Challenges of Solar Cycle Prediction Introduced by 'Rogue' Active Region Emergences *and* Meridional Inflow

Melinda Nagy[1]

Paul Charbonneau[2]
Alexandre Lemerle[3]
Kristóf Petrovay[1]

[1] Eötvös Loránd University, Budapest, Hungary
[2] Université de Montréal
[3] Collège de Bois-de-Boulogne, Montréal

Challenges of prediction

1. **Rogue BMRs**
   One single 'rogue' BMR, as it can have a flux content commensurate to the maximum of the polar cap flux, has a huge impact on the subsequent cycle. Due to this fact, it is very important to treat these extreme events in prediction.

2. **Meridional inflow**
   Potential non-linear mechanism

3. **Torsional oscillation** – next step

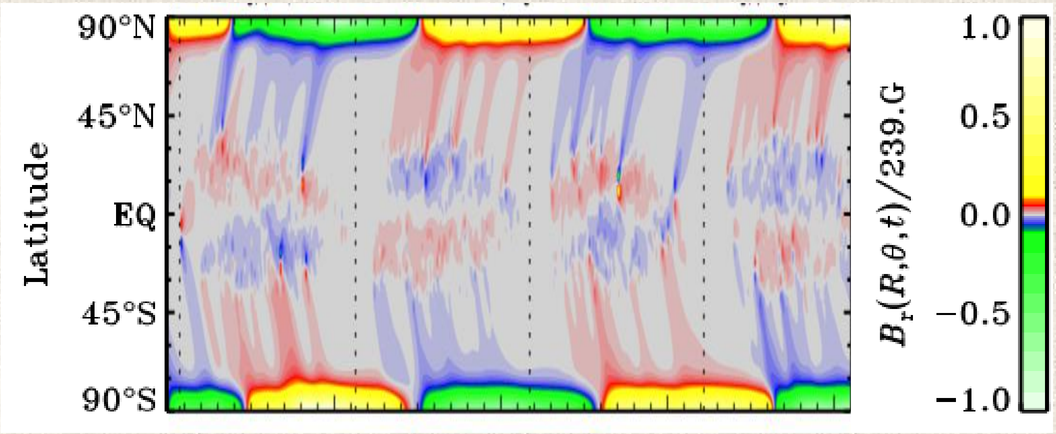
The kinematic „2×2D” Babcock-Leighton dynamo model

Lemerle et al., 2015, ApJ 801; Lemerle & Charbonneau, 2017, ApJ 834

$$\langle B_R \rangle(\theta, t)$$

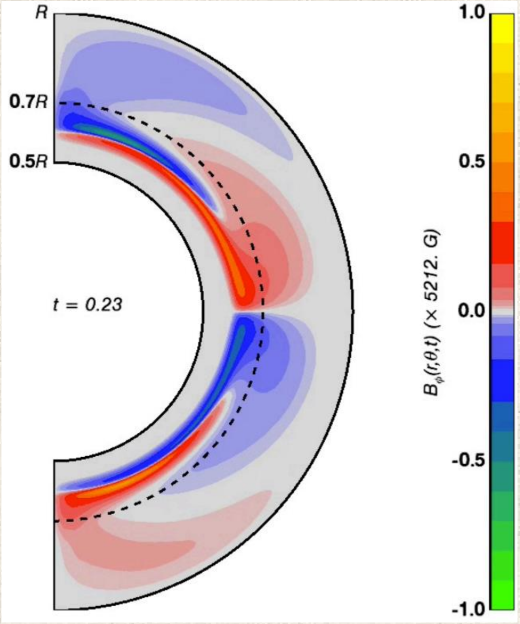
Surface Flux Transport
SFT (2D)

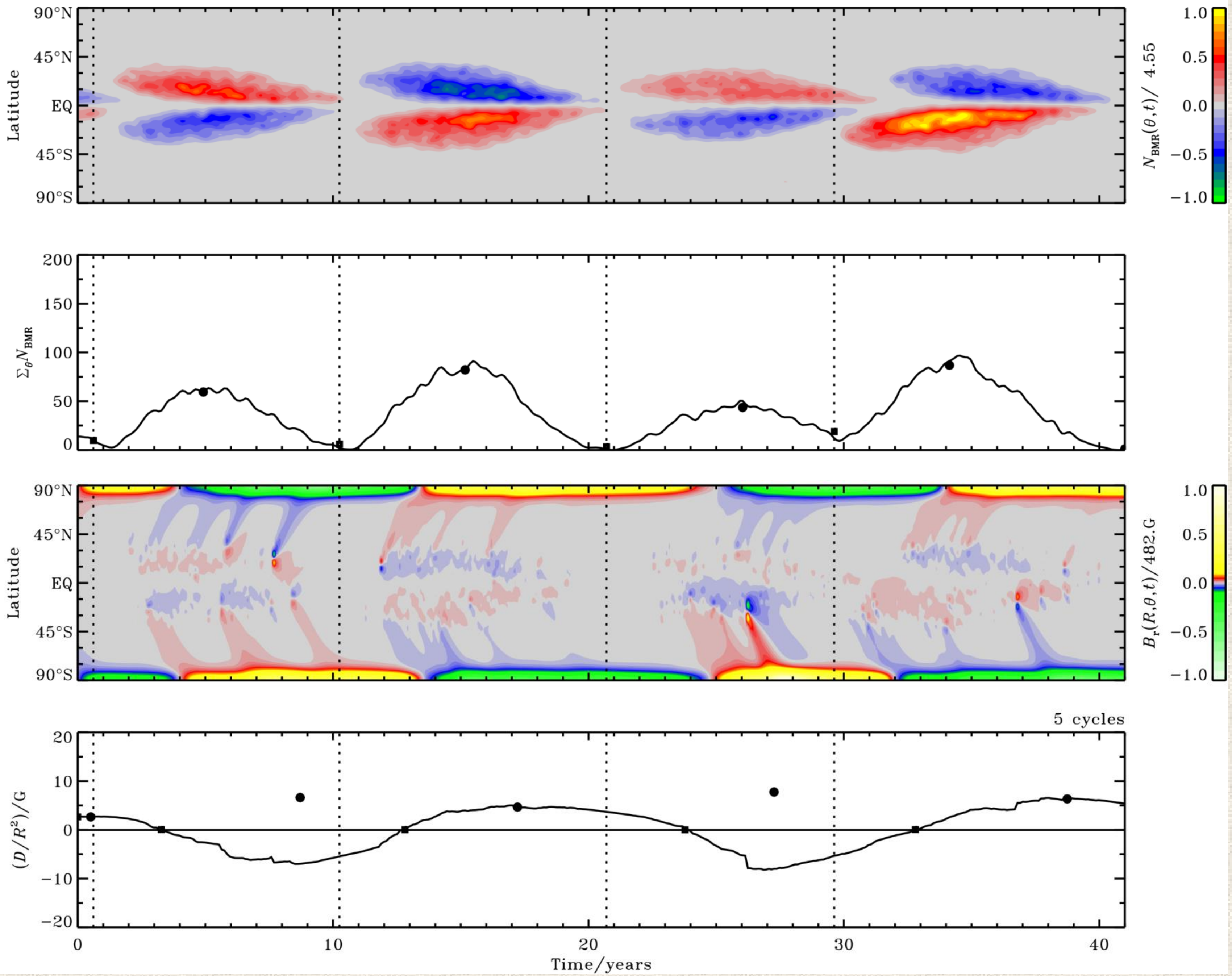
Flux Transport Dynamo
FTD (2D)



Emergence of new BMRs

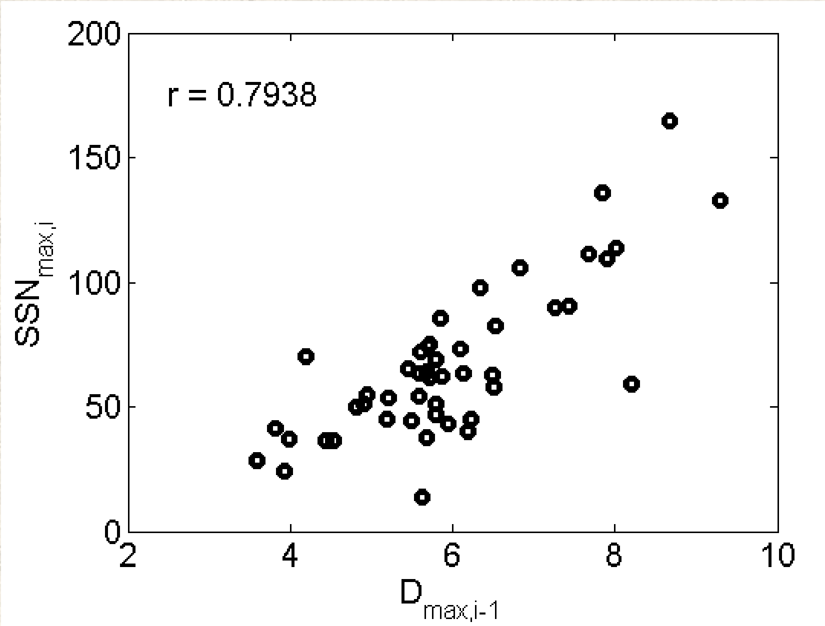
Flux, tilt, separation, etc. chosen randomly based on corresponding distribution functions of cycle 21
(***+ tilt scatter!***)



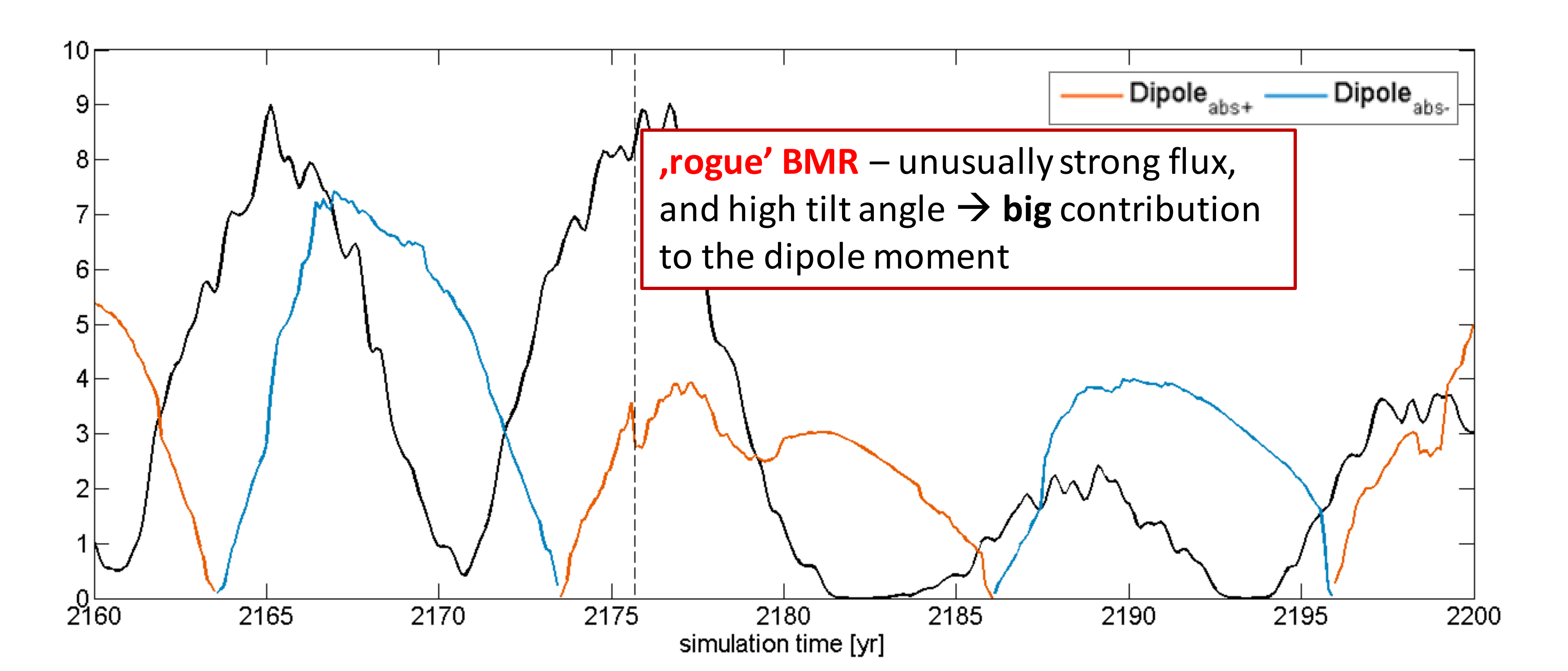


Solar-like Solution

Dipole moment is a good precursor of cycle amplitude:
Svalgaard et al., 2005, GRL, 32, L01104



Solar-like Solution - prediction



Initial contribution to the dipole moment

$$\delta D_{\mathrm{BMR}} \approx F\, d\, \sin\alpha\, \sin\theta$$

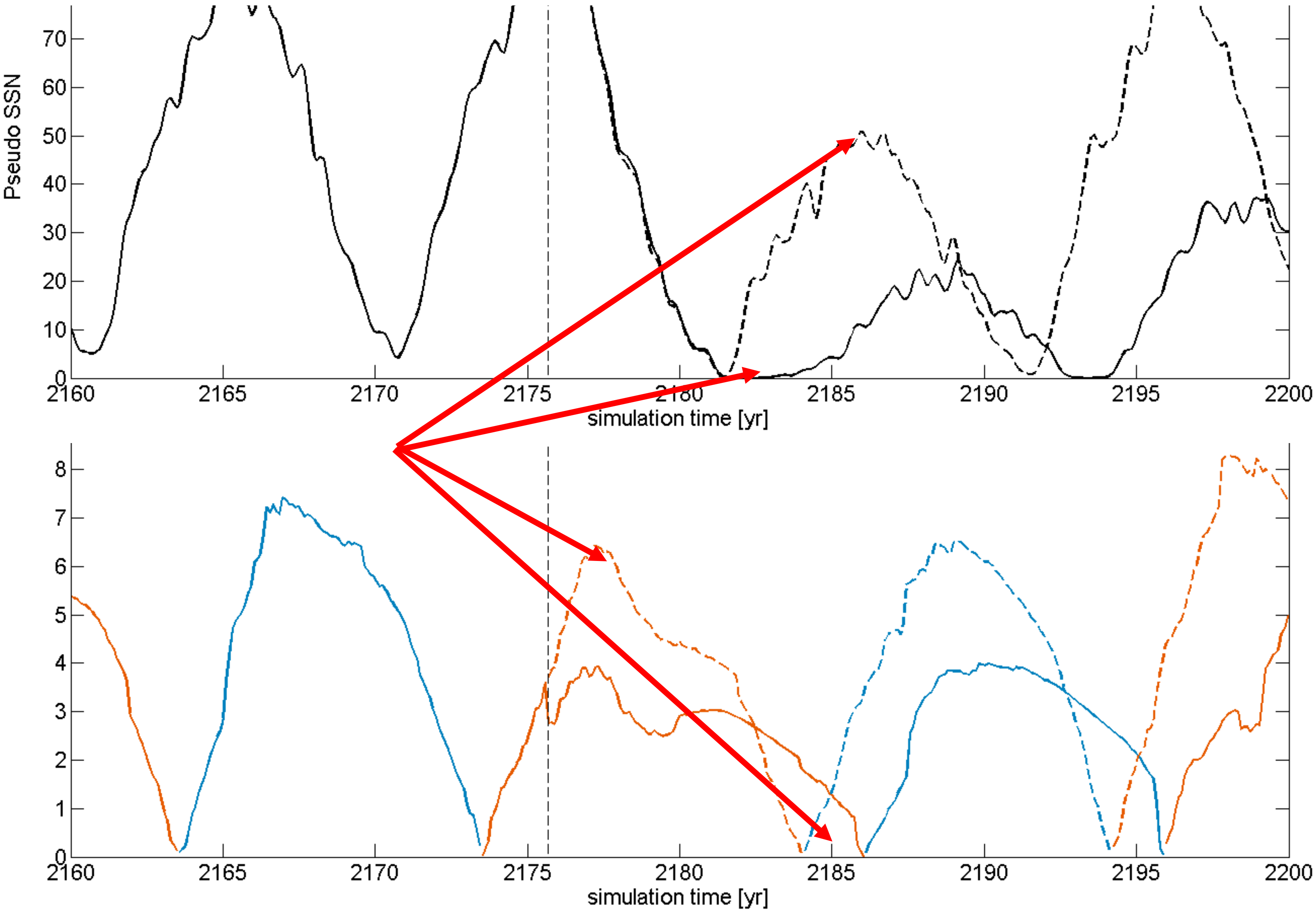
Flux of the trailing polarity

separation

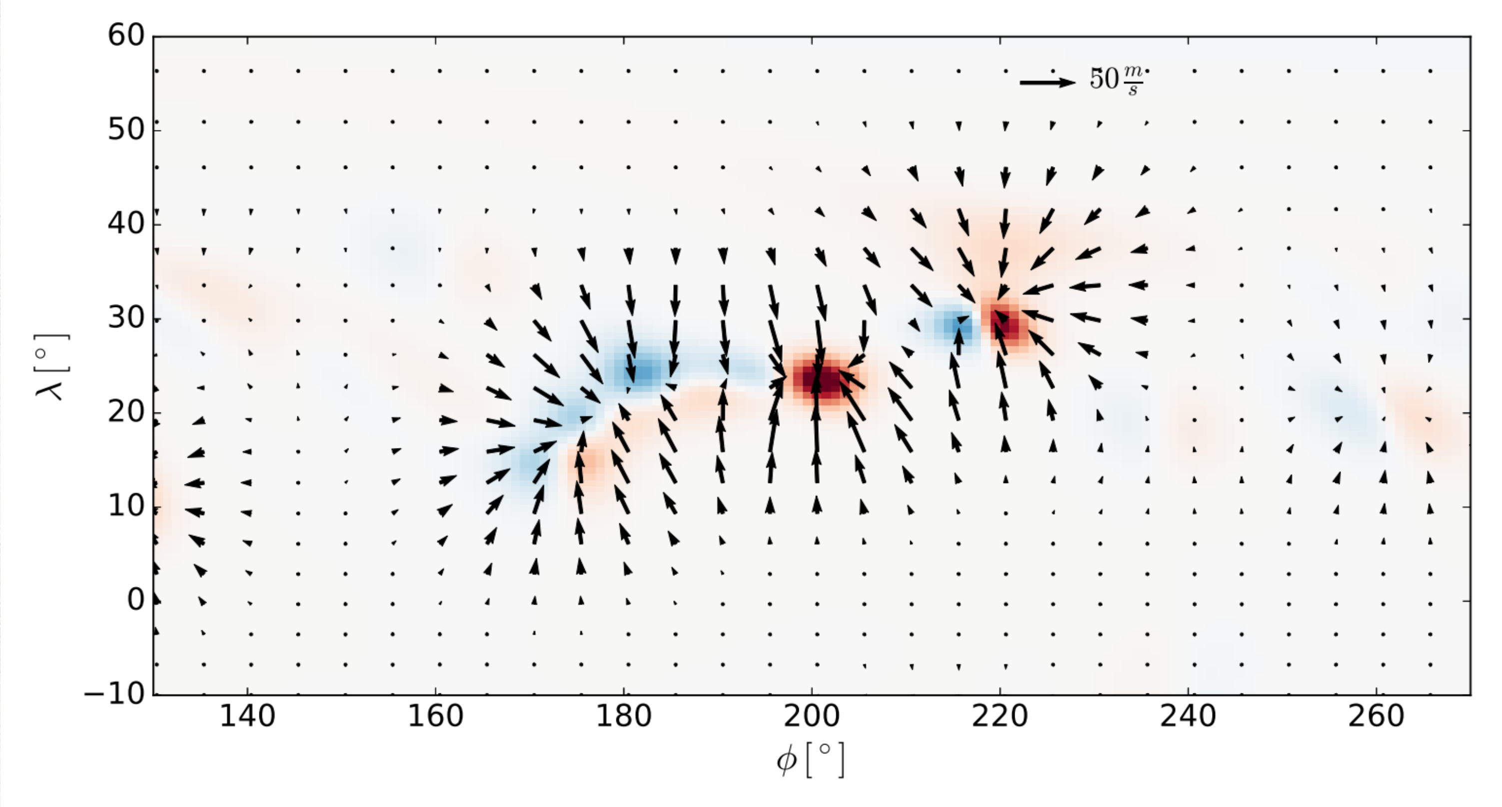
tilt angle

latitude

Solar-like Solution - prediction



Meridional inflow → flow perturbation

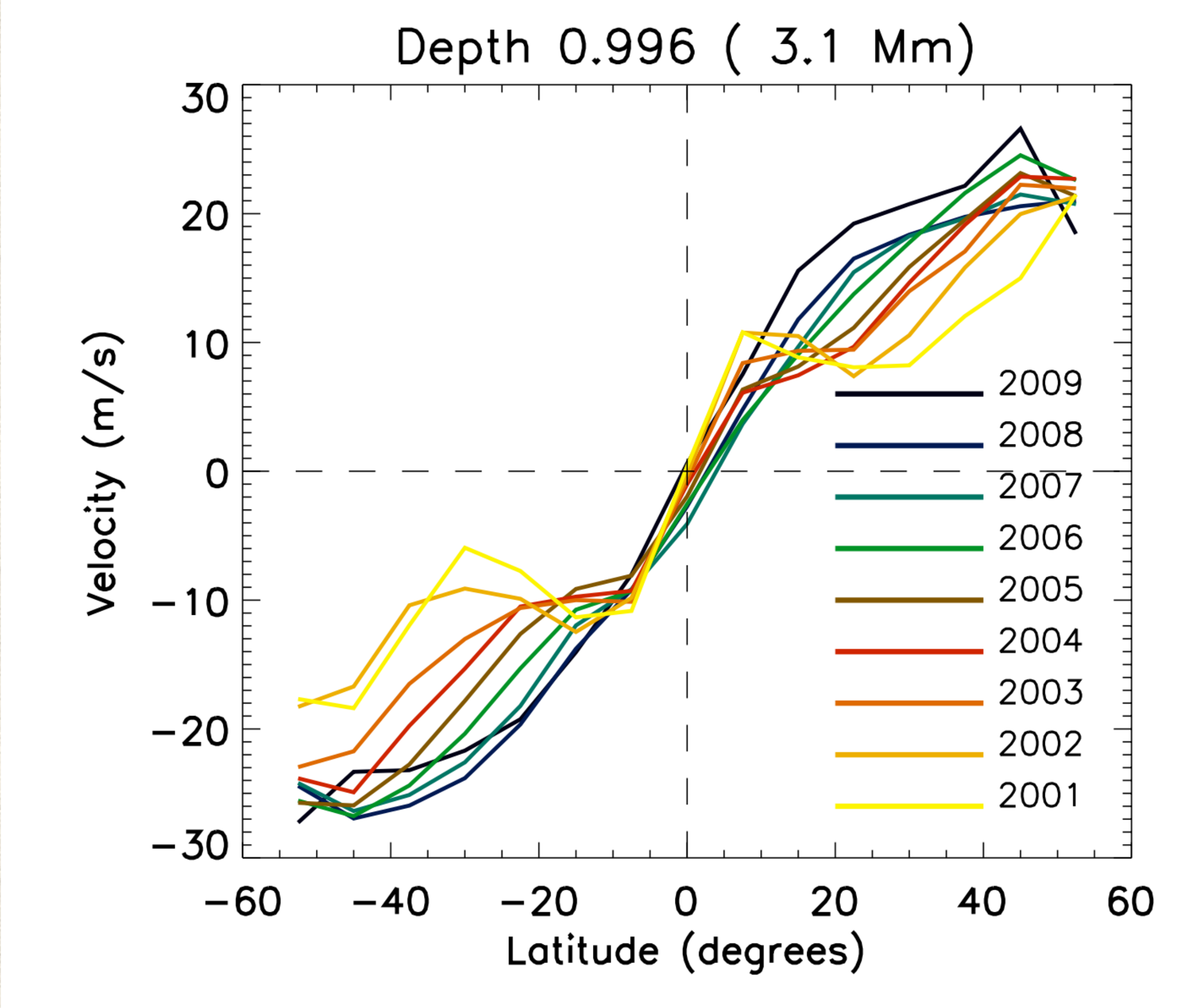


Model of inflows towards an activity complex formed by several emerged BMRs. The colour scale encodes the strength of the magnetic field B_r.
D. Martin-Belda and R. H. Cameron 2017 *A&A* **597**

- The inflows are caused by flows towards individual active regions due to **the local cooling effect of the magnetic field**.
- Surface effect, decreases quickly with depth.
- According to measurements, the inflow strength is about 3-5 m/s on average

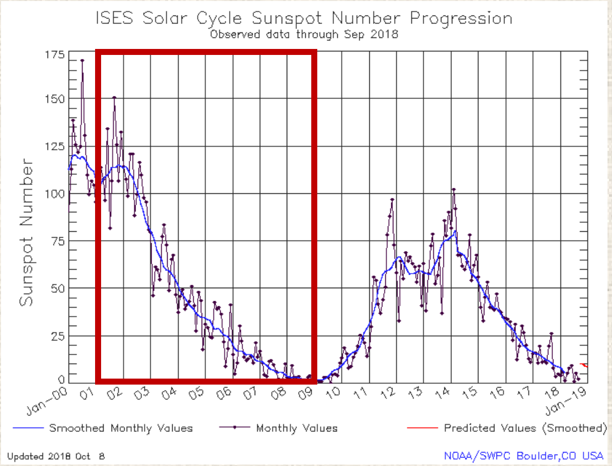
H. C. Spruit 2003 *SoPh* **213**

Meridional inflow → flow perturbation



Helioseismic measurements of the meridional flow during cycle 23: the perturbation caused by the inflows is the strongest at cycle maximum.
I. Gonzalez Hernandez et al. 2010 *ApJ* **713**

The inflows represent a **potential non-linear mechanism** capable of **limiting the build up of the polar fields** and **contributing to the modulation of the solar cycle**.
R. H. Cameron and M. Schüssler 2010 *ApJ* **720**



Models of the meridional inflow

J. Jiang et al. 2010 *ApJ* **717**

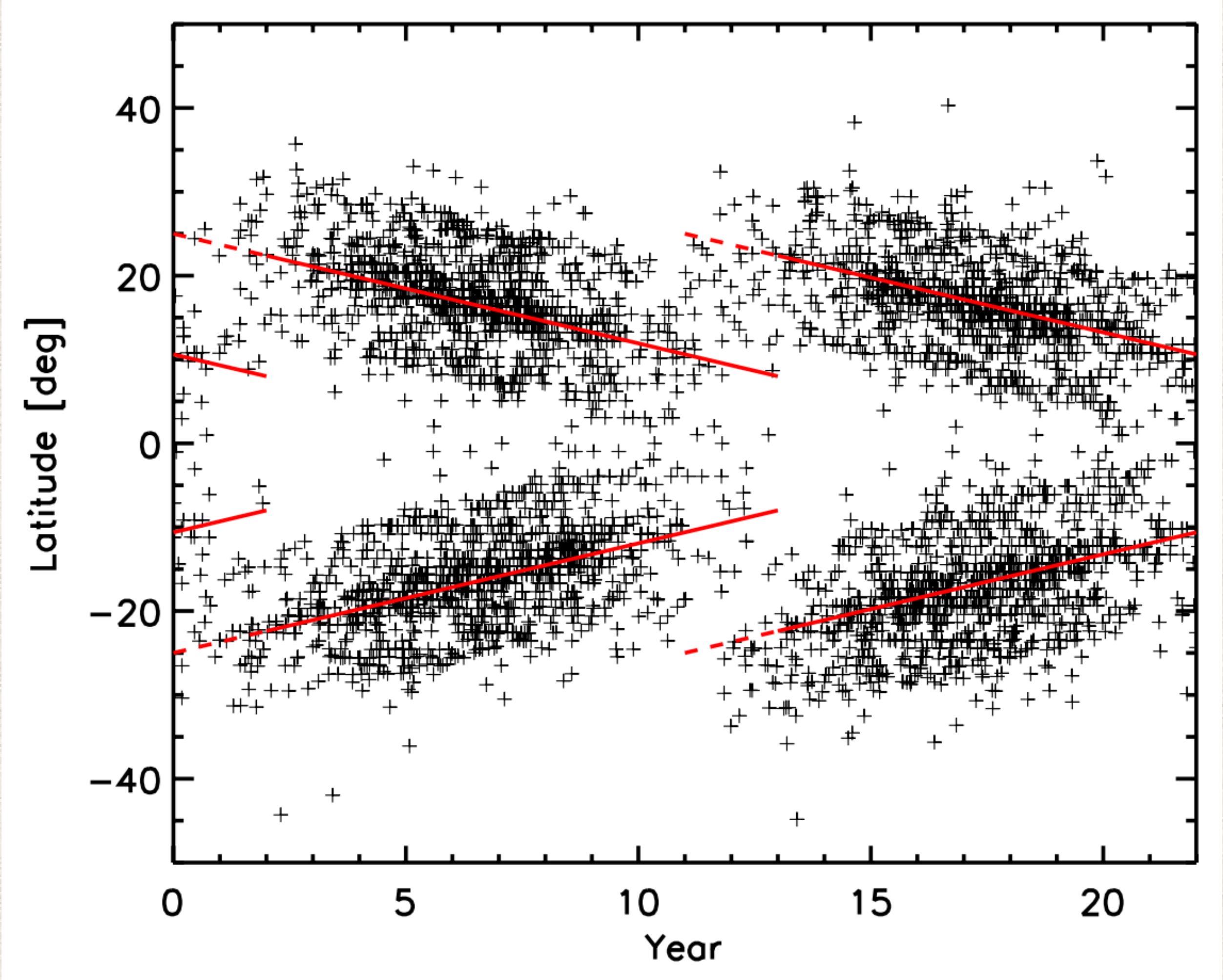
Perturbation in the meridional flow in their Surface Flux Transport model. The inflow belt moves together with the activity belt, fix width and flowspeed.

Result: **reduction of polar fields by ~18%**

$$v(\lambda, t) = \begin{cases} v_{\mathrm{m}} \sin(2.4\lambda) + \Delta v(\lambda, t) & \text{for } |\lambda| \leqslant 75^\circ \\ 0 & \text{otherwise,} \end{cases}$$

where $v_{\mathrm{m}} = 11\ \mathrm{m\ s^{-1}}$ and

$$\Delta v(\lambda, t) = \begin{cases} v_0 \sin[(\lambda - \lambda_{\mathrm{c}}(t))/\Delta\lambda_v] & \text{for } -180^\circ \leqslant (\lambda - \lambda_{\mathrm{c}}(t))/\Delta\lambda_v < 180^\circ \\ 0 & \text{otherwise.} \end{cases}$$



Models of the meridional inflow

J. Jiang et al. 2010 *ApJ* **717**
Perturbation in the meridional flow in their Surface Flux Transport model. The inflow belt moves together with the activity belt, fix width and flowspeed.
Result: **reduction of polar fields by ~18%**

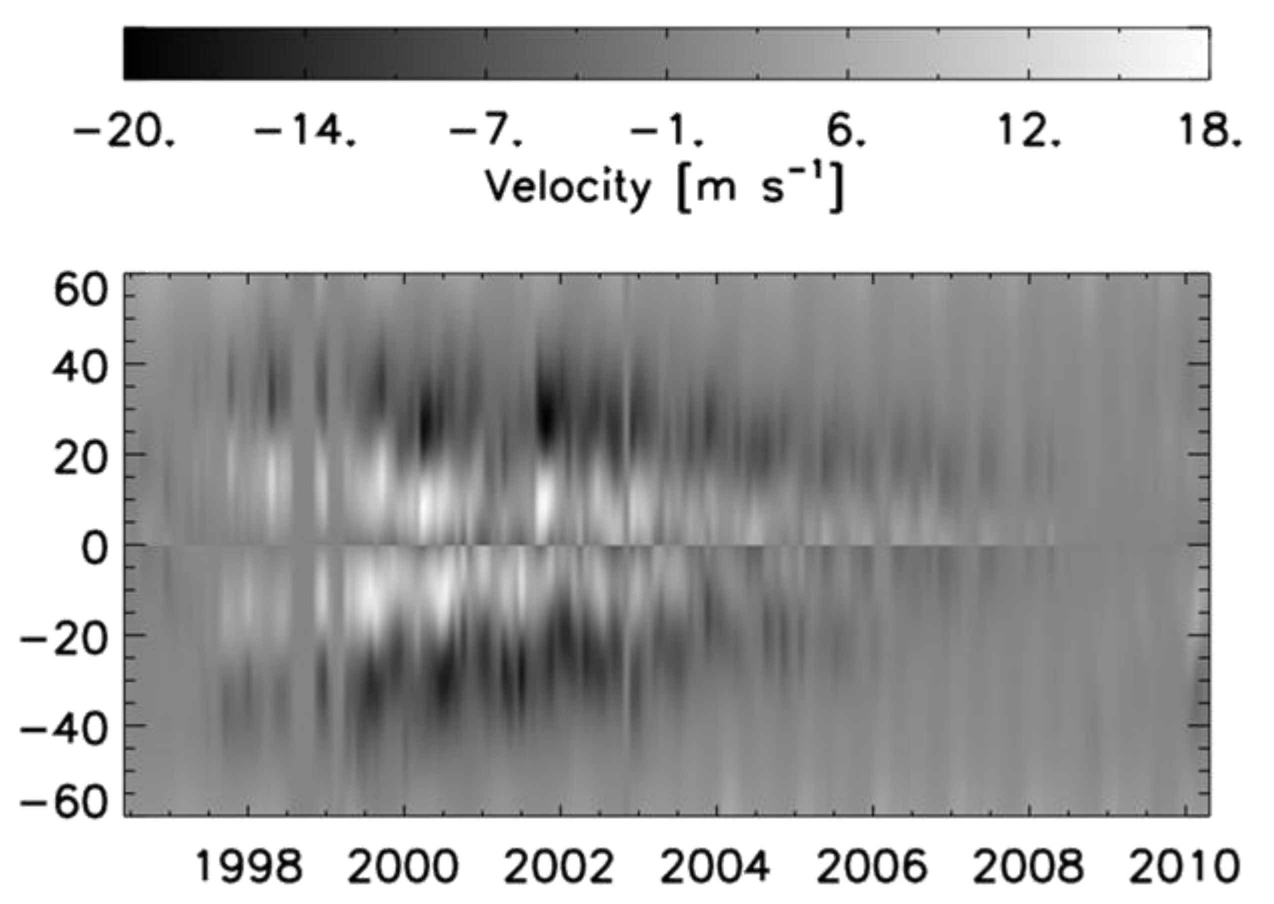
$$v(\lambda, t) = \begin{cases} v_{\mathrm{m}} \sin(2.4\lambda) + \Delta v(\lambda, t) & \text{for } |\lambda| \leqslant 75^\circ \\ 0 & \text{otherwise,} \end{cases}$$

where $v_{\mathrm{m}} = 11 \text{ m s}^{-1}$ and

$$\Delta v(\lambda, t) = \begin{cases} v_0 \sin\left[(\lambda - \lambda_{\mathrm{c}}(t))/\Delta\lambda_v\right] & \text{for } -180^\circ \\ \qquad \leqslant (\lambda - \lambda_{\mathrm{c}}(t))/\Delta\lambda_v < 180^\circ & \\ 0 & \text{otherwise.} \end{cases}$$

R. H. Cameron and M. Schüssler 2010 *ApJ* **720**
Magnetic field dependent flow speed. ← **The flow should depend on the strength of the cycle.**

$$v(\lambda, t) = c_0 \left\{ \frac{d\langle|B|\rangle_\phi(\lambda, t)}{d\lambda} \right\}$$



Meridional inflow in the 2×2D model

$$\Delta v(\lambda, t) = \begin{cases} v_0 \sin\left[(\lambda - \lambda_c(t))/\Delta\lambda_v\right] & \text{for } -180^\circ \leqslant (\lambda - \lambda_c(t))/\Delta\lambda_v < 180^\circ \\ 0 & \text{otherwise.} \end{cases}$$

J. Jiang et al. 2010 *ApJ* **717**

$$\boxed{\Delta v(\mathrm{t}, \mathrm{F}) = v_0(\mathrm{t}, \mathrm{F}) \cdot \sin\left(\frac{\lambda - \lambda_c(\mathrm{t}, \mathrm{F})}{\Delta\lambda(\mathrm{t}, \mathrm{F})}\right),} \quad \text{for: } -180^\circ \leq \frac{\lambda - \lambda_c(\mathrm{t},\mathrm{F})}{\Delta\lambda(\mathrm{t},\mathrm{F})} < 180^\circ$$

Based on the concept of Jiang et al. , BUT:

- Flow parameters defined with the parameters of the emerged active regions.
- Calculated separately for the two hemispheres – asymmetry
- Updated at each internal dynamo timestep

Meridional inflow in the 2×2D model

$$\boxed{\Delta v(\mathrm{t},\mathrm{F}) \;=\; v_0(\mathrm{t},\mathrm{F}) \cdot \sin\left(\frac{\lambda - \lambda_c(\mathrm{t},\mathrm{F})}{\Delta\lambda(\mathrm{t},\mathrm{F})}\right),}$$

$$\text{for: } -180° \leq \frac{\lambda - \lambda_c(\mathrm{t},\mathrm{F})}{\Delta\lambda(\mathrm{t},\mathrm{F})} < 180°$$

$$v_0(\mathrm{t},\mathrm{F}) \;=\; v_{00} \cdot \arctan\left(\frac{\Sigma F_i}{F_{00}}\right)$$

Flow velocity

<u>v_{00} = 5 m/s</u> – observations (5.25 m/s; 5.50 m/s; 7.50 m/s)

F_{00} = 4.99 10^{21} Mx (average unsigned flux)

F_i – flux of BMRs emerged during an internal dynamo timestep

$$\lambda_c(\mathrm{t},\mathrm{F}) \;=\; \frac{\Sigma(\lambda_i \cdot F_i)}{\Sigma F_i}$$

Flux-weighted centroid of the inflow belt

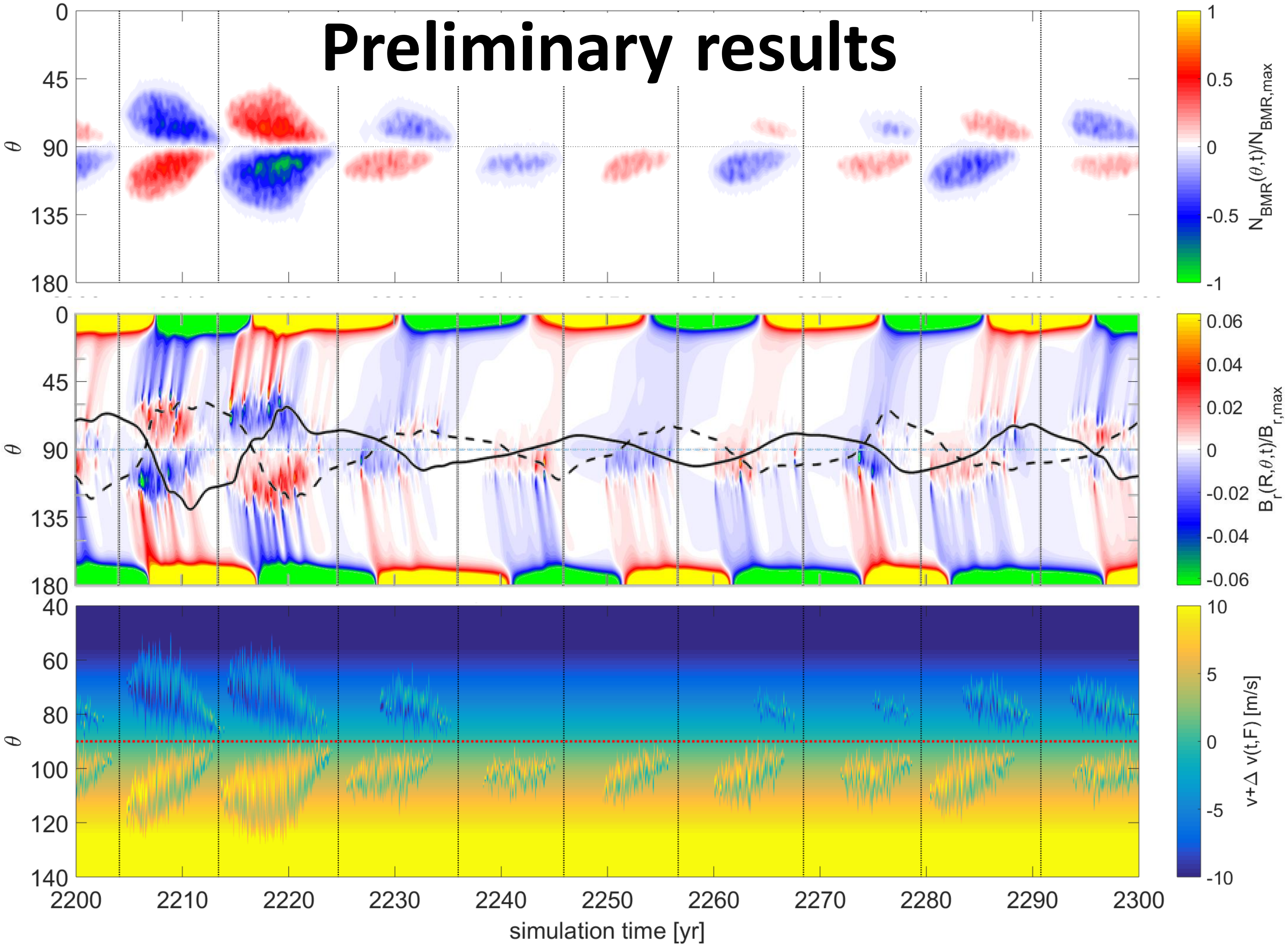
λ_i –midpoints of BMRs

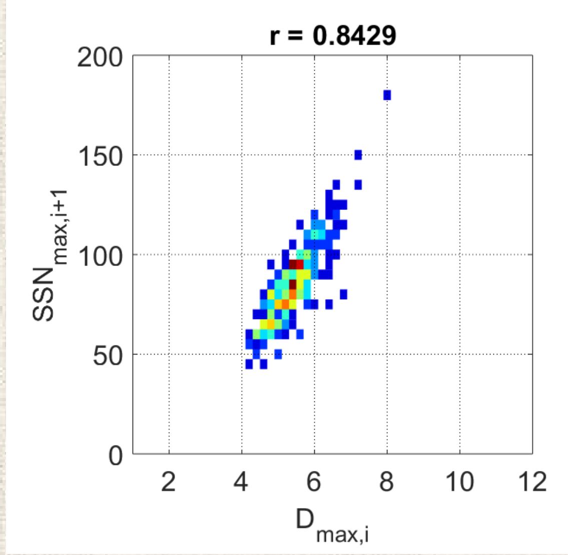
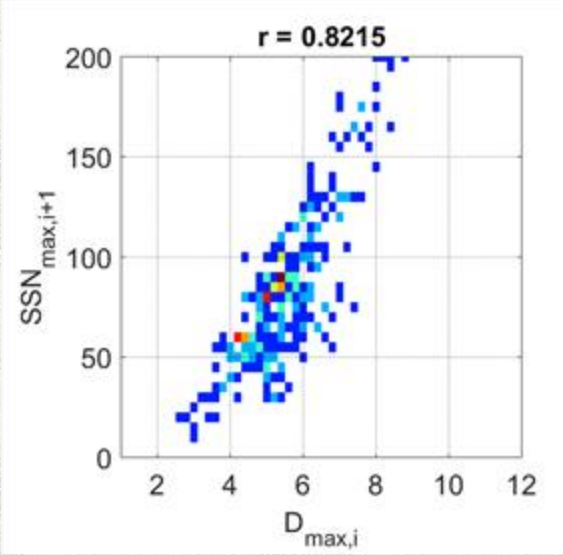
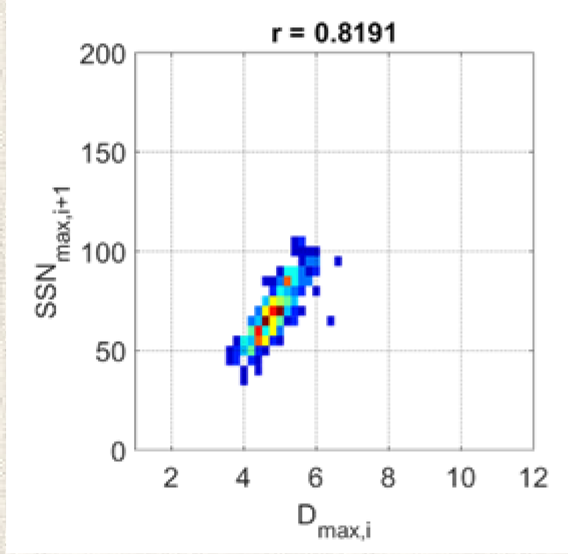
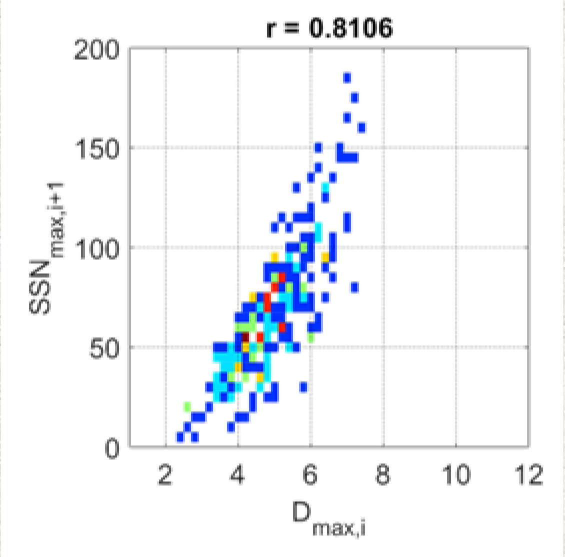
$$\Delta\lambda(\mathrm{t},\mathrm{F}) \;=\; \frac{1}{2}\sqrt{\frac{1}{n}\left(\lambda_i - \lambda_c(\mathrm{t},\mathrm{F})\right)^2}$$

Width of the inflow belt

n – number of emerged BMRs on the North / South

Preliminary results



	Reduced stochasticity (tilt angle varies according to Joy's law; non-stochastic separation)	**Full stochasticity**
No inflow		
Inflow (v_{00} = 7.5 m/s)		

Reduced stochasticity

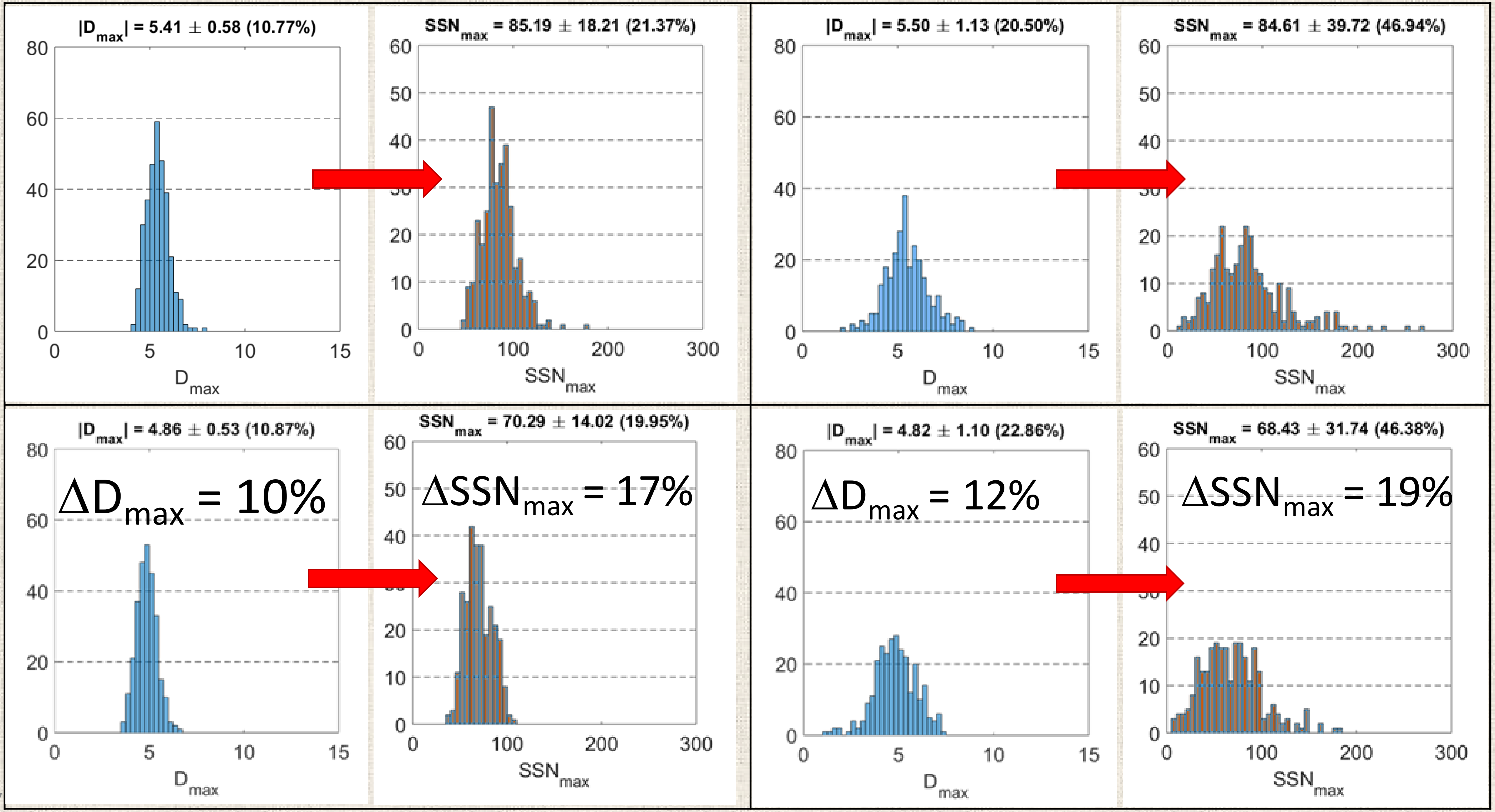
(tilt angle varies according to Joy's law; non-stochastic separation)

Full stochasticity

No inflow

Inflow

(v_{00} = 7.5 m/s)



Conclusions

Flux dependent meridional inflow is added to the 2×2D Babcock-Leighton solar dynamo model.

<u>Results</u>:

- The inflow reduces the dipole moment by ~10% → reduction in the cycle amplitudes, too (*cycle prediction!*)
- Cross-equatorial flows → stronger hemispheric coupling (*asymmetry!*)

<u>Next step:</u>

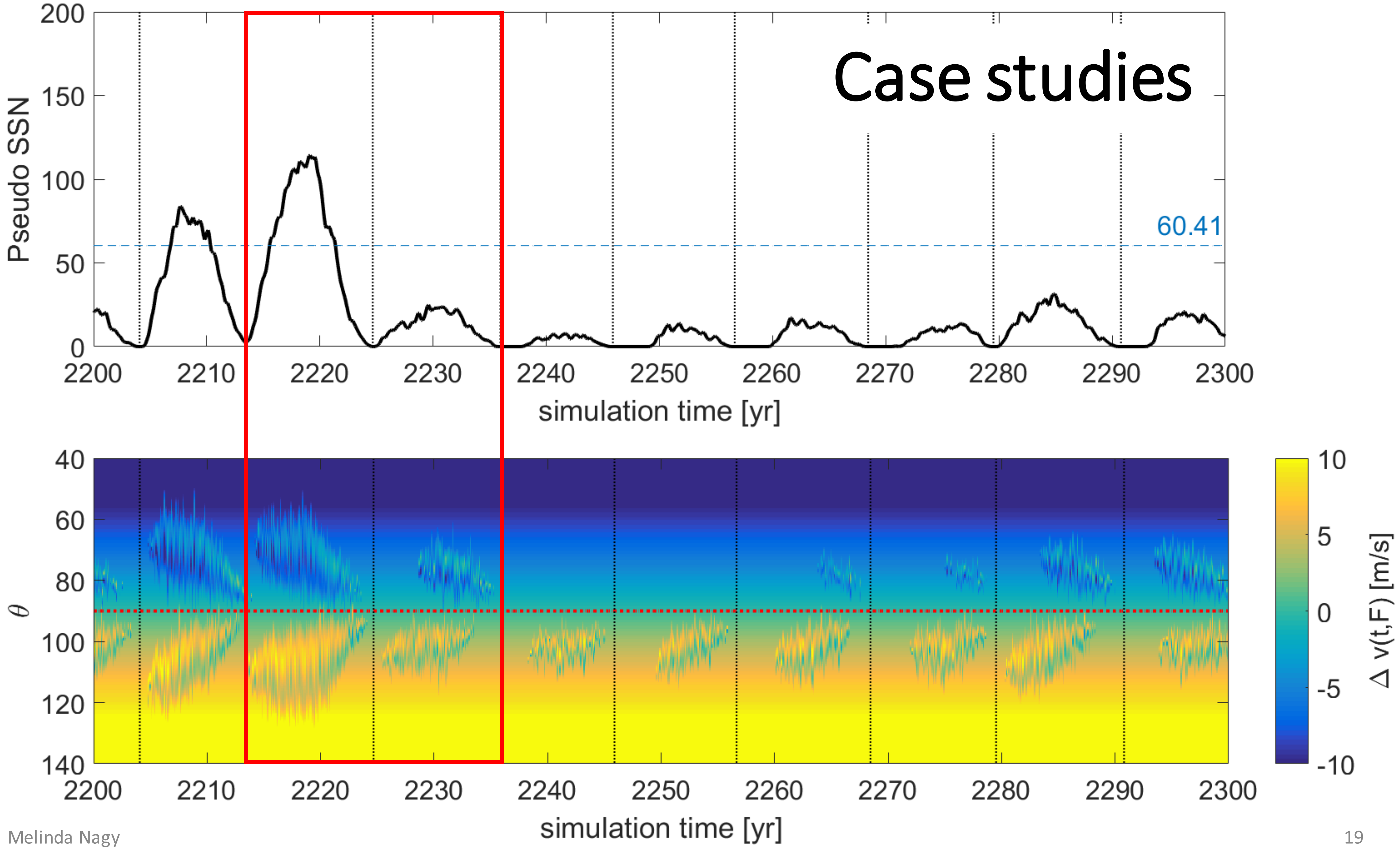
- Link cross-equatorial flows to hemispheric asymmetry
- More case studies to investigate the impact of meridional inflows on cycles with different amplitude (different effects are proposed)

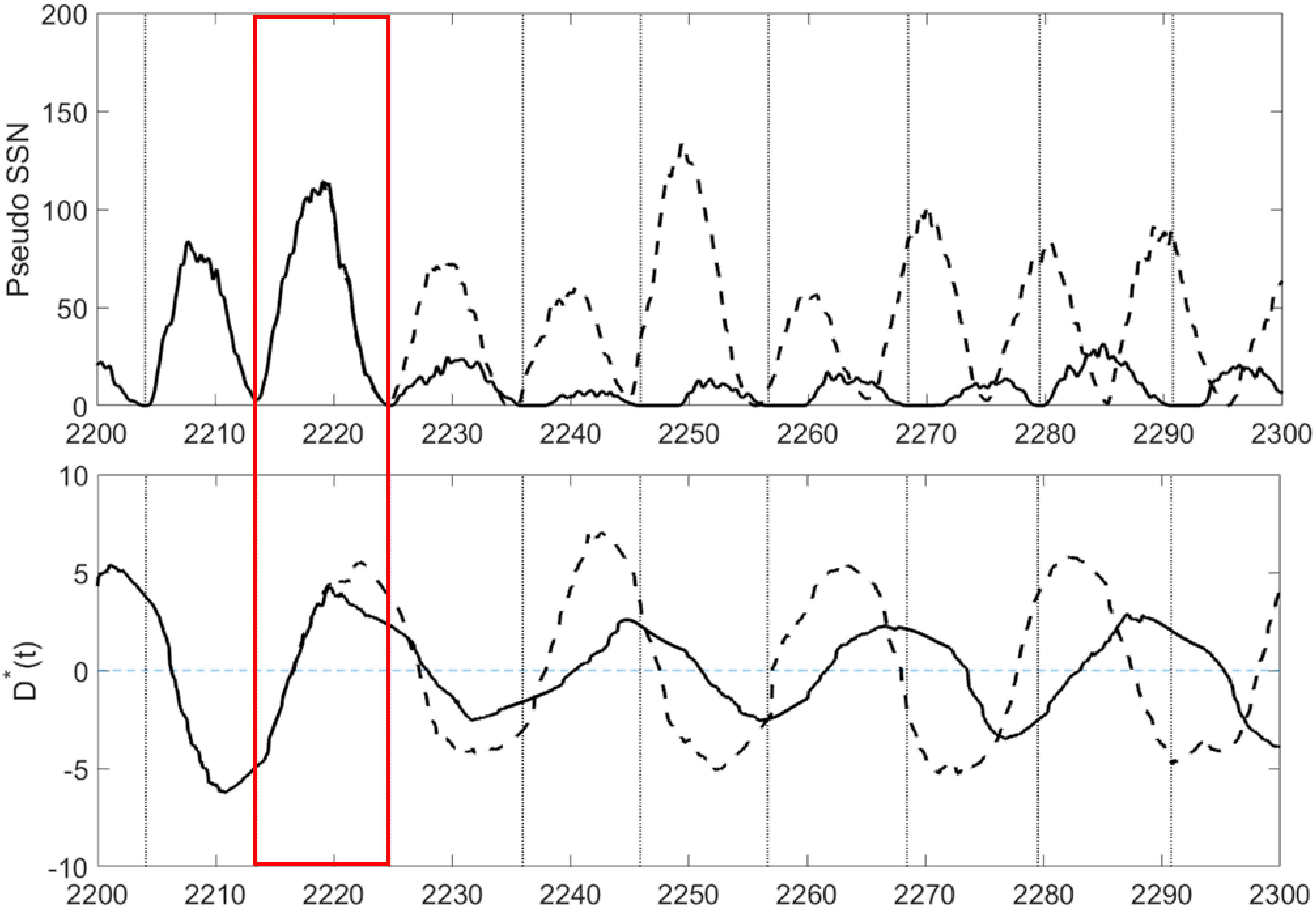
Thank you for your attention!

Acknowledgement:

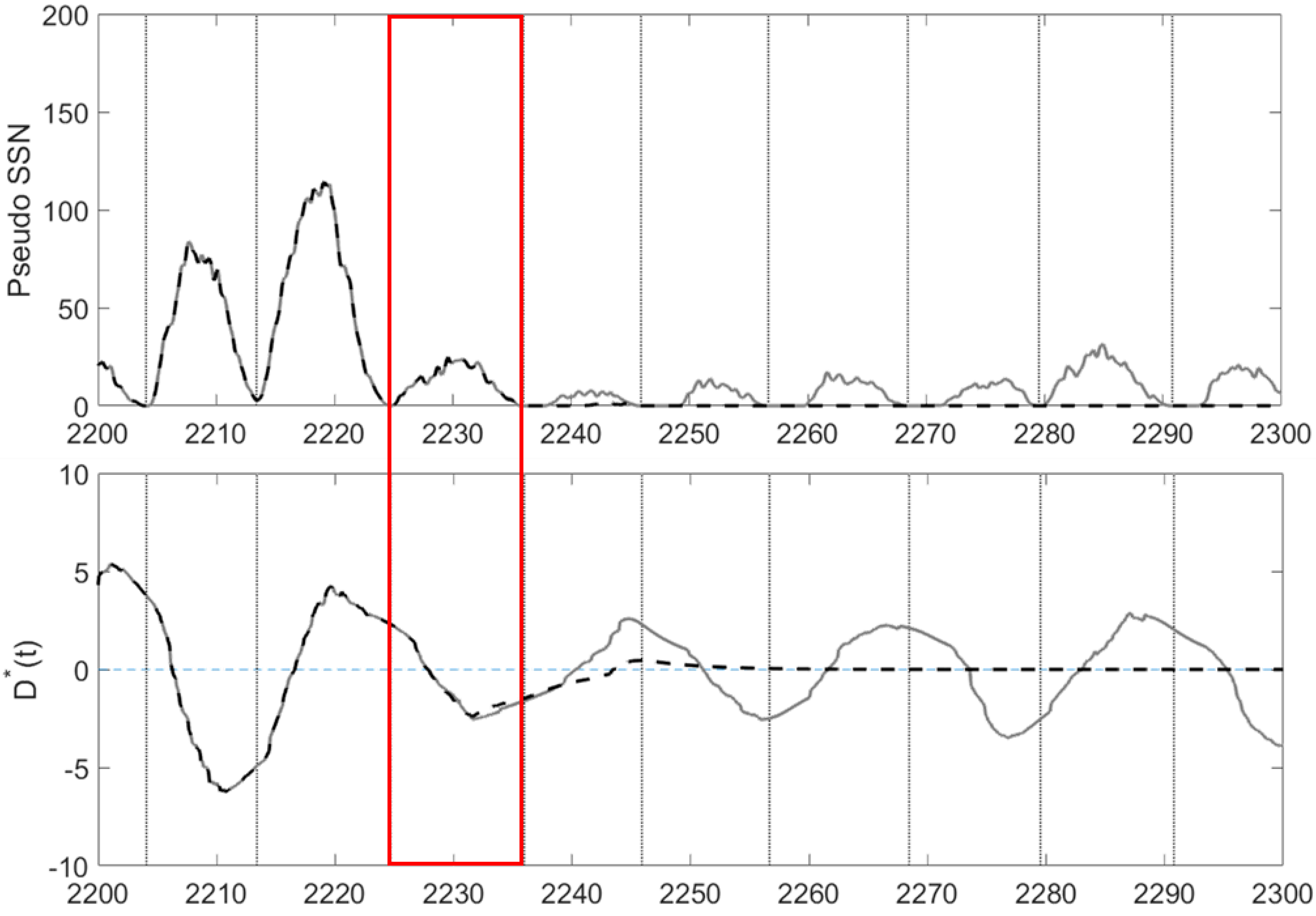
This research is supported by the ÚNKP-18-3 New National Excellence Program of the Ministry of Human Capacities and by the Hungarian National Research, Development and Innovation Office (NKFI grant no. K128384).

Case studies

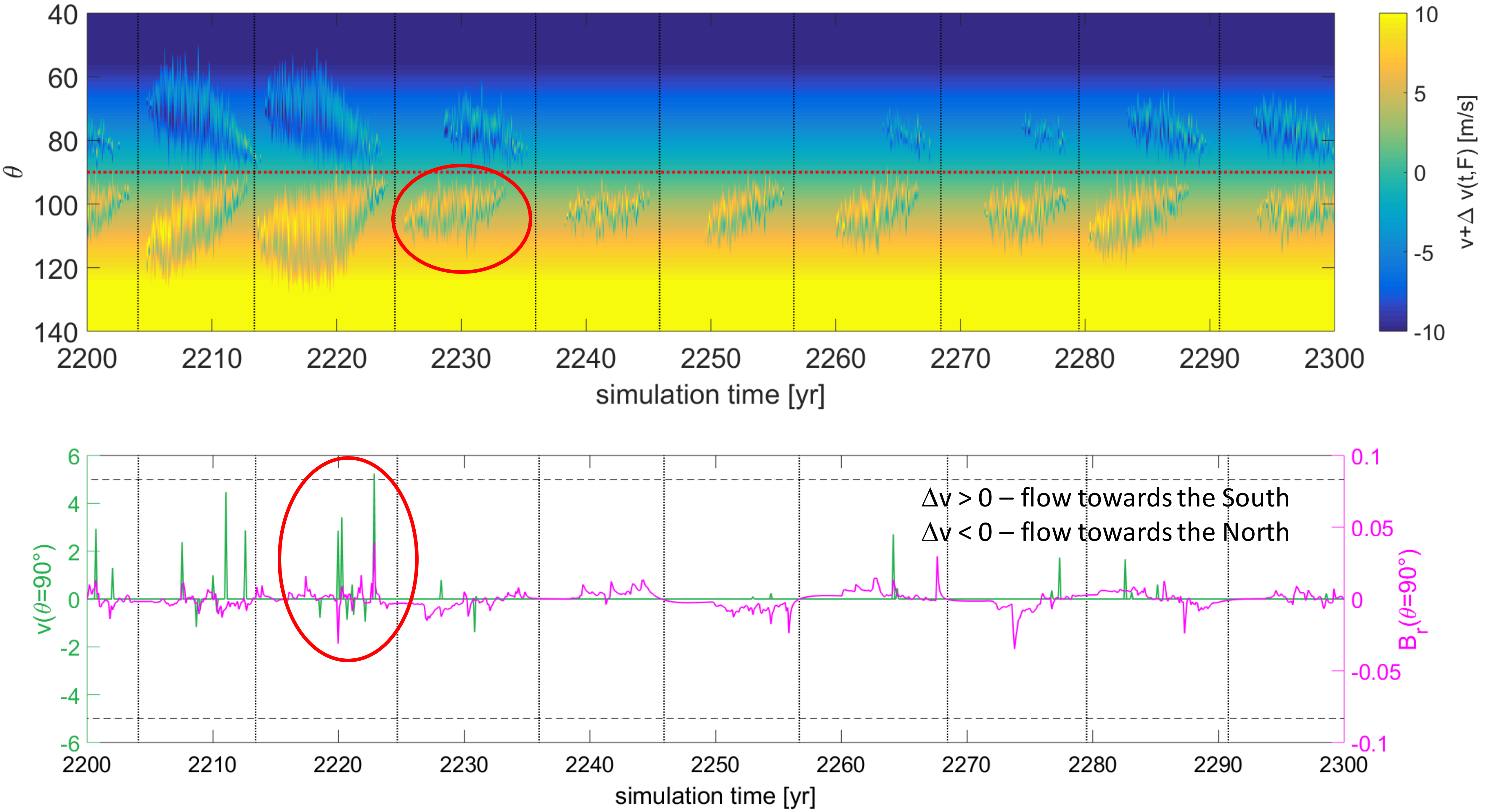




Pseudo SSN
200
150
100
50
0
2200
2210
2220
2230
2240
2250
2260
2270
2280
2290
2300
D*(t)
10
5
0
-5
-10
2200
2210
2220
2230
2240
2250
2260
2270
2280
2290
2300



Pseudo SSN
200
150
100
50
0
2200
2210
2220
2230
2240
2250
2260
2270
2280
2290
2300
D*(t)
10
5
0
-5
-10



θ
v+Δ v(t,F) [m/s]
simulation time [yr]
Δv > 0 – flow towards the South
Δv < 0 – flow towards the North
v(θ=90°)
B_r(θ=90°)
simulation time [yr]

Models of the meridional inflow

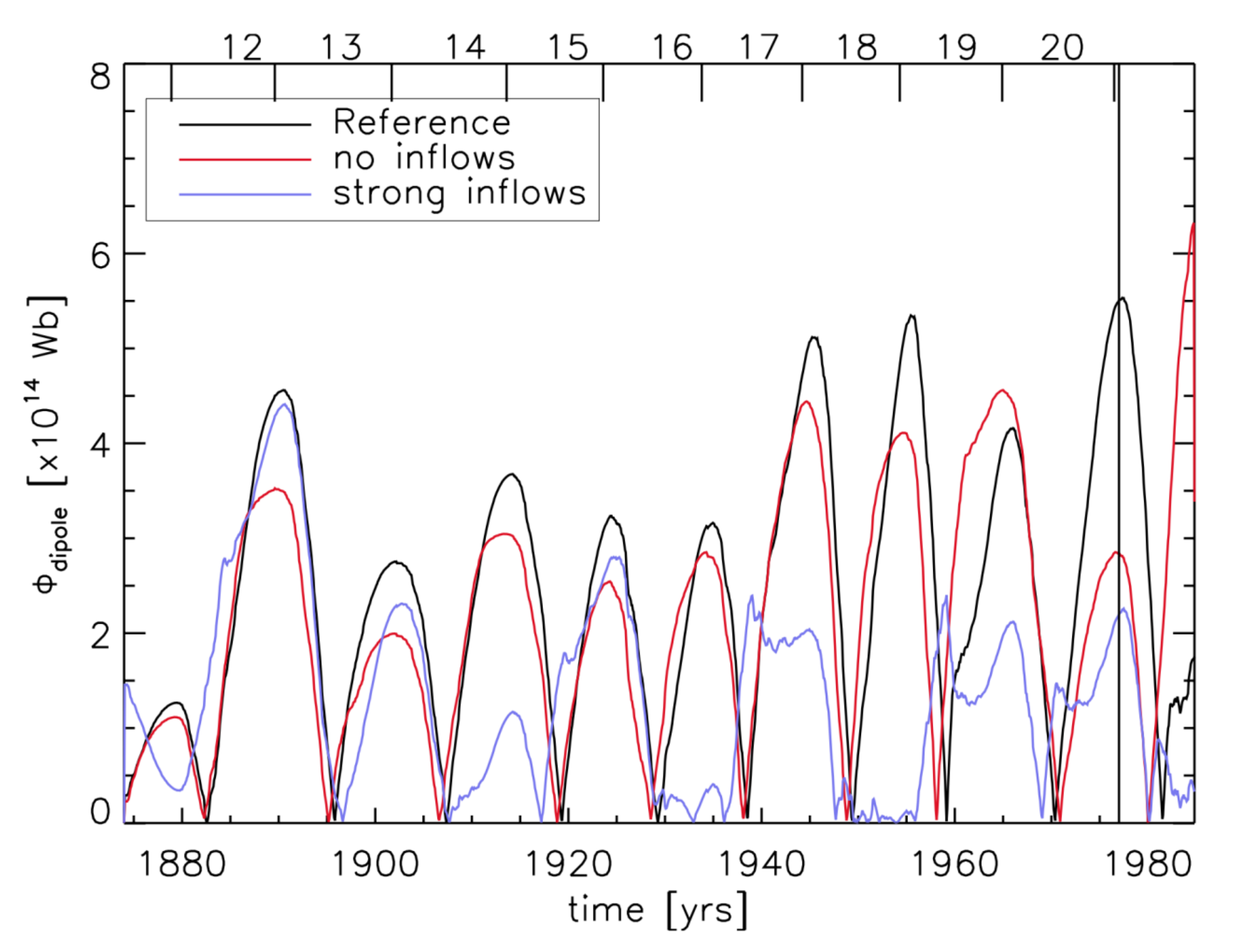
R. H. Cameron and M. Schüssler 2012 *A&A* **548**

Cross-equatorial flows:

- BMRs close to the equator:
  enhanced flux transport between hemispheres ->
  it strengthens the dipole moment
  (in case of weak cycles)

- In general:
  converging flows decrease the tilt angle of the BMRs ->
  lower contribution to the dipole moment
  (in case of strong cycles, where the activity belts are further from the equator, this effect will **weaken the dipole moment**)

Nonlinear feedback!



Reduced stochasticity

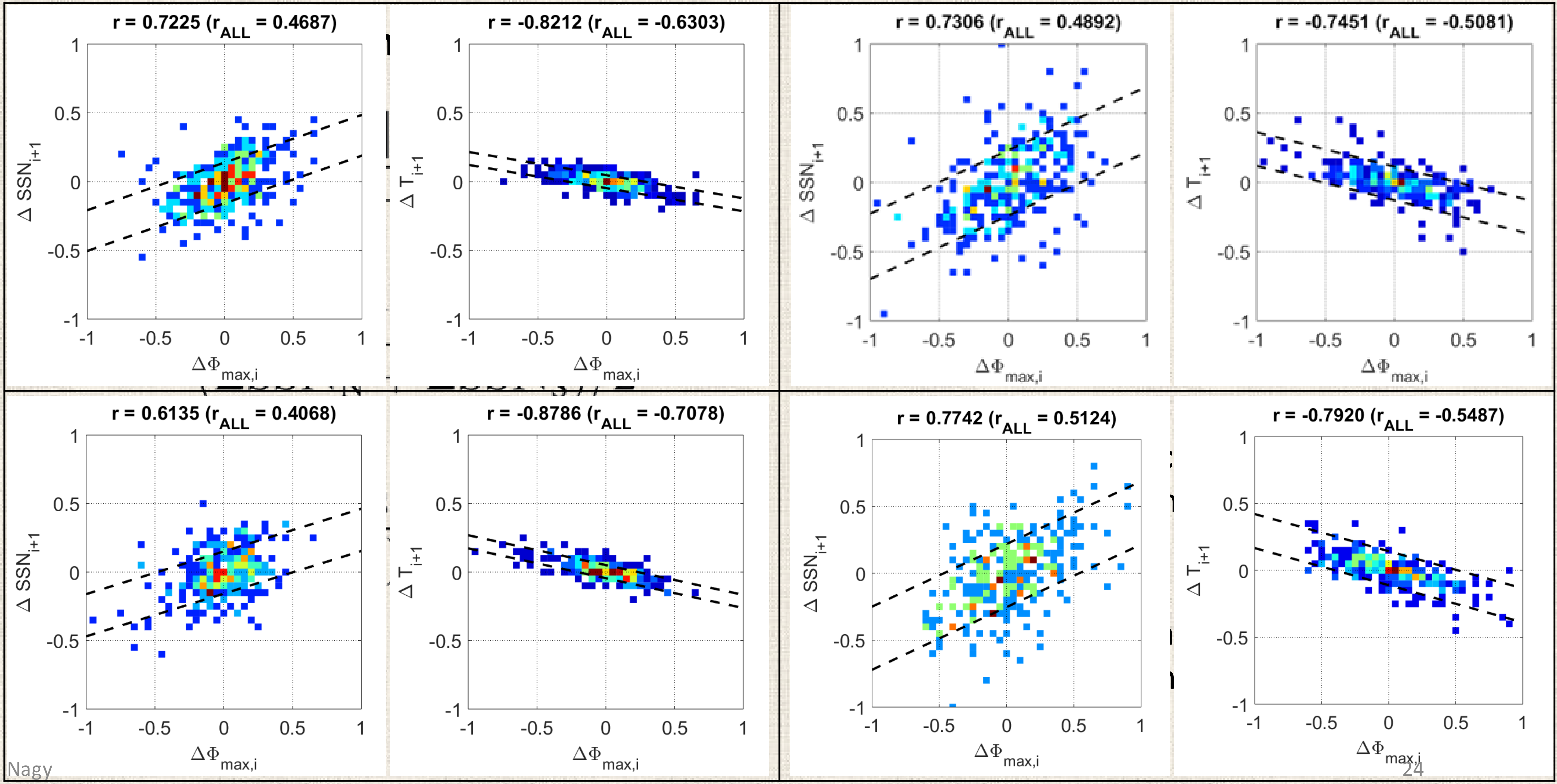
(tilt angle varies according to Joy’s law; non-stochastic separation)

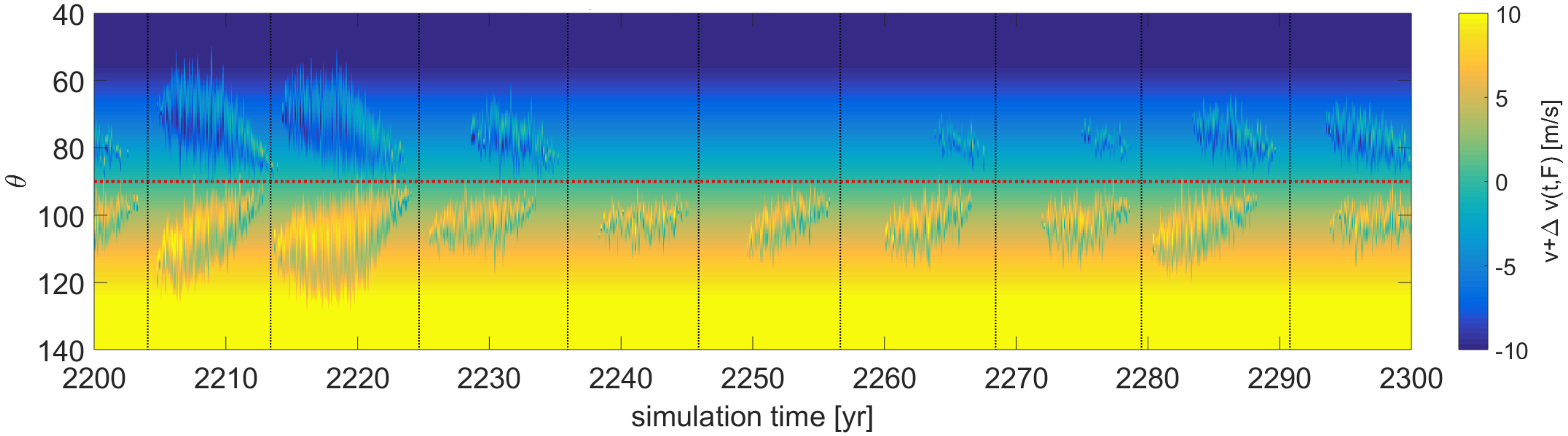
Full stochasticity

No inflow

Inflow

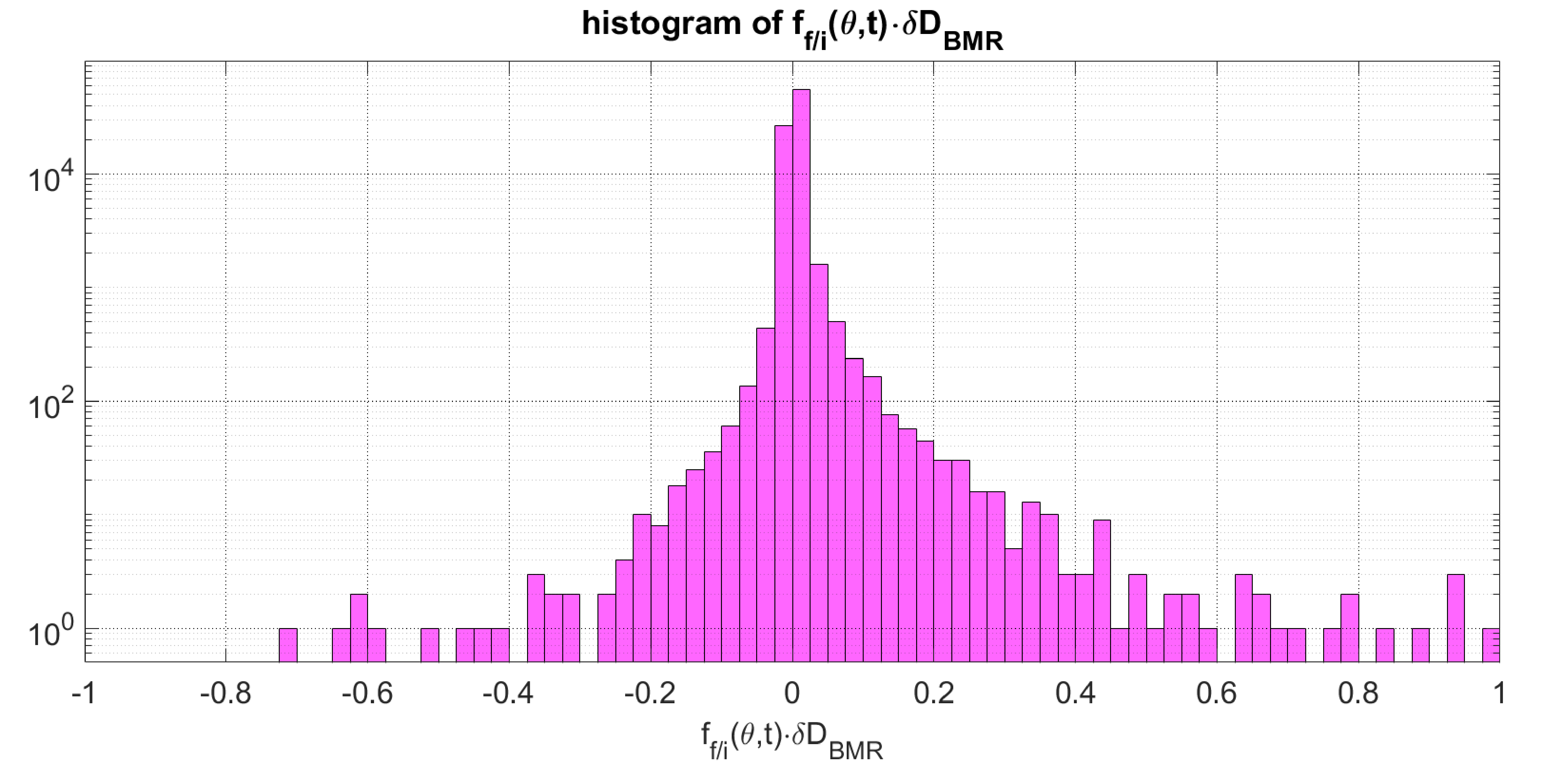
(v_{00} = 7.5 m/s)



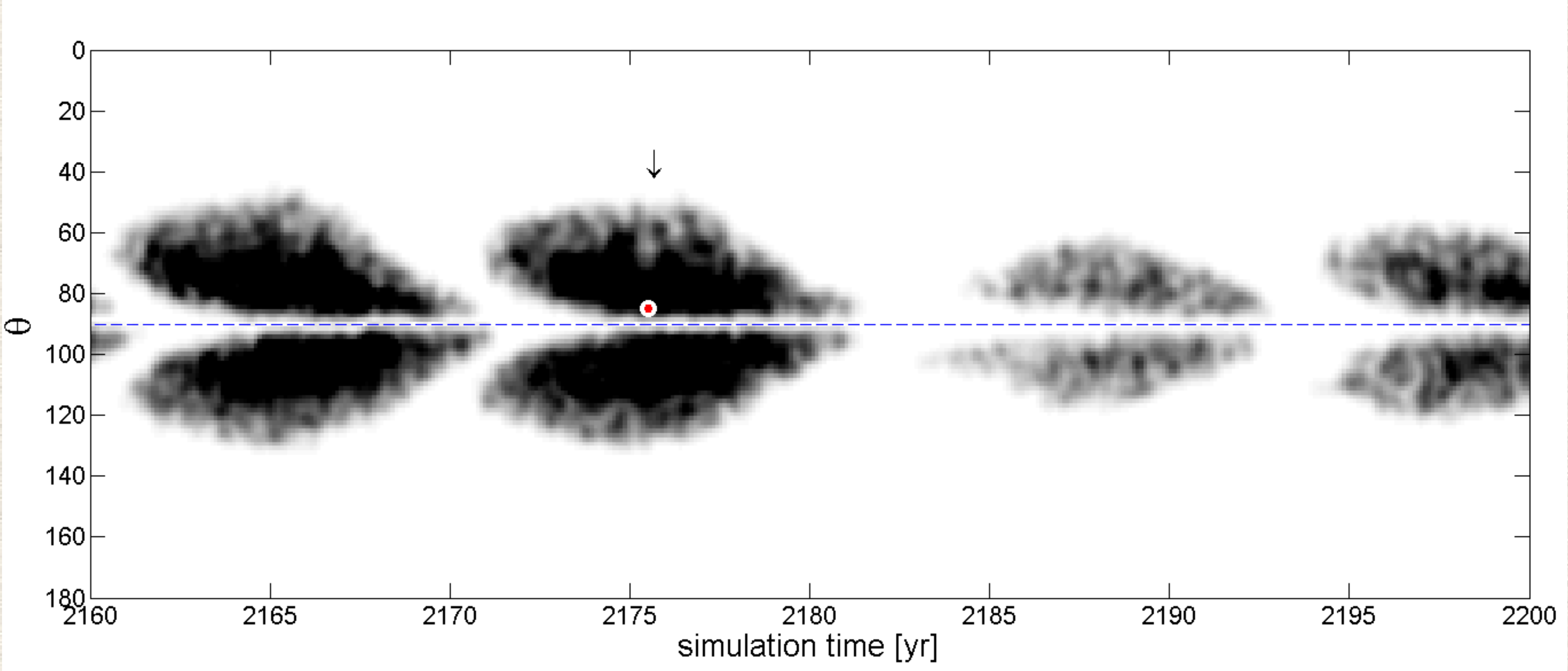


Full simulation with flux dependent inflow and stochastic tilt & separation.

- Cycle-to-cycle variation
- Hemispheric asymmetry
- Cross-hemispheric flows


histogram of $f_{f/i}(\theta,t)\cdot\delta D_{BMR}$
10^4
10^2
10^0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$f_{f/i}(\theta,t)\cdot\delta D_{BMR}$

Method



Date	θ_{Lead}	θ_{Trail}	α	d	F_{Trail} [10^{23}Mx]	δD_{BMR}
2175.68	84.80	89.50	-8.54	31.65	2.43	$-0.2210*10^{23}$