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Utilisation de l'hélicité magnétique dans la prévision des éruptions solaires

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Efficiency of flares & eruptions forecasting

- Multiplication of daily forecasts centers and methods: MET Office, SWPC, SIDC, …

- **Barnes et al. 2016**: comparison of a large number of forecasting methods with a common dataset:
  - **"[…], none of the methods achieves a particularly high skill score. […].Thus there is considerable room for improvement in flare forecasting."**

(Crown et al. 12)

SUCCESS RATES AND SKILL SCORES FOR THE SAMPLE PARAMETERS

Parameter	Success Rate	Heidke Skill Score	Climatological Skill Score
No Flare	0.908	0.000	0.000
Φ_{tot}	0.922	0.153	0.197
E_e	0.916	0.081	0.231
R	0.922	0.144	0.242
B_{eff}	0.913	0.072	0.220

Table 4. Performance on All Data with Reference Forecast

Parameter/ Method	Statistical Method	C1.0+, 24 hr ApSS	C1.0+, 24 hr BSS	M1.0+, 12 hr ApSS	M1.0+, 12 hr BSS	M5.0+, 12 hr ApSS	M5.0+, 12 hr BSS
B_{eff}	Bayesian	0.12	0.06	0.00	0.03	0.00	0.02
ASAP	Machine	0.25	0.30	0.01	-0.01	0.00	-0.84
BBSO	Machine	0.08	0.10	0.03	0.06	0.00	-0.01
WL_{SG2}	Curve fitting	N/A	N/A	0.04	0.06	0.00	0.02
NWRA MAG 2-VAR	NPDA	0.24	0.32	0.04	0.13	0.00	0.06
$\log(\mathcal{R})$	NPDA	0.17	0.22	0.01	0.10	0.02	0.04
GCD	NPDA	0.02	0.07	0.00	0.03	0.00	0.02
NWRA MCT 2-VAR	NPDA	0.23	0.28	0.05	0.14	0.00	0.06
SMART2	CCNN	0.24	-0.12	0.01	-4.31	0.00	-11.2
Event Statistics, 10 prior	Bayesian	0.13	0.04	0.01	0.10	0.01	0.00
McIntosh	Poisson	0.15	0.07	0.00	-0.06	N/A	N/A

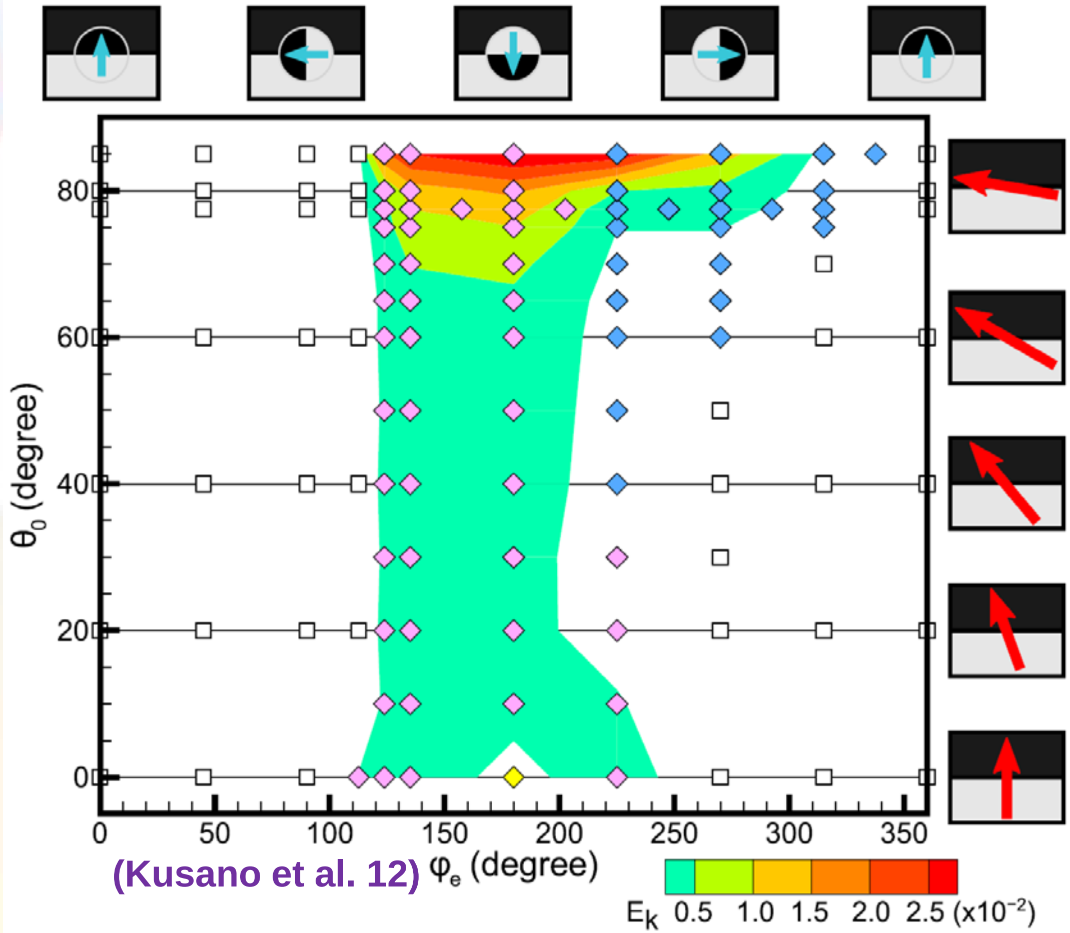
(Barnes et al 16)

Eruptivity prediction & numerical modeling

- **Search for eruptivity criterion is almost exclusively based on observational datasets …**
- **… and barely benefits from the recent tremendous improvements in numerical modeling .**

- Useful numerical models must present several cases either eruptive or stable, ideally
  - > 2 cases
  - depending on few number of parameters

- **Kusano et al. 2012**: parametric analysis based on relative orientation of large scale sheared polarity and small scale



(Kusano et al. 12)

Motivations & Methodology

- **Goal: use flux emergence simulations to look for efficient eruptivity criterion**
  - **Leake et al. 2013 and Leake et al. 2014**:
    - **7 flux emergence simulations**
    - 3D visco-resistive MHD eq. solved with Lagrangian-remap code **(Arber et al. 2001)**
    - **lead to eruptive and non-eruptive cases**
    - **varying only an unique initial parameter**

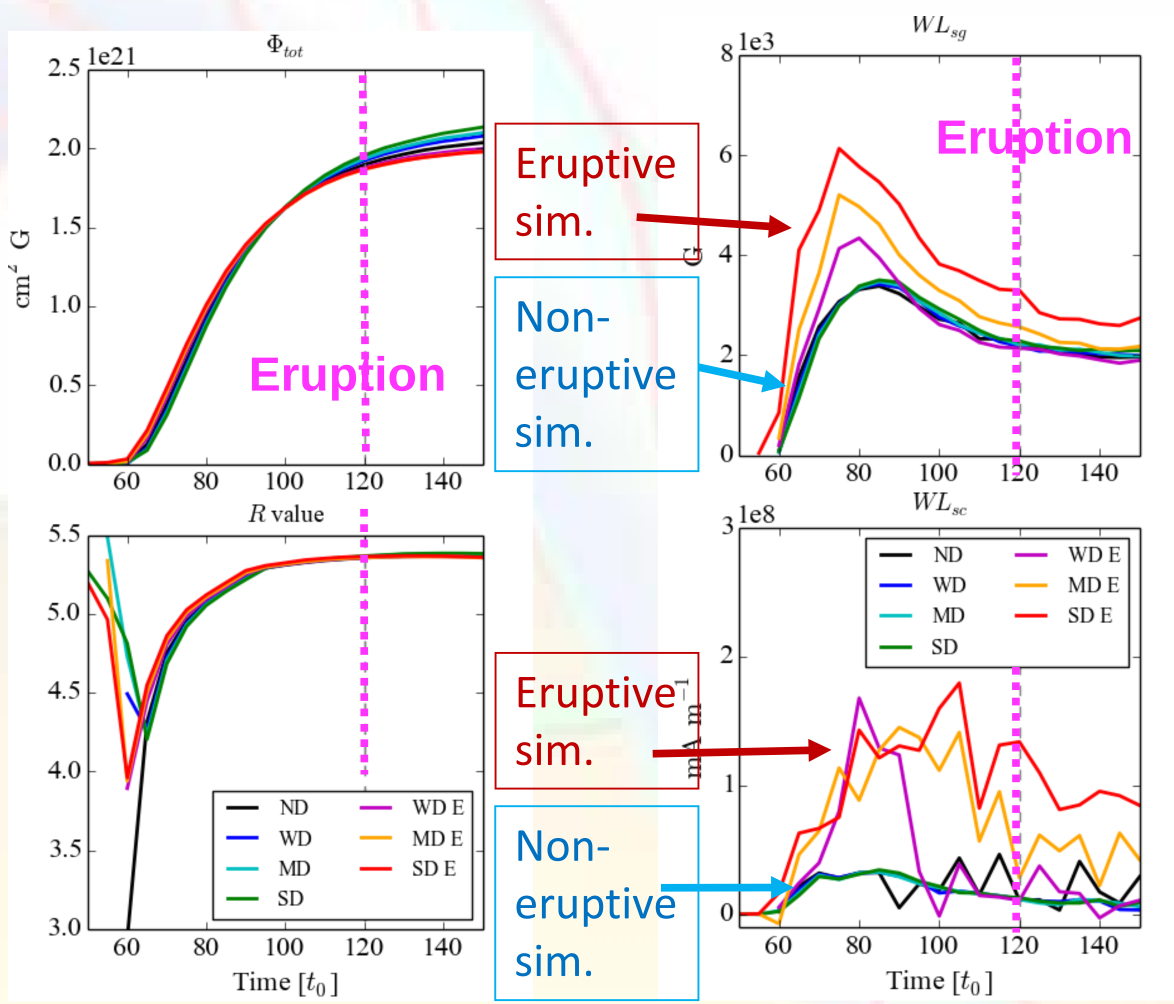
(Leake et al. 13, 14)

- Methodology: - extract part of the magnetic field,
  - compute different physical quantities,
  - search for the ones that discriminates between the eruptive and non-eruptive case
- **Guennou et al. 17**: **2D photospheric mag. field**
  - similarly to observed data
  - 99 physical quantities studied.
- **This talk: 3D coronal magnetic field B(z>0)**

Search for eruptivity criterion

- **Goal: search for eruptivity indicators from 3D coronal magnetic datacube**
- Good eruptivity criterion should:
  - Discriminate eruptive and non-eruptive sim. during pre-eruptive phase
  - Reach its highest value
    - for eruptive simulation only,
    - during the pre-eruptive phase only.
  - Present similar trend for eruptive and non-eruptive sim. in post-eruptive phase

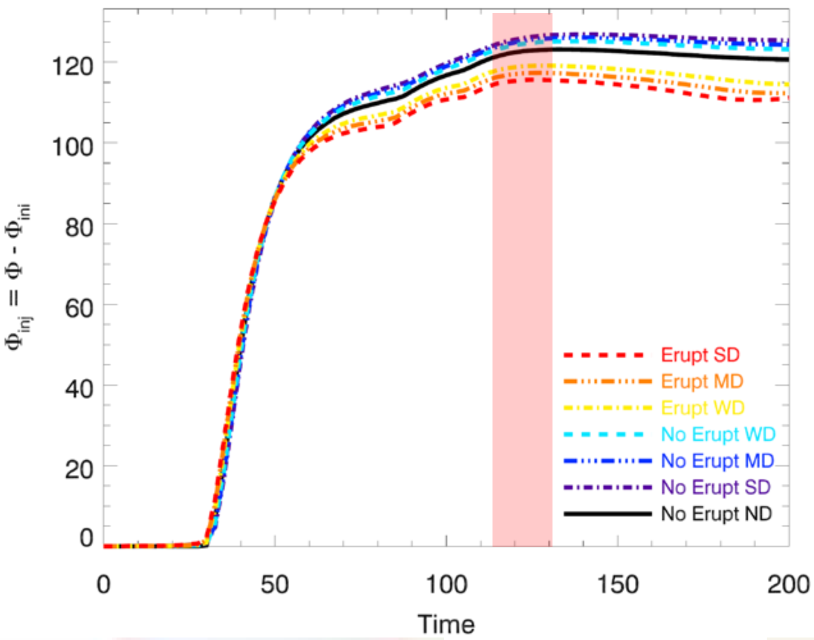
Useless Criteria **Pertinent Criteria**



(Guennou et al. 17)

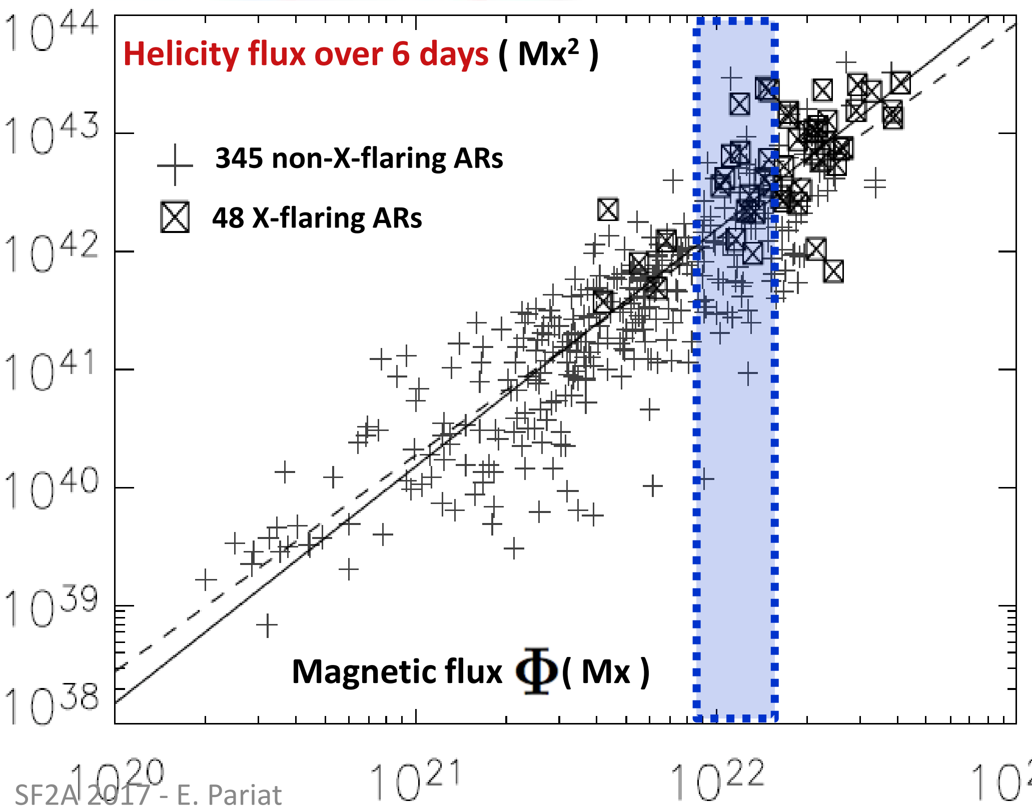
Magnetic fluxes

(Pariat et al. 17)



- Reference magnetic flux depends on the arcade field strength
- **Injected flux by emerging flux rope is roughly identical for all 7 simulations**

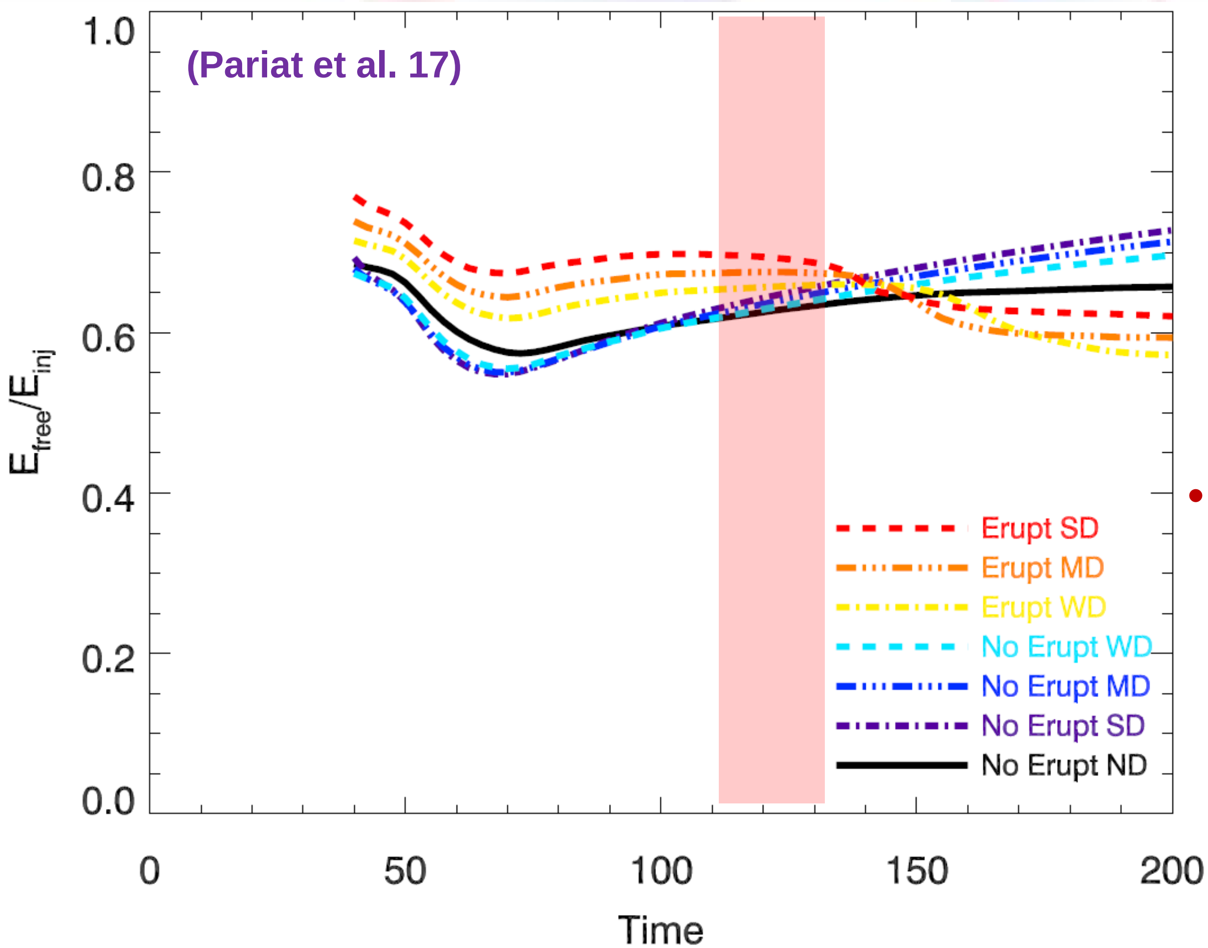
(Labonté et al. 07)

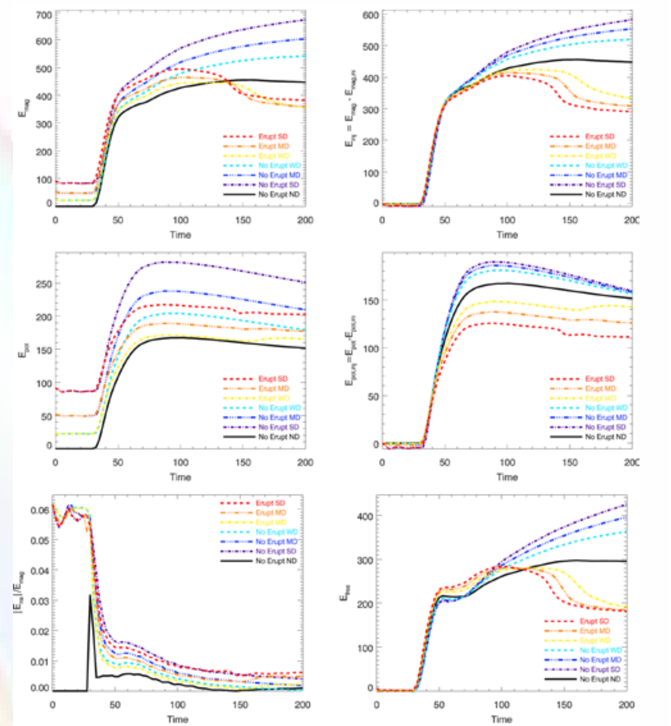


- Limits of the model: eruptivity criterion valid given a roughly constant injected magnetic flux.
- **➔ determining why active regions with a given magnetic flux erupt and others do not.**

Magnetic energies

- Magnetic energies are not well discriminating between the different simulations and do not provide reliable eruptivity diagnostics





- **Ratio of free magnetic energy to injected energy is marginally an indicator of eruptivity of the system**
  - not strongly discriminative:
  - maximum value for eruptive flare are only marginally above non-eruptive ones.

Relative Magnetic Helicity

$$H = \int_{\mathcal{V}} \mathbf{A} \cdot \mathbf{B} \, \mathrm{d}\mathcal{V}$$

- **Magnetic helicity of MHD plasmas** **(Elsasser 1956)**
  - **signed scalar** value: magnetic flux weighted Gauss Linking Number of pairs of magnetic field lines **(Moffatt 1968)** : signed level of entanglement & twist of field lines
  - **Invariant in ideal MHD** **(Woltjer 1958)**, **quasi-invariant for impulsive non-ideal processes** **(Taylor 1974, Pariat et al. 2015)**
  - Impact on dynamic of magnetic reconnection: **e.g. Linton et al. 2001, Del Soro et al. 2010**
  - Indications of relation with enhanced solar eruptivity: **Nindos et al. 2004, Labonte et al. 2007, Park et al. 2008, 2010, Tziotziou et al. 2012**

- **Useful quantity for natural plasmas: Relative Magnetic Helicity**: helicity of a studied field relative to a reference field **(Berger 1984, Finn & Antonsen 1985).**

$$H_{\mathcal{V}} = \int_{\mathcal{V}} (\mathbf{A} + \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \; \mathrm{d}\mathcal{V}$$

with boundary condition :

$$(\mathbf{B}_{\mathrm{p}} \cdot \mathrm{d}\mathbf{S})\,|_{\partial\mathcal{V}} = (\mathbf{B} \cdot \mathrm{d}\mathbf{S})\,|_{\partial\mathcal{V}}$$

- Gauge invariant provided that studied and reference fields share the same magnetic-flux distribution on the whole boundary.

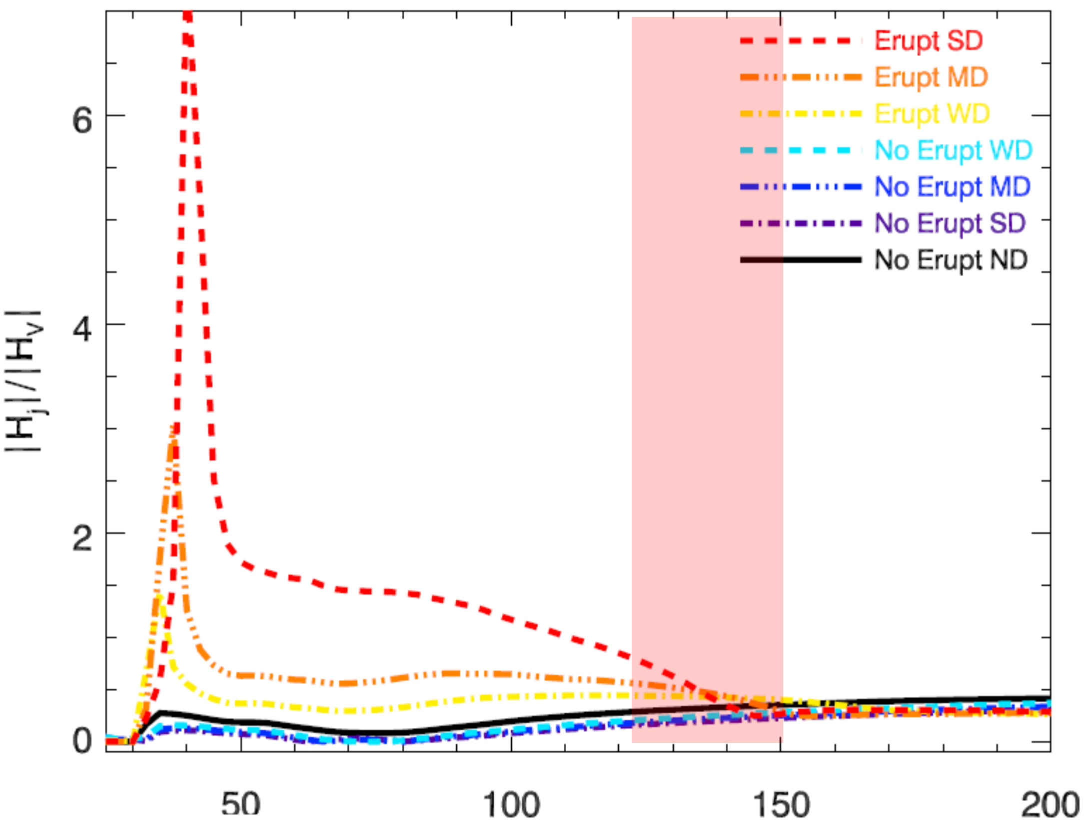
Relative magnetic helicity decomposition

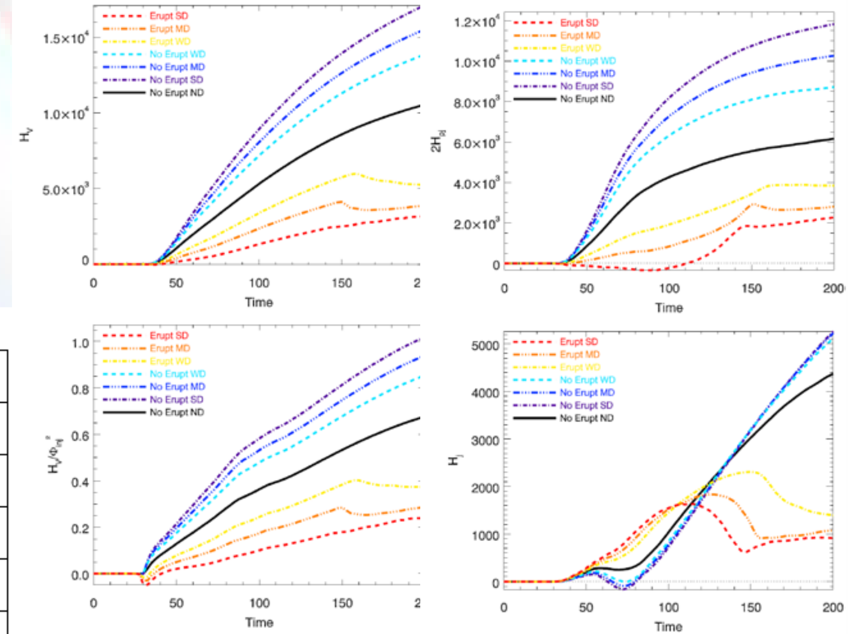
$$
\begin{aligned}
H_V &= H_{\mathrm{j}} + 2H_{\mathrm{pj}} \quad \text{with} \\
H_{\mathrm{j}} &= \int_{\mathcal{V}} (\mathbf{A} - \mathbf{A}_{\mathrm{p}}) \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \, \mathrm{d}\mathcal{V} \\
H_{\mathrm{pj}} &= \int_{\mathcal{V}} \mathbf{A}_{\mathrm{p}} \cdot (\mathbf{B} - \mathbf{B}_{\mathrm{p}}) \, \mathrm{d}\mathcal{V}
\end{aligned}
$$

- **Berger et al. 2003 :** relative magnetic helicity can be decomposed in 2 quantities:
  - H_j = magnetic helicity of the current-carrying/non-potential field B_j
  - H_{pj} = intra-helicity between potential and current carrying fields
- H_V, H_j, & H_{pj} are all gauge invariant.

$|H_j|/|H_V|$: excellent eruptivity indicators

- While magnetic helicities are clearly discriminating between the different simulations, they do not provide reliable eruptivity diagnostics





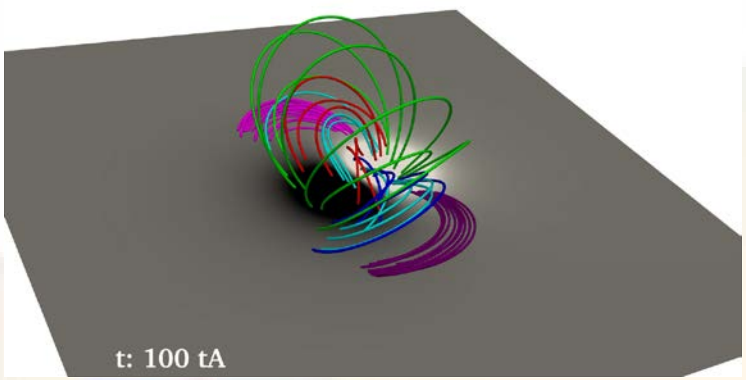
(Pariat et al. 17)

$$
\begin{aligned}
H_V &= H_j + 2H_{pj} \quad \text{with} \\
H_j &= \int_{\mathcal{V}} (\mathbf{A} - \mathbf{A}_p) \cdot (\mathbf{B} - \mathbf{B}_p)\, d\mathcal{V} \\
H_{pj} &= \int_{\mathcal{V}} \mathbf{A}_p \cdot (\mathbf{B} - \mathbf{B}_p)\, d\mathcal{V}
\end{aligned}
$$

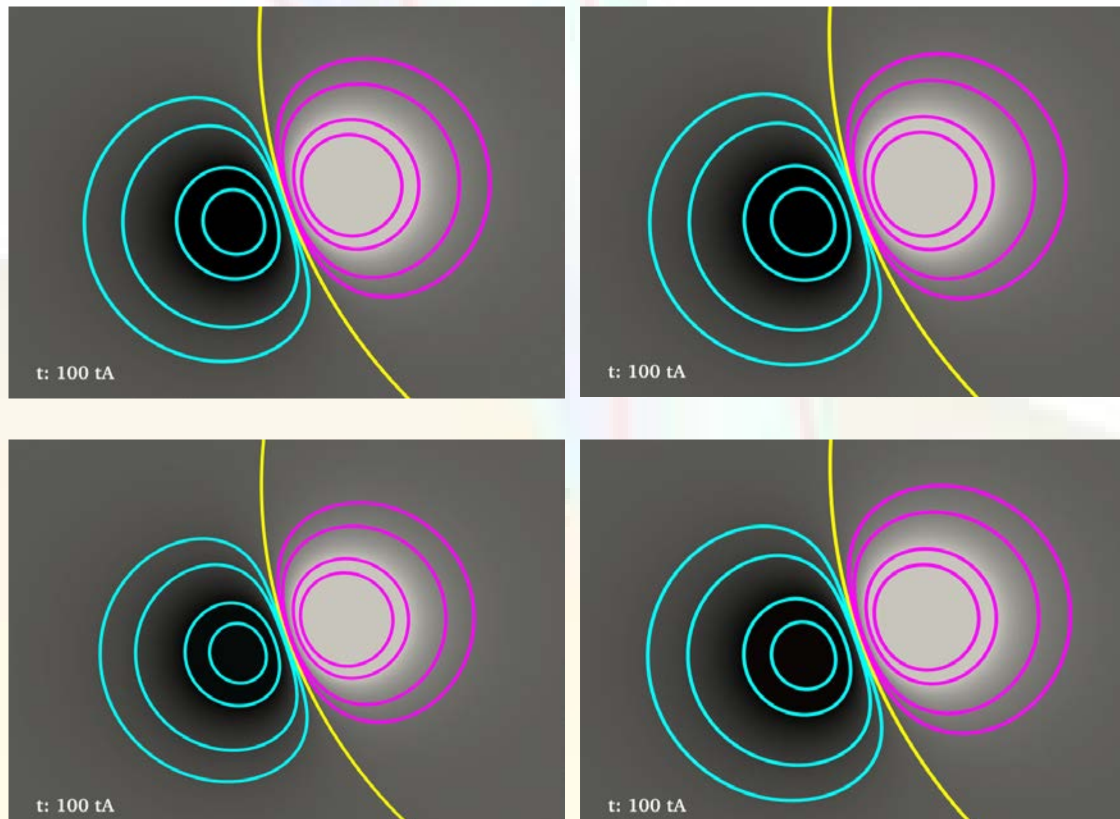
- **$|H_j|/|H_V|$ appears as an excellent eruptivity predictor of these sims.**

Further evidences : torus-instability triggered eruptive simulations

- **Zuccarello et al. 2015**: parametric eruptive simulations (available @ MEDOC)
- **4 different line-tied boundary driving patterns** with different: shear around the PIL magnetic flux dispersion + 1 non-eruptive control case (diffusion)
- **Precise determination of the onset time, t_{erupt}, thanks to numerous relaxation runs initiated at regular stage of the simulations**

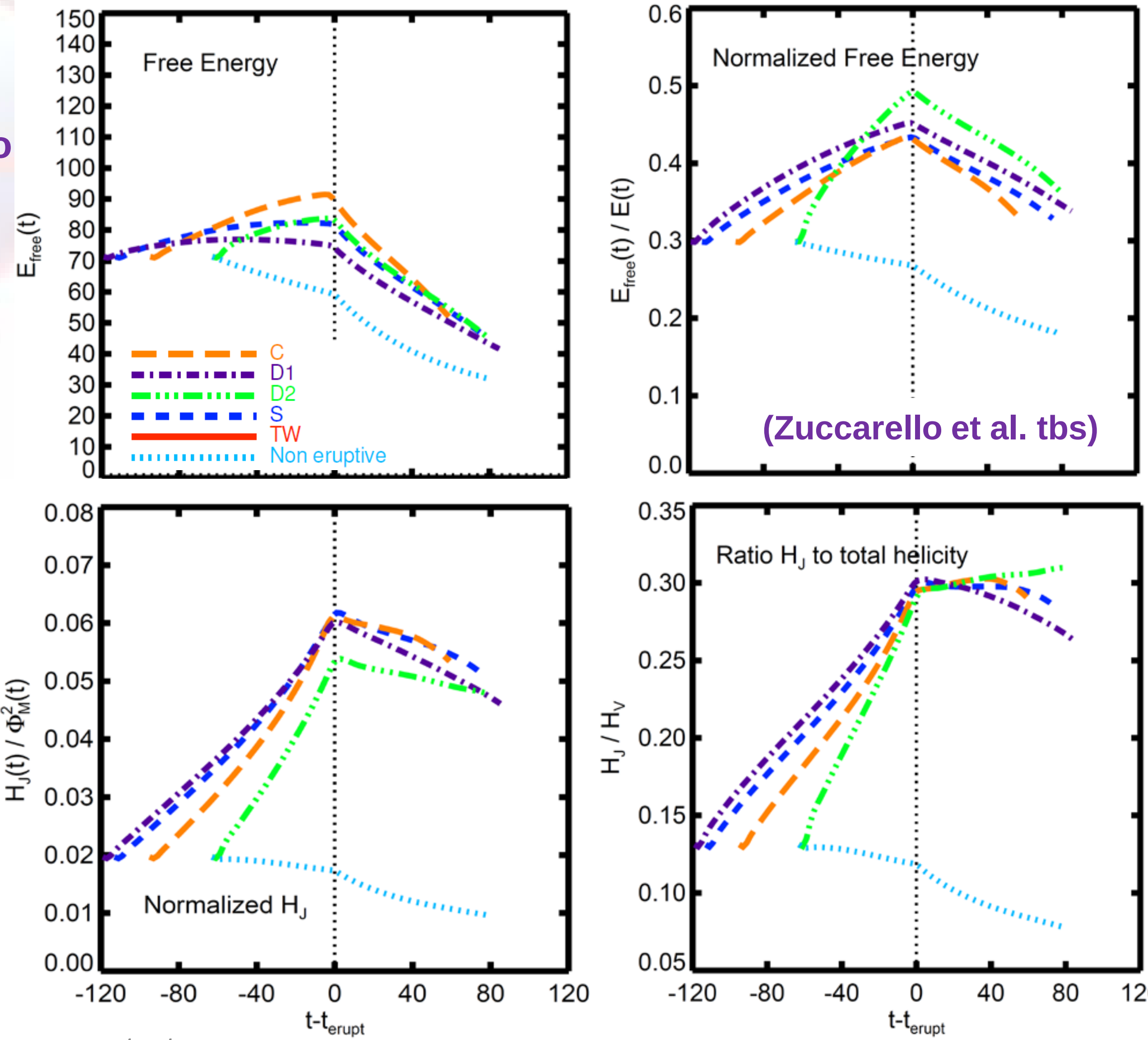


(Aulanier et al. 10, Zuccarello et al. 16)



Further evidences : torus-instability triggered eruptive simulations

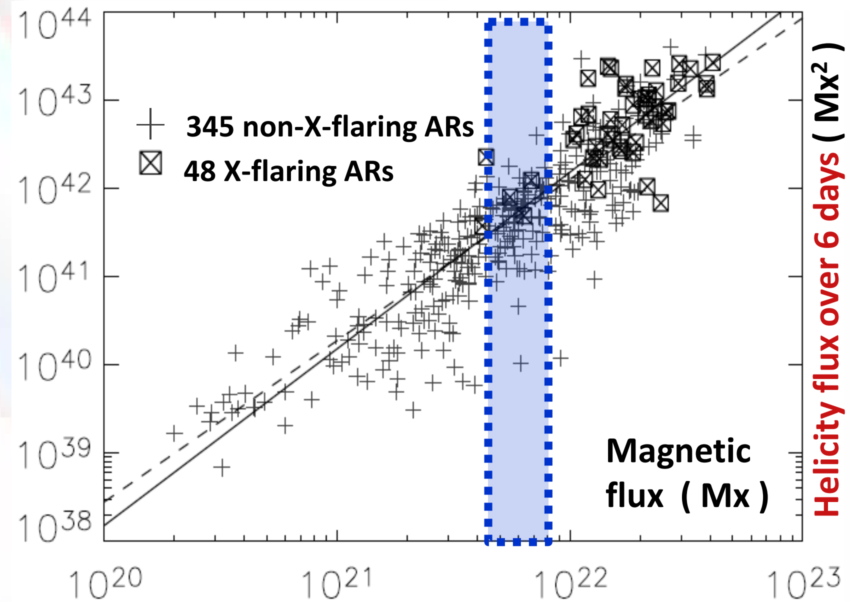
- Computation of several quantities at the sim. respective t_{erupt} : **Zuccarello et al. to be submitted.**
- **Despites different boundary drivers and t_{erupt}, eruptions are triggered when $|H_j|/|H_V|$ reaches the same value:**
  - <4% dispersion
  - within measurement precision of helicity
- All other quantities have dispertions of values above 8 % at t_{erupt} , including torus instability criteria

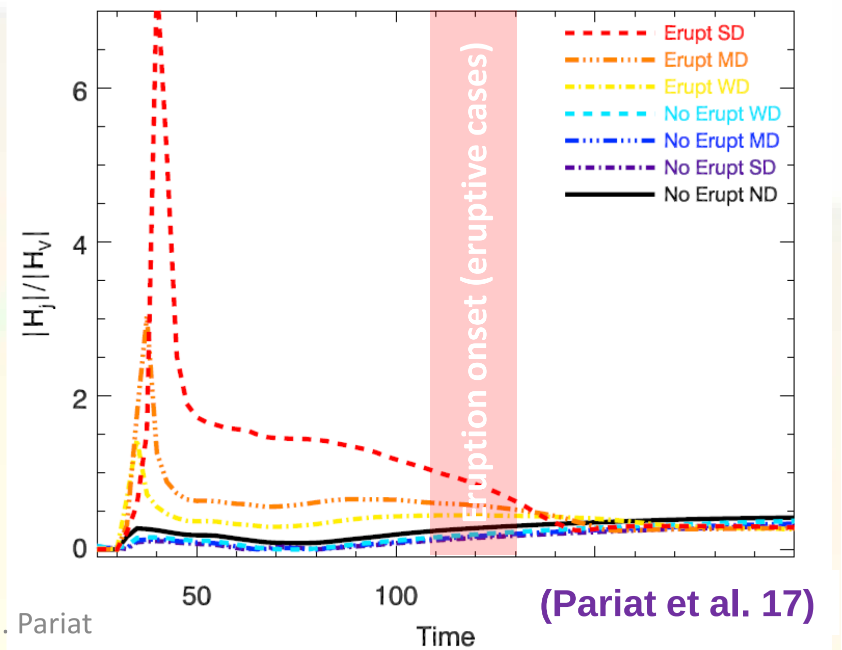


Conclusions

- (too) Rare attempts to use parametric numerical simulation to study eruptivity proxy of solar active events.
- **The ratio |Hj|/|Hv| is an excellent indicator of the eruptivity state in several numerical models**
  - 15 different numerical simulations
  - inducing 11 eruptions & 6 stable systems
  - in 4 very different magnetic configuration
  - performed by 3 different MHD numerical codes
- **BUT: our understanding of relative magnetic helicity is not “mature” enough**
  - not simply/directly measurable from standard observations
  - actual def. of relative helicity may not be optimal: e.g. not simply additive quantity.

(Labonté et al. 07)





(Pariat et al. 17)

Thanks for your attention