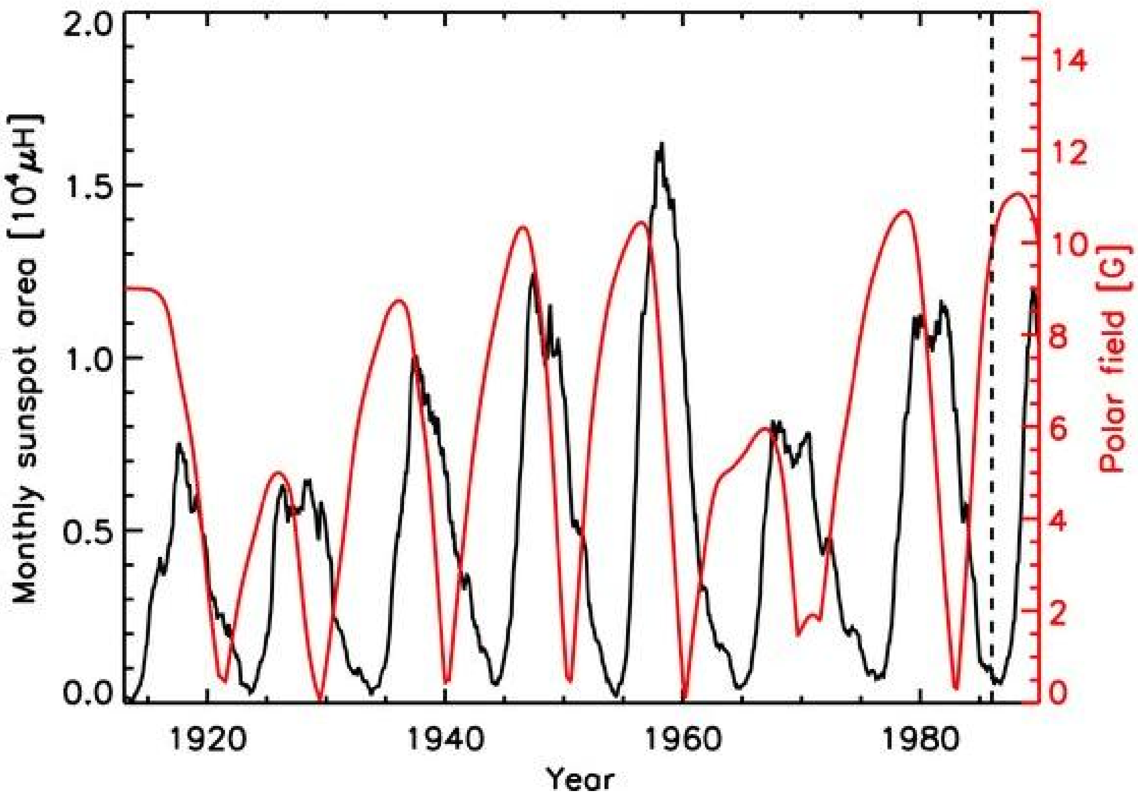
(b) Tilt $\times$ amplitude $\Rightarrow$ next cycle ampl.





Gives rise to idea of "tilt quenching" — a nonlinear feedback mechanism governing cycle to cycle variations.

Effect incorporated into SFT model: Cameron et al. (2010)



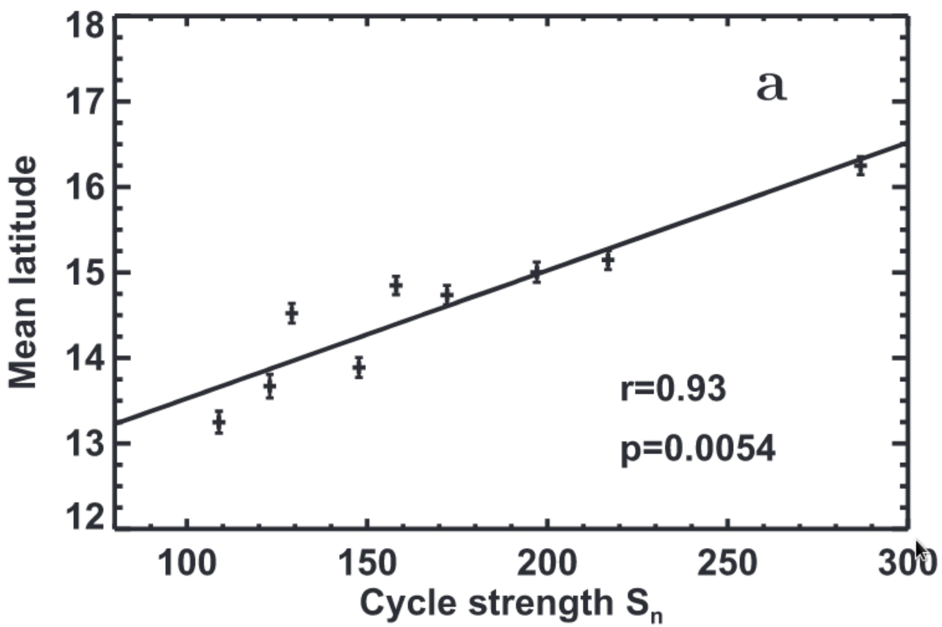
Explained by variations in meridional inflow pattern:

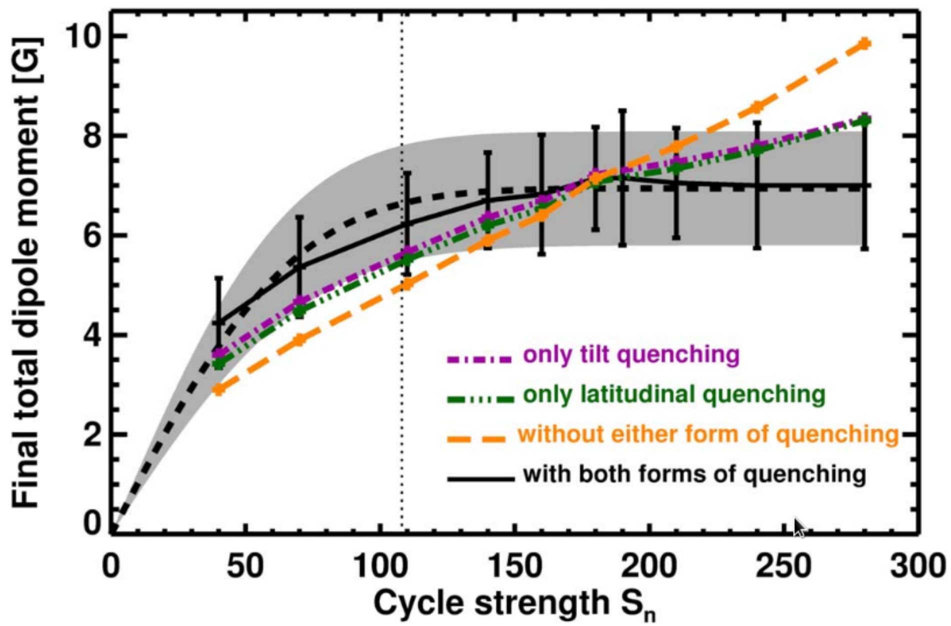
Cameron & Schüssler (2012), Martin-Belda & Cameron (2018)

Surface flux transport (SFT) models with tilt quenching reproduce observed variations in polar field well — except cycle 24

LATITUDE QUENCHING

More robust evidence than for tilt quenching:

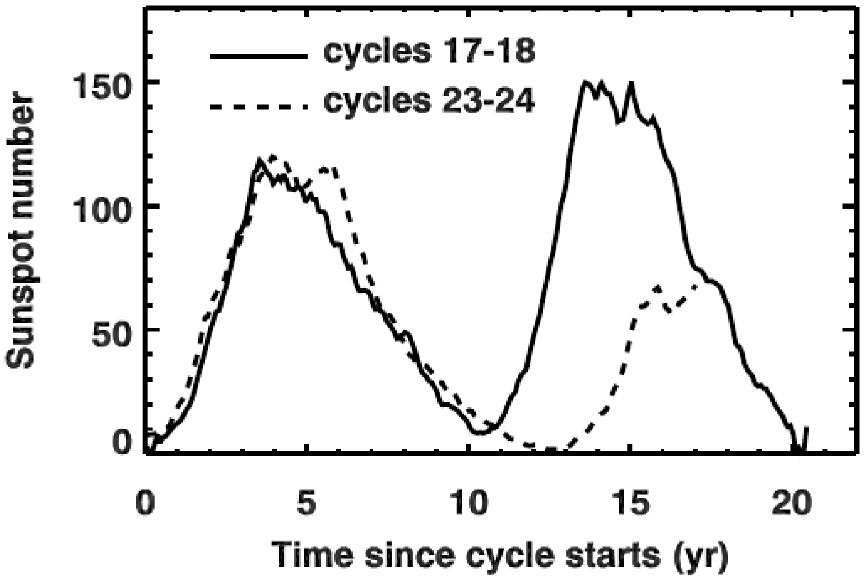


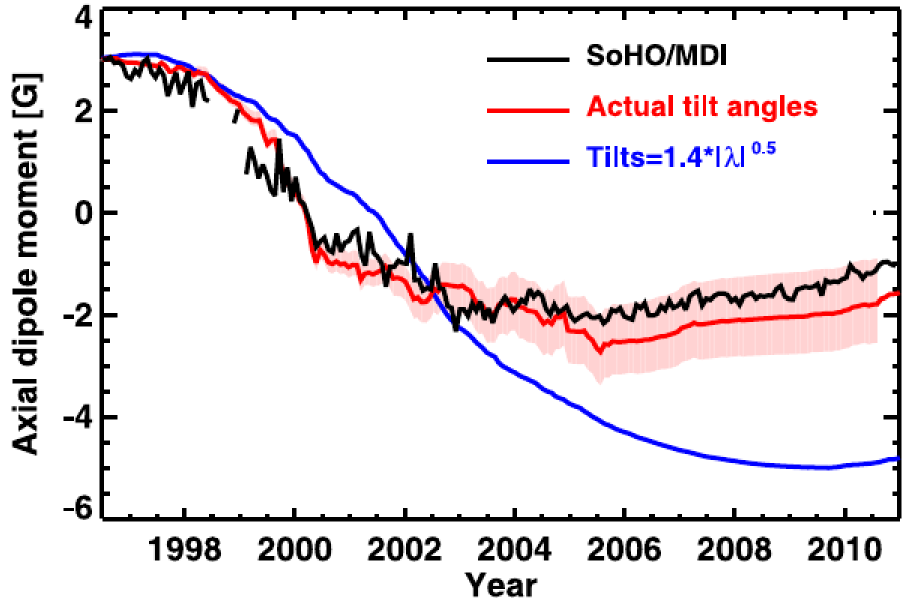


Jiang (2020)

RANDOM FLUCTUATIONS AND ROGUE ACTIVE REGIONS

Effect of scatter in Joy's law considered by Jiang et al. (2014).





Jiang et al. (2015)

Random fluctuations in Joy's law $\Rightarrow$ unpredictable deviations.
Cycle 23/24 explained as a 2σ fluke due to rogue low-latitude ARs.
Theoretical background: Cameron & Schüssler (2015)

Total poloidal flux $\sim$ surface flux $\Rightarrow$ a single large AR can make a difference

A bipolar AR contributes $\delta D_{\mathrm{BMR}} \approx F\, d\, \sin\alpha\, \sin\theta$

$\Rightarrow$ to make a difference, an AR needs to be

– large
– unusually tilted (esp. non-Joy/non-Hale — or very "overJoy")
– at low latitudes

Such "rogue" active regions can play havoc with the cycle.

(Cameron et al. 2013; Nagy et al. 2017)

Adjective [edit]

rogue (*comparative* **more rogue**, *superlative* **most rogue**)

1. (*of an animal, especially an elephant*) Vicious and solitary.
2. (*by extension*) Large, destructive and unpredictable.
3. (*by extension*) Deceitful, unprincipled. [quotations ▼]
4. Mischievous, unpredictable. [quotations ▼]

$\Rightarrow$ form of SFT source term is crucial! $\Rightarrow$ role of dynamo models

COMBINING THE FLUX TRANSPORT DYNAMO WITH SFT MODELS

3D models combining BL/FT dynamo with SFT models:

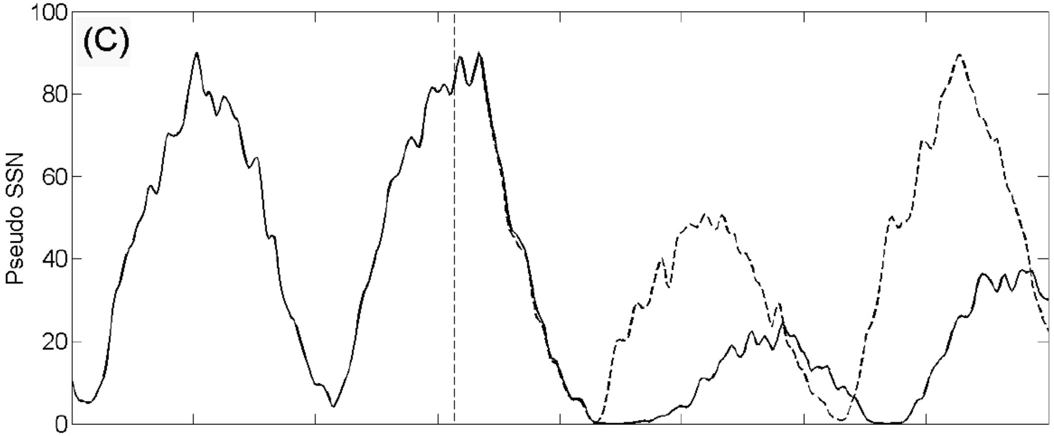
– Yeates (Yeates & Munoz-Jaramillo 2013; Yeates, Baker & van Driel-Gesztelyi 2015)

– STABLE model (Miesch & Dikpati 2014; Miesch & Teweldebirhan 2015)

– 2×2D model: carefully fine-tuned to Sun + numerically efficient

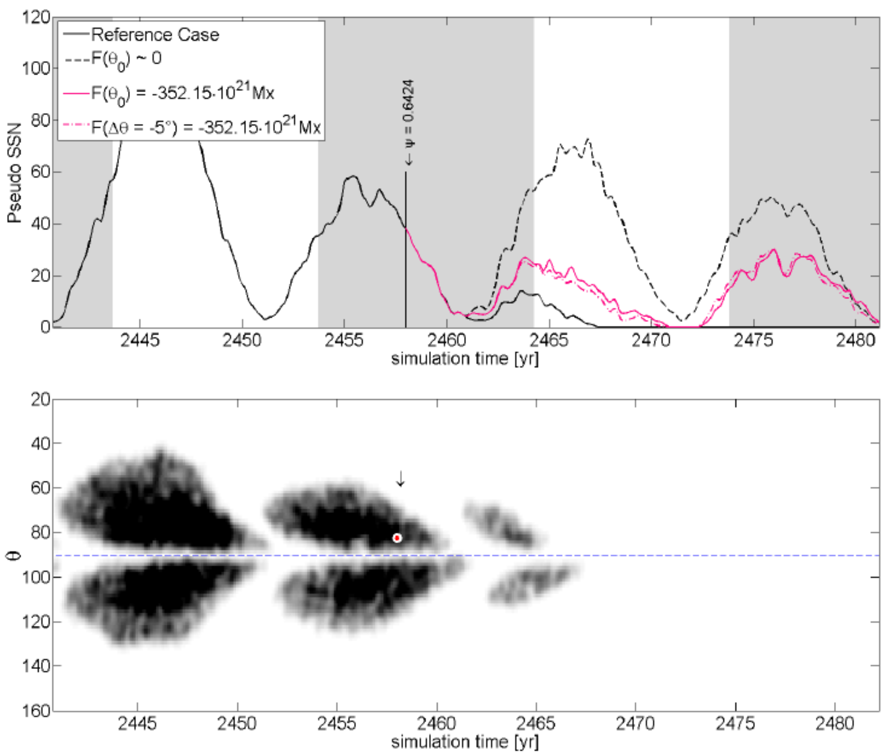
(Lemerle & Charbonneau 2015, 2016)

Nagy et al. (2017): Removing a single AR can change the course radically:



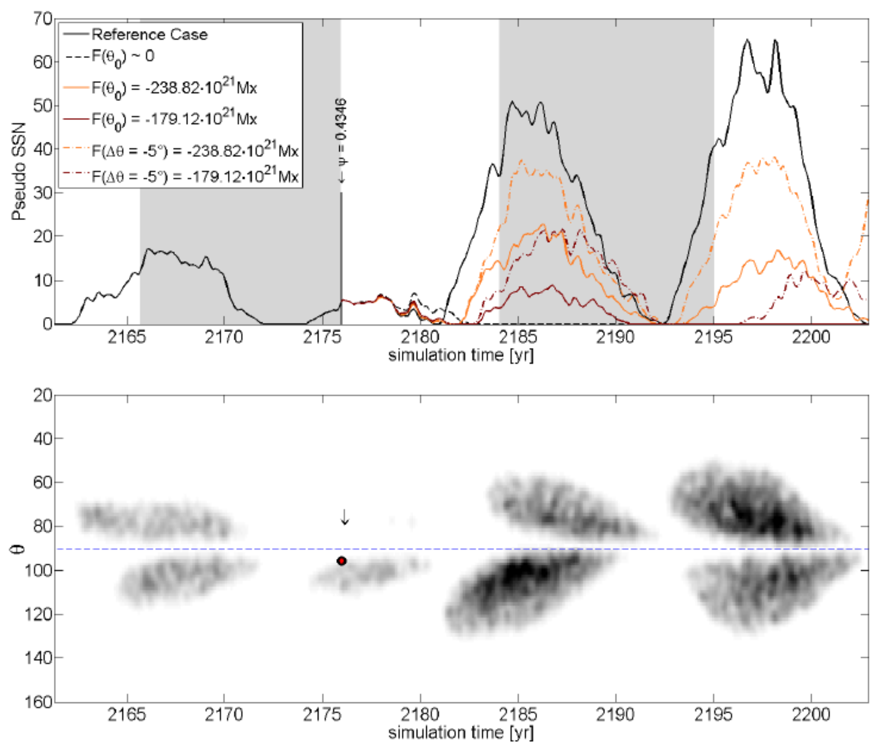
Anti-Joy, $F = 2.4 \cdot 10^{23}$ Mx, $d = 31°, \Phi = 3°$

The spot that killed the dynamo:



Anti-Joy, $F = 7 \cdot 10^{23}$ Mx, $d = 20°$, $\Phi = 5.5°$

The spot that saved the dynamo:



Over-Joy, $F = 4 \cdot 10^{23}$ Mx, $d = 32°$, $\Phi = -10°$

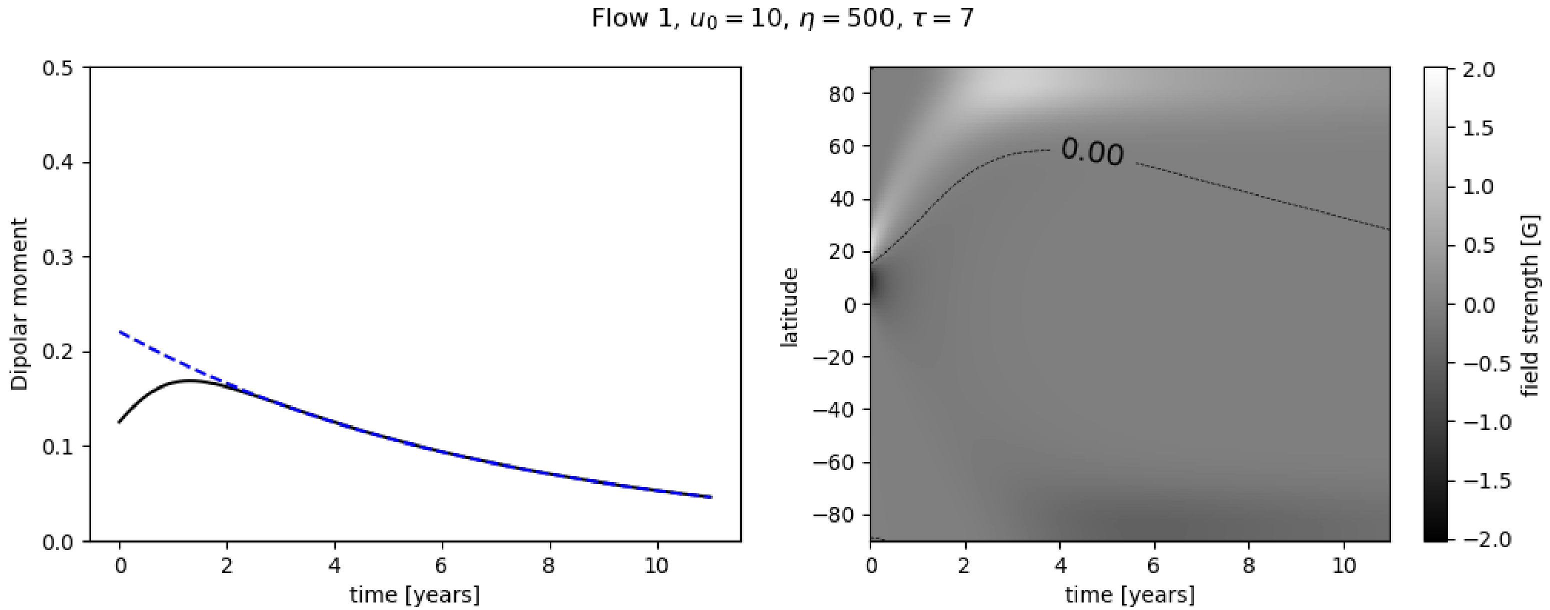
Nagy et al. 2017

WHAT MAKES A ROGUE AR?

A bipolar AR contributes

$$\boxed{\delta D_1 = \frac{3}{4\pi R^2}\Phi\, d\, \sin\alpha\, \cos\lambda}$$

δD_1 is only the *initial* dipole contribution.
To evaluate final contribution δD_f, SFT is needed:

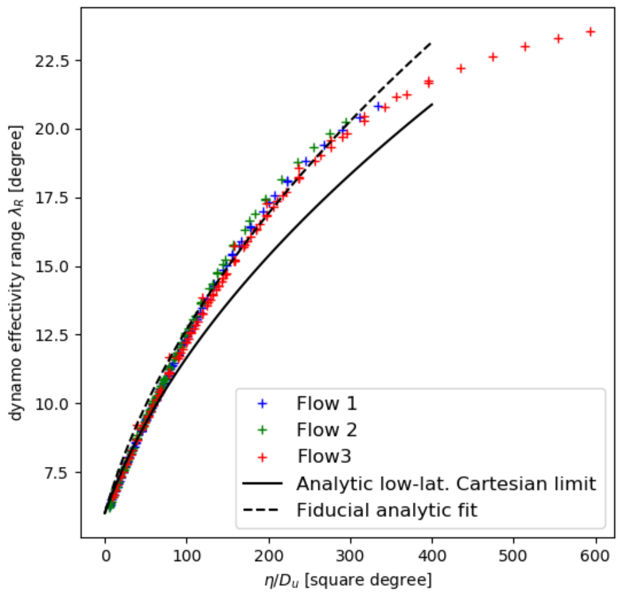


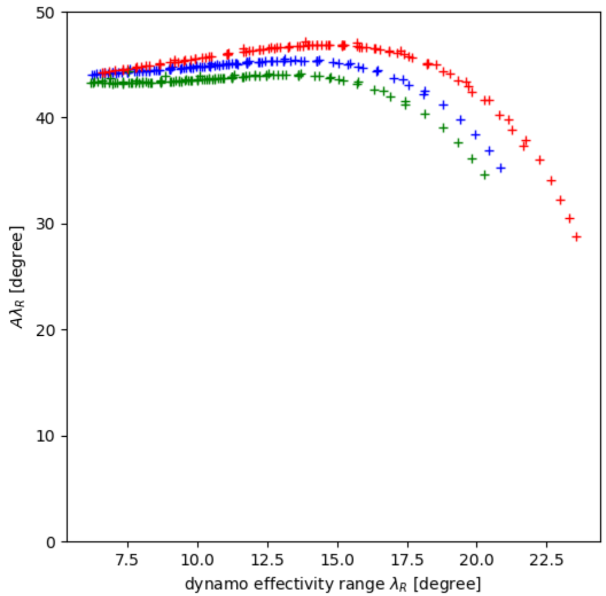
For the asymptotic dipole contribution factor $f_\infty = \delta D_\infty / \delta D_1$ an asymptotic analytic formula was derived by Petrovay, Nagy & Yeates (2020):

$$f_\infty = \frac{a}{\lambda_R} \exp - \frac{\lambda_0^2}{2\lambda_R^2} \qquad \text{with} \qquad a = \left(\frac{2}{\pi}\right)^{1/2} \frac{n+1}{n+2} \qquad n \simeq 8.$$

This Gaussian latitude dependence was first noted by Jiang et al. (2014) in a numerical study.

The dynamo effectivity range λ_R and the amplitude factor show a universal dependence on SFT parameters:



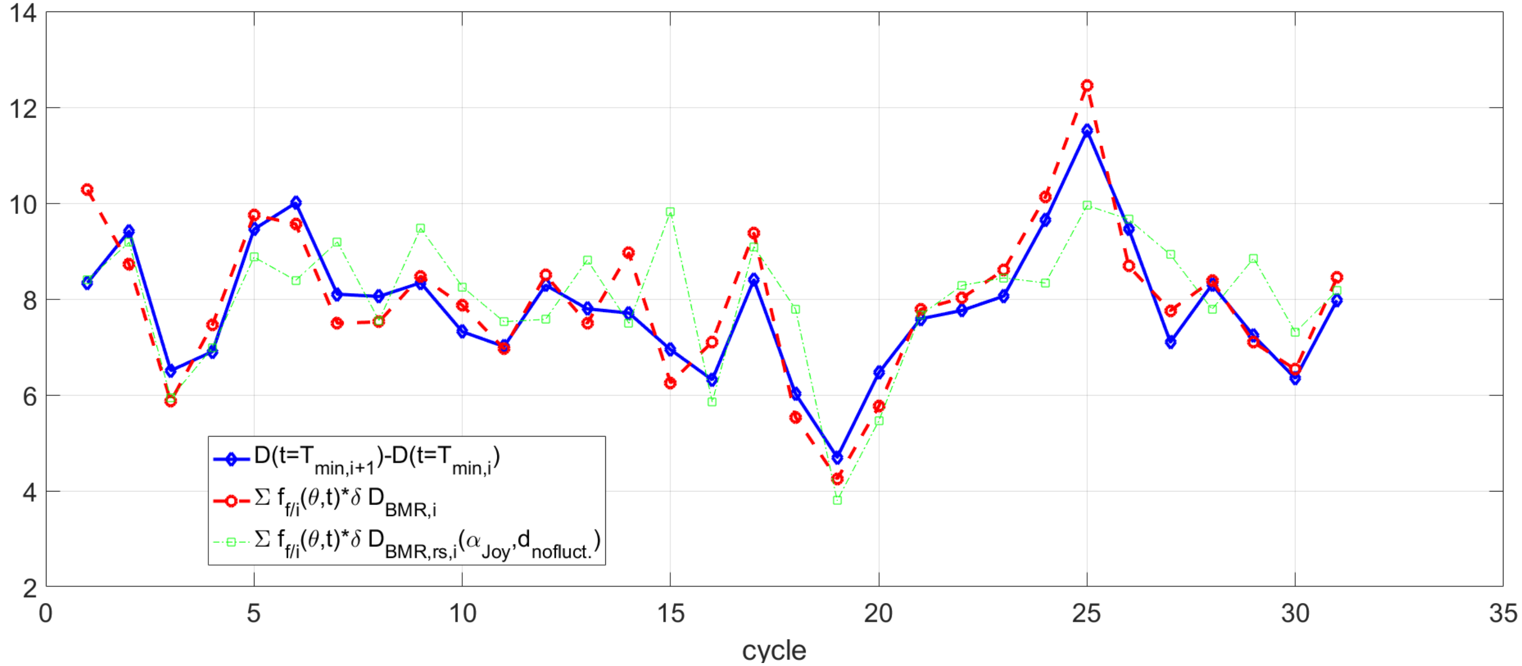


⇒ solution of the SFT partial diff.eq. can be bypassed and substituted by an algebraic summation

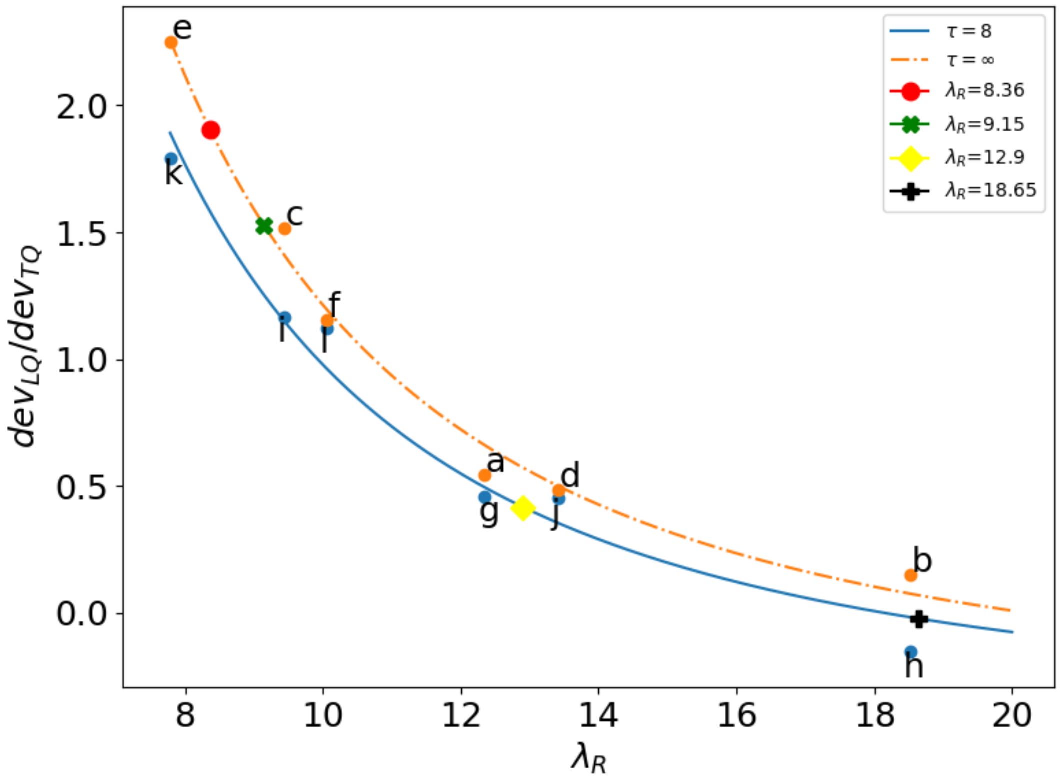
$$D_{n+1} - rD_n = \sum_{i=1}^{N_{\rm tot}} f_{\infty,i}\, \delta D_{1,i}\, e^{-(t_{n+1}-t_i)/\tau} \qquad r = e^{-(t_{n+1}-t_n)/\tau}$$

Only 3 parameters — no need to worry about the choice of a flow profile!

f_{fi} comes from a 1D SFT model but confirmed in a comparison with the 2D SFT component of the 2×2D dynamo model (Lemerle et al. 2017):



SFT model grid with different param.combinations, fitted to observed typical cycles:
$\Rightarrow$ relative importance of tilt quenching vs. latitude quenching determined by λ_R:



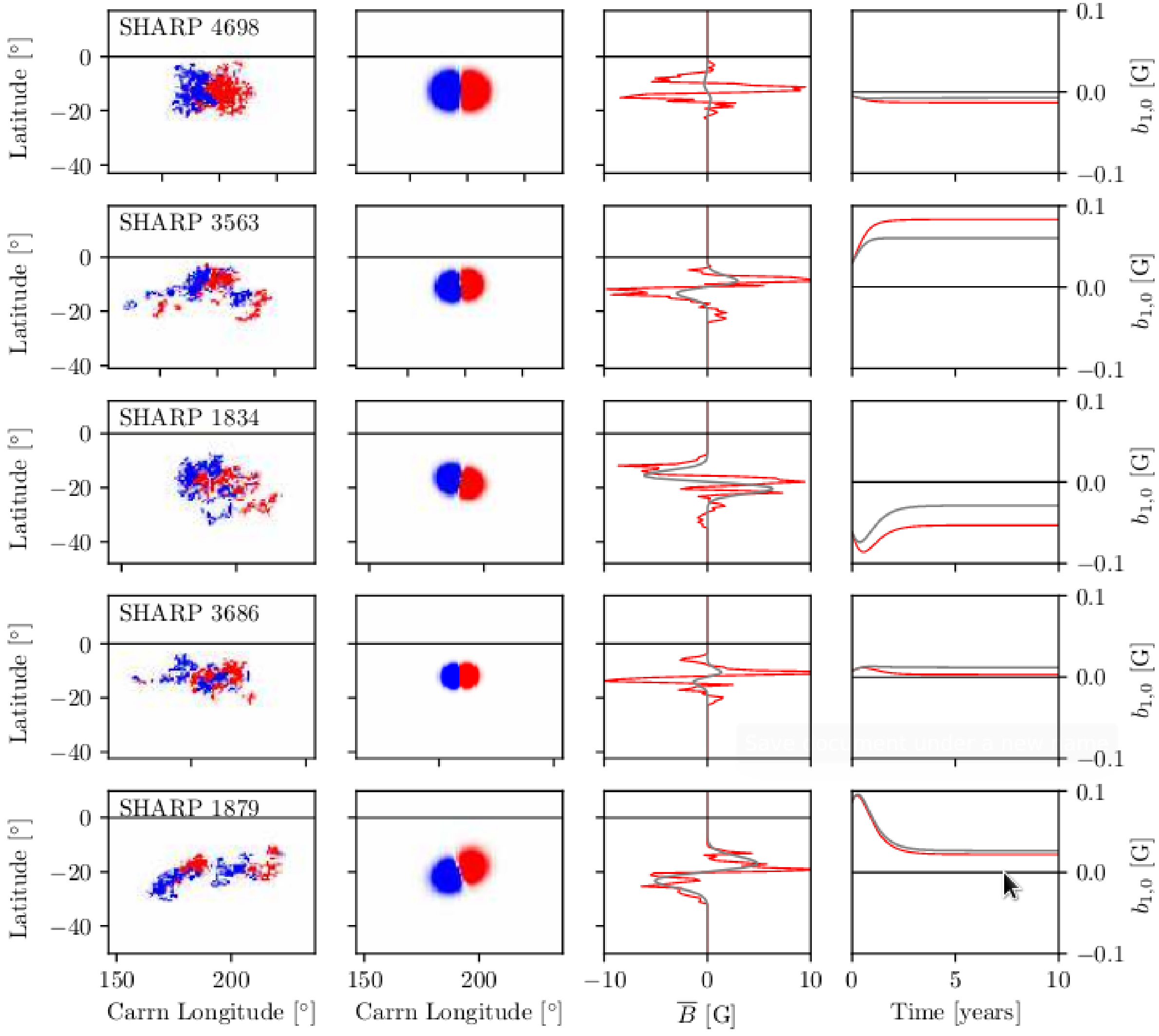
Talafha et al. (2022)

Form of dependence agrees with analytic result based on the algebraic method:

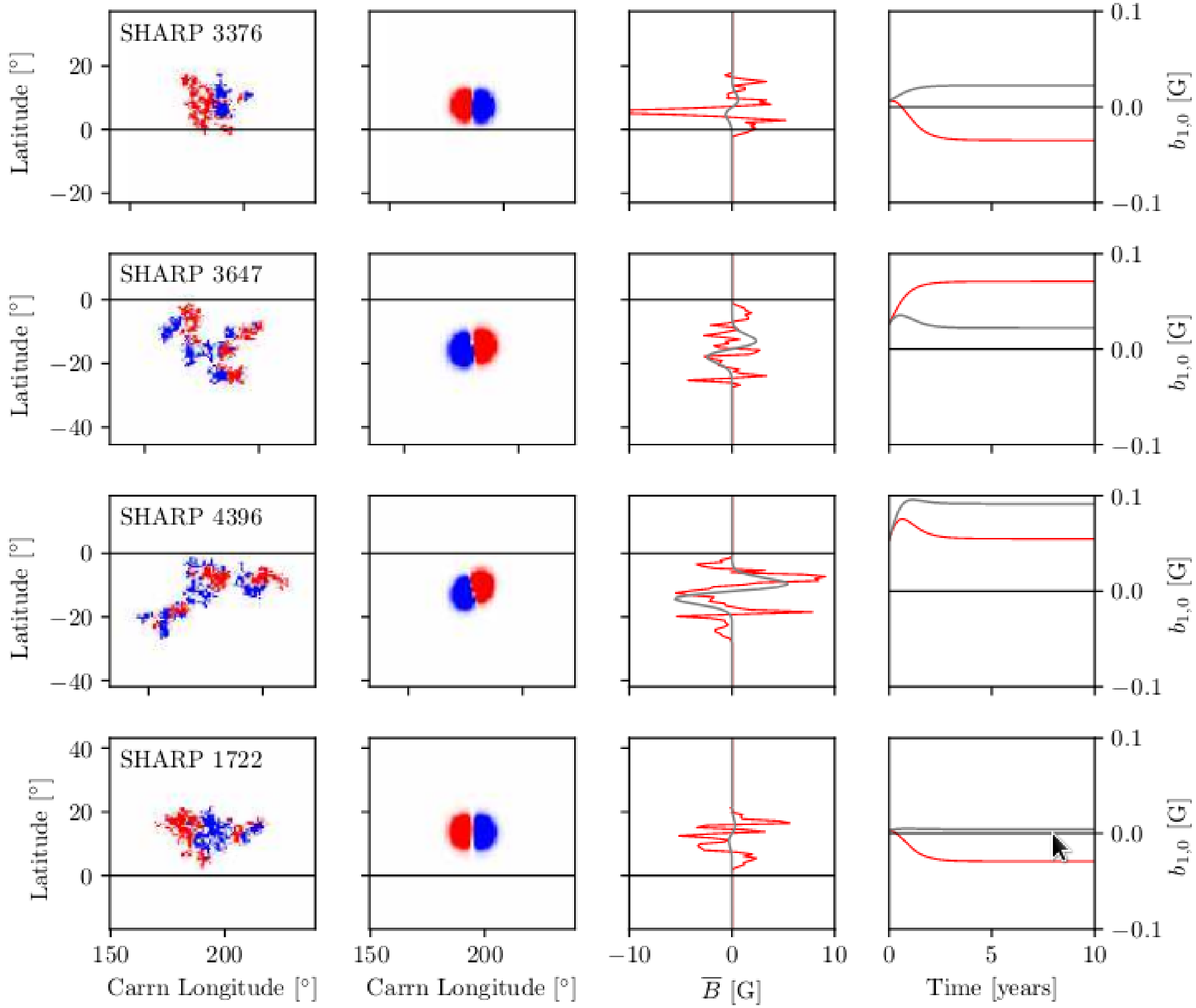
$$\boxed{\mathrm{dev}_{LQ}/\mathrm{dev}_{TQ} \sim C_1(\overline{\lambda_0}) + C_2(\overline{\lambda_0})/\lambda_R^2}$$

Yeates (2020): Extract azimuthally averaged B for HARPS regions; feed into SFT.

The 4 biggest regions:



In some cases, major discrepancies:



SUMMARY

Linear time series approach:

– periodicities may or may not be real
– if real, may be useful for predicting secular ($\gtrsim 50$ yr) variations
– but cycle-to-cycle variations are dominated by nonlinear and stochastic effects
– G-O rule an open issue

Nonlinear time series approach: dubious validity, unless maybe carefully formulated

– time series of SSN may not contain all the necessary information
– stochastic noise with non-Gaussian stats

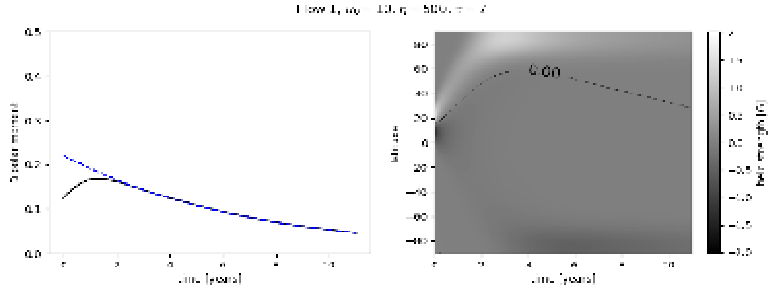
Precursors work well when evaluated around cycle minimum.

(may also work 4 years after reversal, cf. Kumar et al. 2021)
Range 3–4 years, possibly up to 7.

Model-based approach is needed for longer term forecasts :

an area of active research.

THE UNDERLYING MECHANISM



Poloidal source

(AR dipole contribution)

Surface flux transport

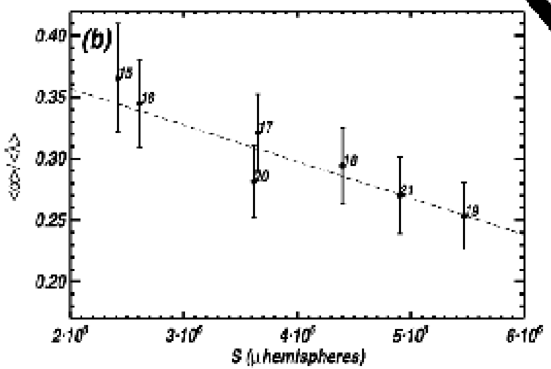
Polar field

Nonlinearities

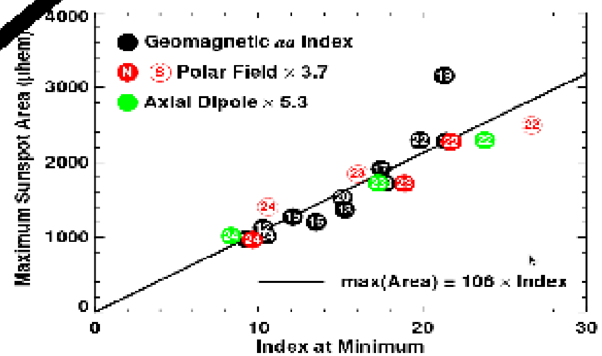
+ fluctuations

Linear

amplification



Toroidal field



Model-based approaches:

– SFT modelling with modelled source term
– Nonlinear, stochastically forced dynamo models incorporating inidividual ARs (or at least their rough representation)

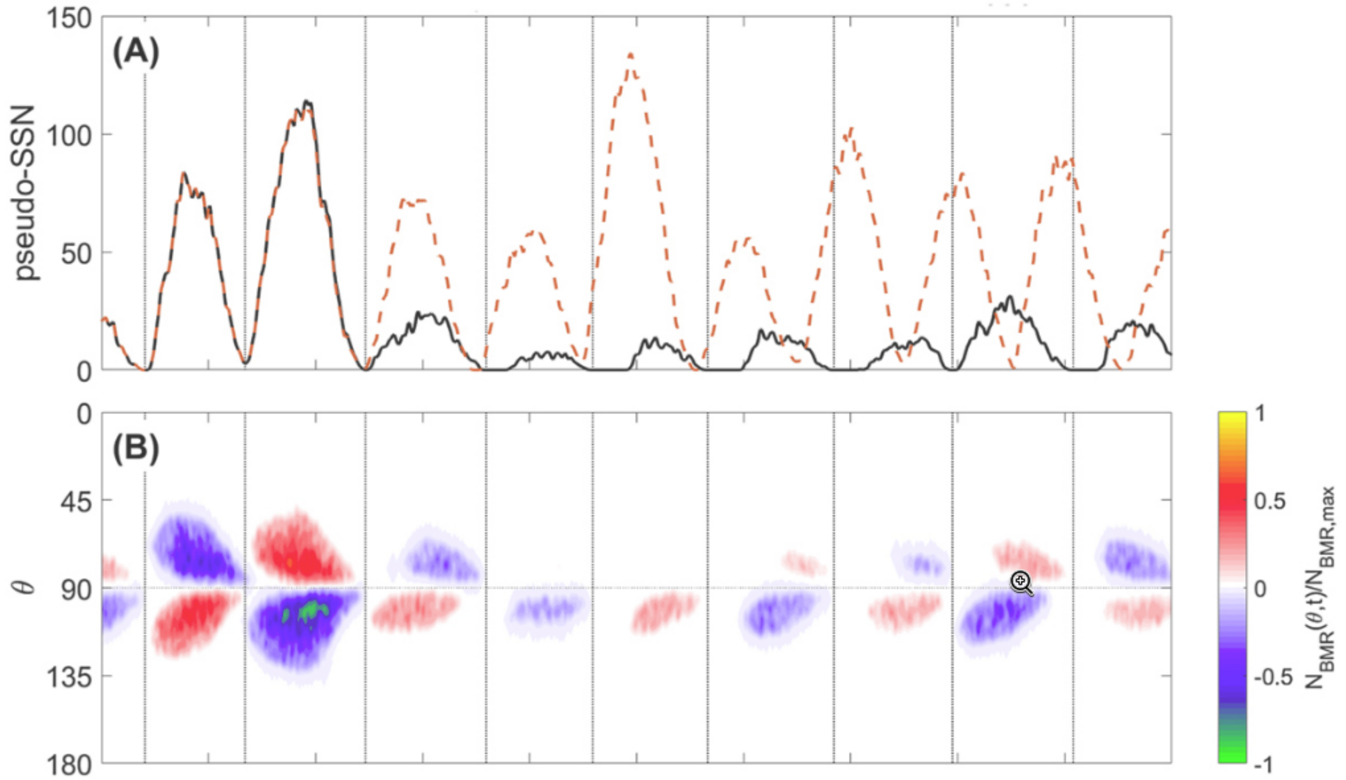
Main issue: importance of various nonlinear feedbacks vs. random fluctuations .

In particular:

- tilt quenching vs. latitude quenching vs. meridional flow modulation.
- role and identification of rogue active regions .

Where do we stand? 1. Interpreting historical variations

We have analogies...



Nagy, Lemerle & Charbonneau (2020)

... but for quantitative reproduction we would need more reliable data
+ a way to identify rogue candidates.

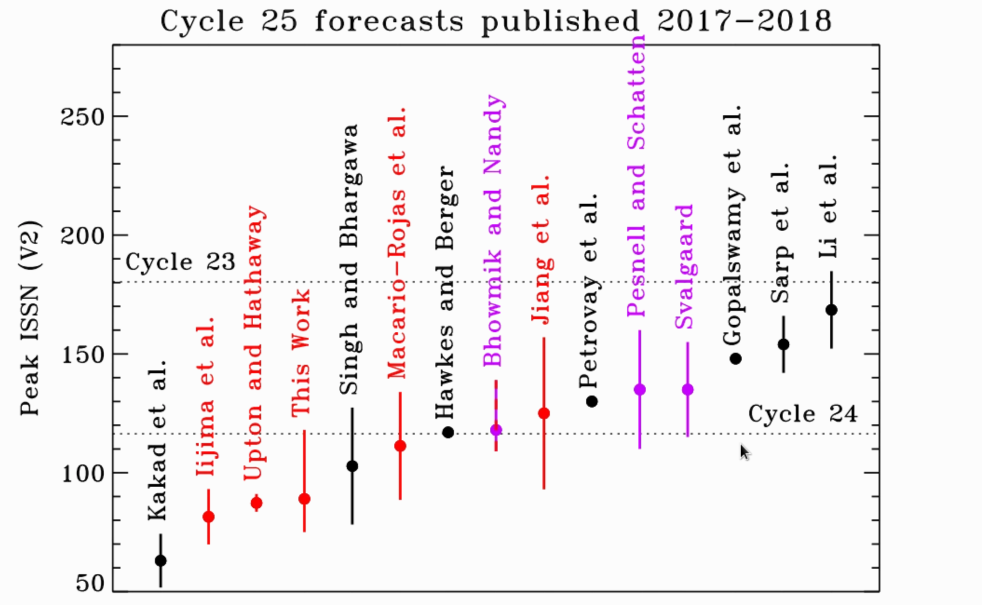
Where do we stand? 2. Forecasting Cycle 25

Polar precursor yields a peak $S_n = 126$ (Kumar et al. 2021)

Evaluating it in 2017.0 (4 yrs after reversal): 120 ± 25

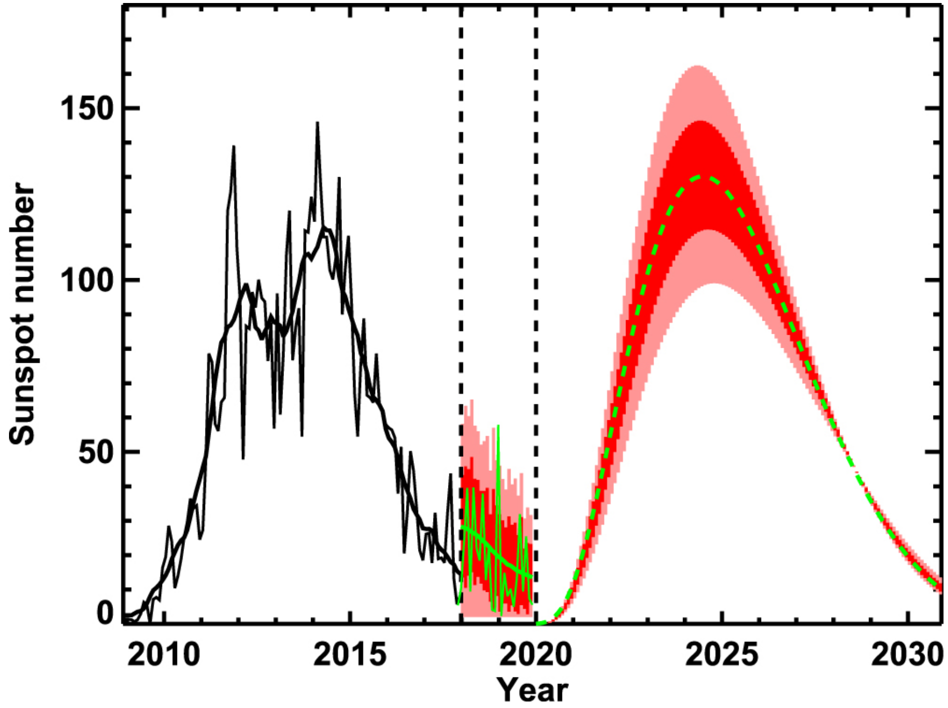
(For reference, cyc. 24 peaked at 114.)

Model-based forecasts yield generally comparable results...

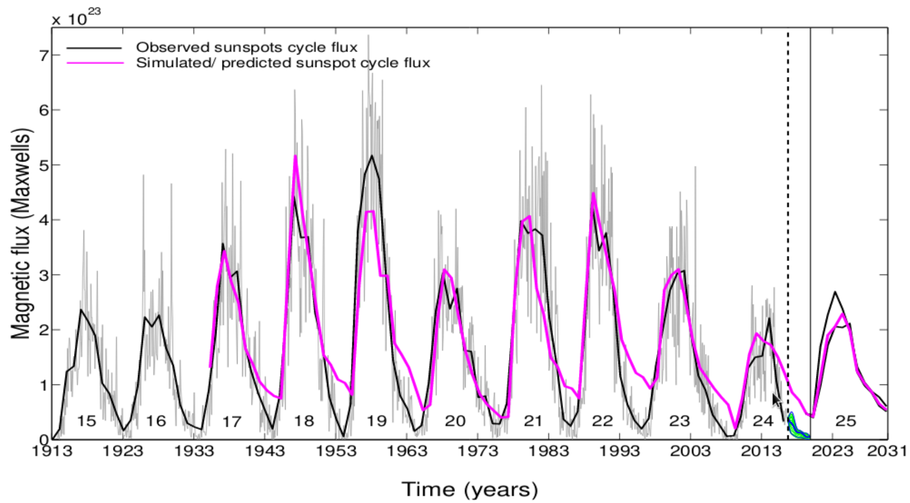


Labonville, Charbonneau & Lemerle (2019)

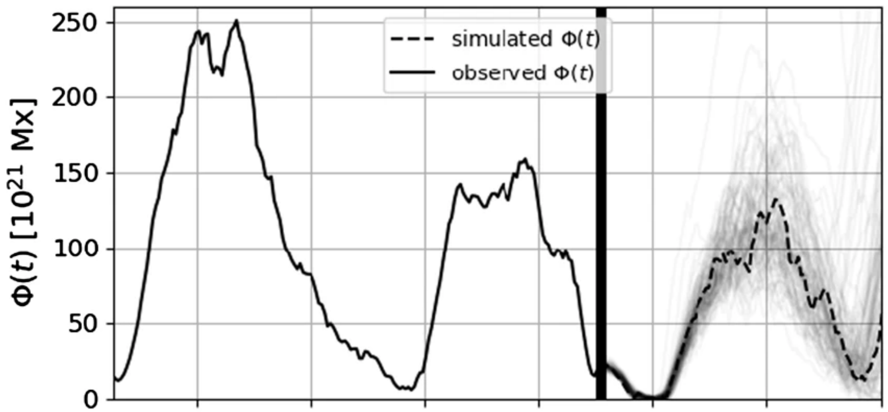
... but still depend on model details:



Jiang et al. (2018)



Bhowmik & Nandy (2018)



Labonville, Charbonneau & Lemerle (2019)