Information flow within the magnetosphere-ionosphere system: insights from ensemble-based transfer entropy

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European Geosciences Union 2022 General Assembly

EGU General Assembly 2022

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Aim - Storms/Substorms relationship

Case study: information flow within MI system during storms and substorms

Case study: storm-substorm relationship.

Storms and **substorms** are the manifestations of the magnetosphere-ionosphere response to solar wind driving [Gonzalez et al. 1994; Kamide et al. 1998].

Why is this problem particularly important?

Their relationship is related to the internal physical mechanisms responsible to dissipating the incoming energy

Why is this problem particularly important?

Correct understanding of the information transfer within this system helps to improve forecasting models.

Two contrasting views:

I. A magnetic storm is driven by the successive occurrence of multiple substorms (e.g. **[Akasofu, 1968; De Michelis et al. 2011; Stumpo et al. 2020]**).

II. Storms and substorms are two independent processes both driven by a southward IMF **[Kamide, 1992; McPherron, 1988; Manshour et al. 2021; Runge et al. 2018]**.

Main problem:

The information flow may not be stationary in time.

Idea:

Use an ensemble of AE and Sym-H time series sampled during activity periods and compute the information flow using a sliding window

Method:

Information flow is estimated with the transfer entropy measure **[Schreiber, 2000]**

The transfer entropy is the generalization of **Granger (predictive) Causality (GC)**

The classical scheme of GC:

$$Y_t = a_0 + \sum_{k=1}^{L} b_{1k} Y_{t-k} + \sum_{k=1}^{L} b_{2k} X_{t-k} + \epsilon_t$$

IF:
$$\begin{cases} b_{2k} \neq 0 \text{ for some } k \Rightarrow X \text{ cause } Y \\ b_{2k} = 0 \ \forall k \Rightarrow X \text{ does not cause } Y \end{cases}$$

Essentially a statistical test based on the idea of regression.

Problem: the classical scheme only accounts for **linear interactions**

Information theory allows to test **Granger causality** without the assumption of an underlying model

The information flow is formalized as a distance from the **generalized Markov condition**

$$p(y_i \,|\, \mathbf{y}_{i-1}^{(k)}, \mathbf{x}_{i-\tau}^{(l)}) = p(y_i \,|\, \mathbf{y}_{i-1}^{(k)})$$

Satisfied if and only if the future state of Y does not depend on the past of X

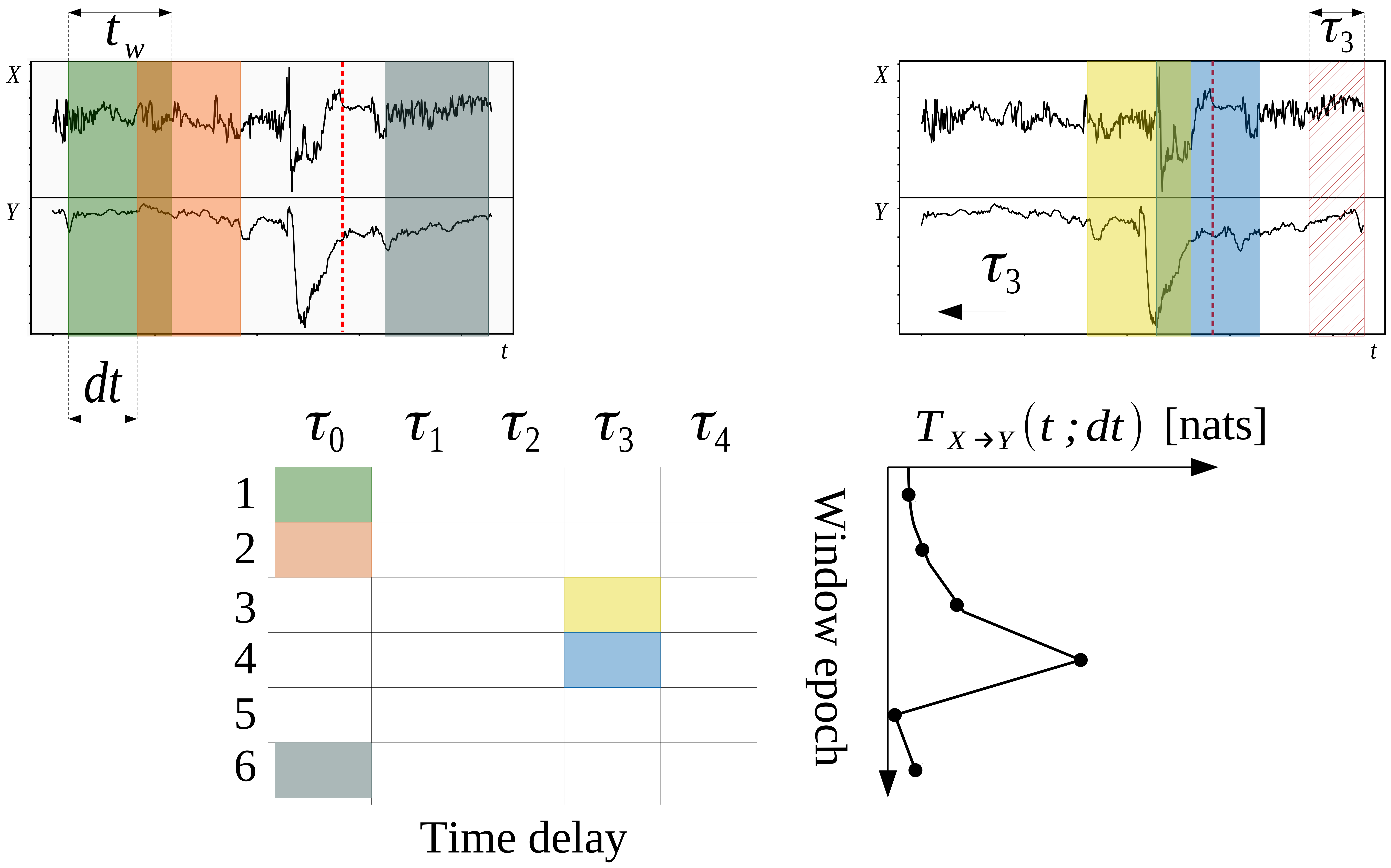
We use the Kullback-Leibler divergence to measure the distance from Markov condition

Inf. Flow From X to Y

$$T_{X\to Y}(\tau) = \sum_{y_i, \mathbf{y}_{i-1}^{(k)}, \mathbf{x}_{i-\tau}^{(l)}} p(y_i, \mathbf{y}_{i-1}^{(k)}, \mathbf{x}_{i-\tau}^{(l)}) \log \frac{p(y_i \,|\, \mathbf{y}_{i-1}^{(k)}, \mathbf{x}_{i-\tau}^{(l)})}{p(y_i \,|\, \mathbf{y}_{i-1}^{(k)})} \geq 0$$

Model free

Methods - Local Transfer Entropy



14 realizations of Sym-H and AE

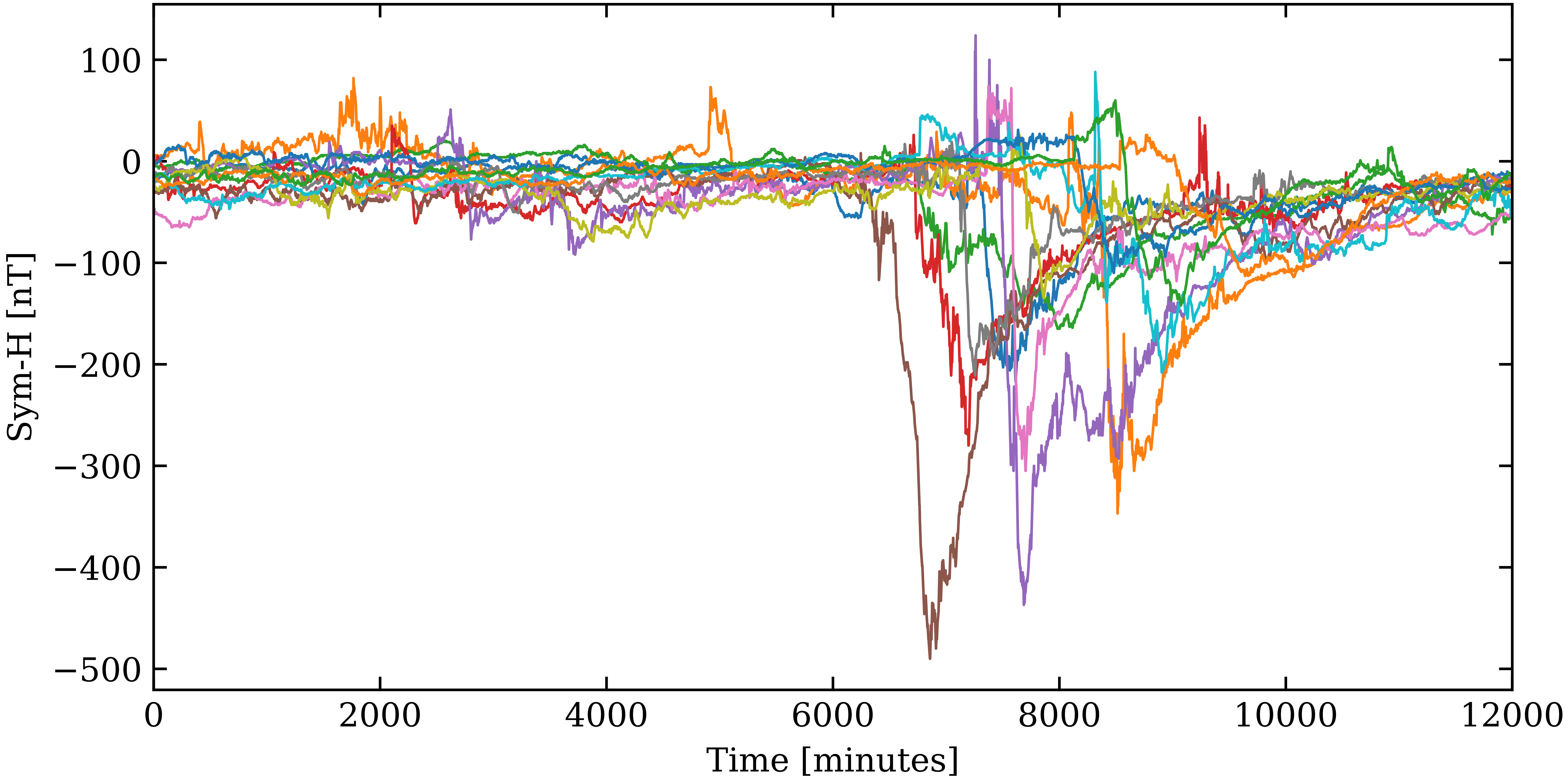
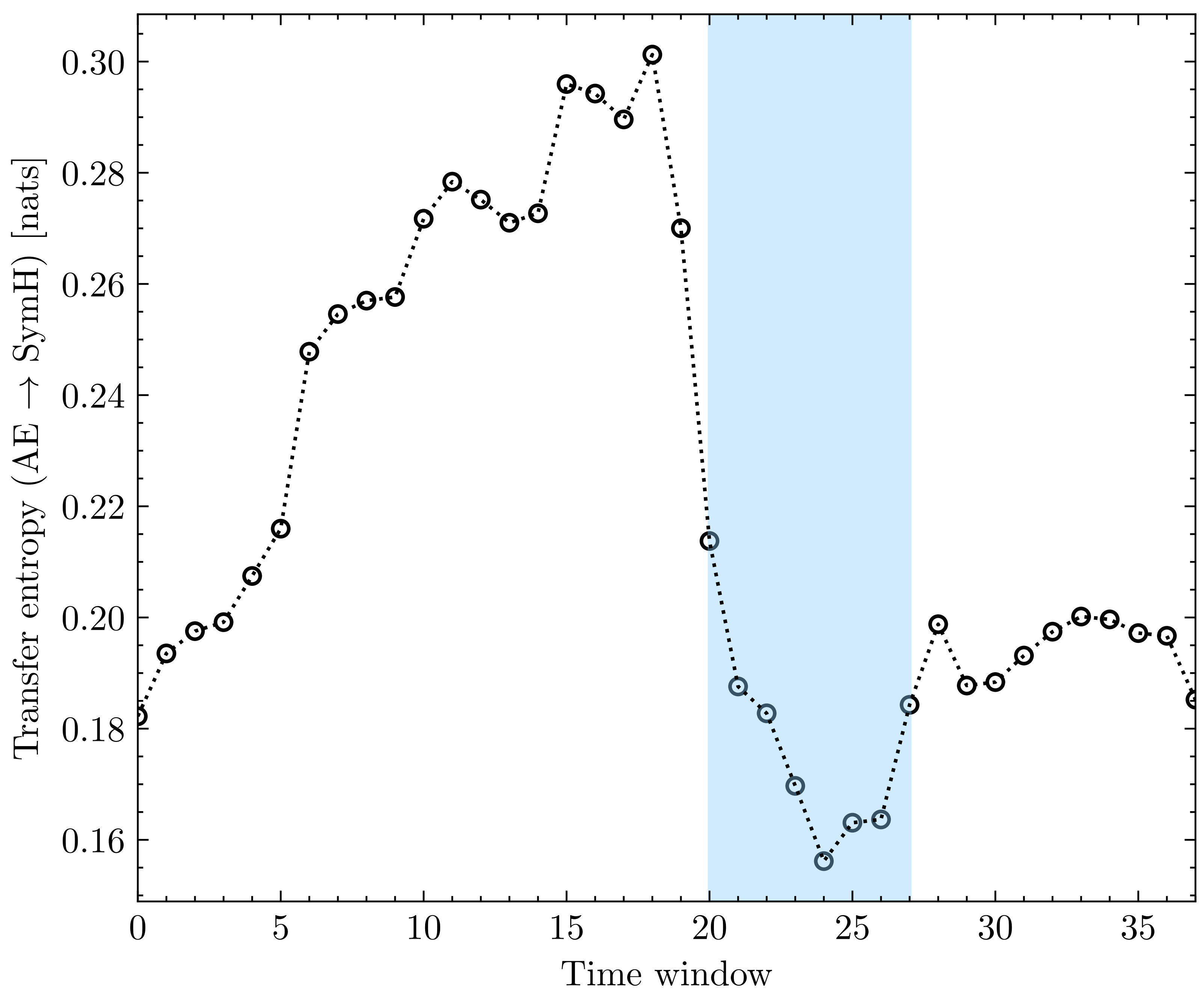


Table: events in the dataset

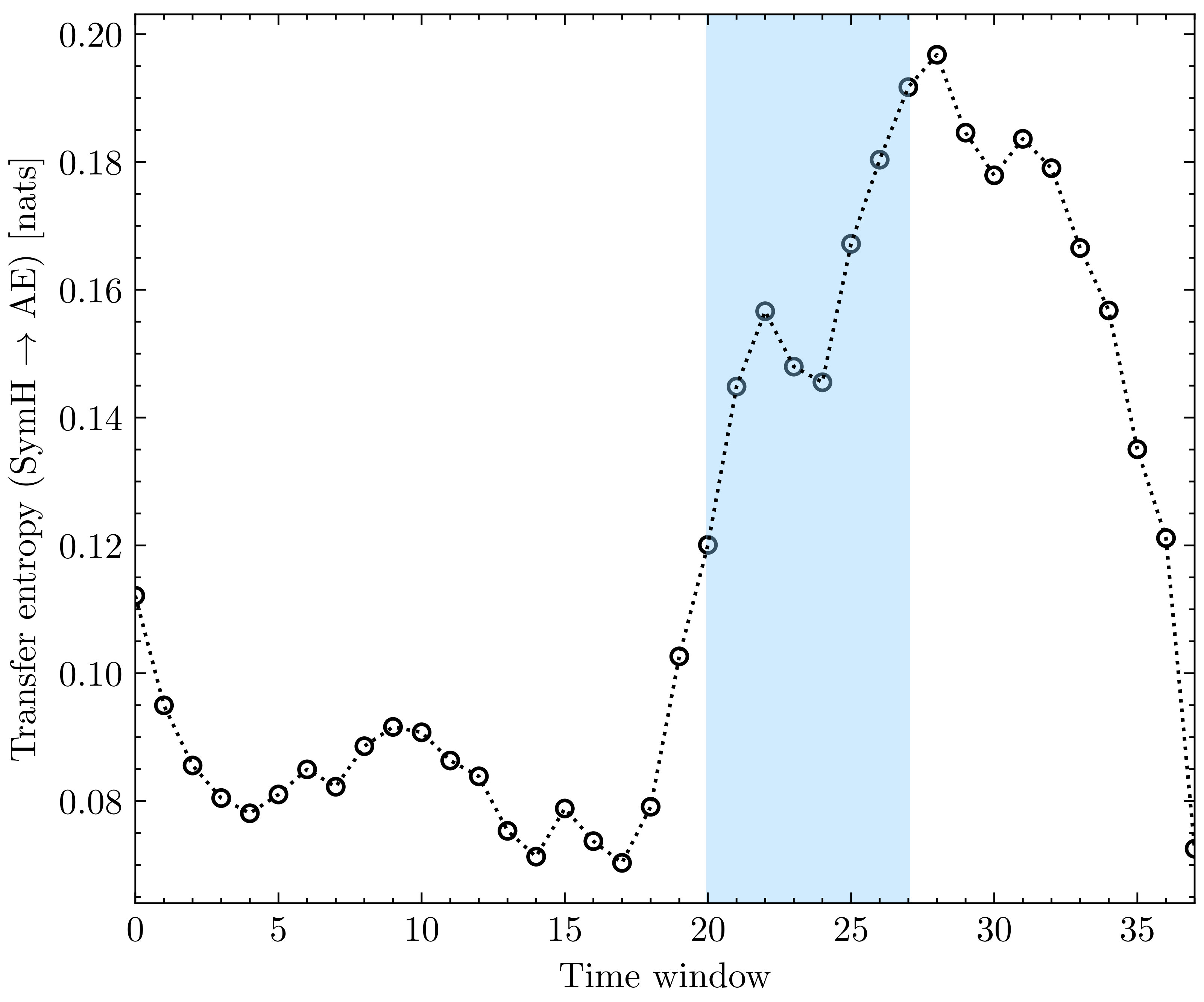
Date	min(Sym-H) (nT)
1998-09-25	-217
2000-07-15	-347
2001-03-20	-165
2001-04-01	-280
2003-11-21	-437
2005-05-15	-490
2006-12-15	-305
2015-01-07	-211
2015-03-17	-135
2015-06-22	-208
2016-03-06	-110
2016-10-12	-114
2017-05-27	-142

Results (Sym-H <—> AE)

AE —> Sym-H



Sym-H —> AE



- (Preliminary) Results suggest the existence of a non-trivial information flow within the magnetosphere-ionosphere system during storms and substorms.
- We evidenced an enhancement of the information flow from AE to Sym-H localized **during the pre-storm phase** and a feedback process in the opposite direction during the main phase.
- Agreement with observations of ionospheric ions (O^+) populating the ring current during the development of the storm.

Future works:

I. Analysis with larger dataset
II. Statistical thresholding
III. Conditional analysis to remove the influence of IMF

Acknowledgements

The OMNI data were obtained from the Space Physics Data Facility (SPDF) Coordinated Data Analysis Web (CDAWeb) interface at https://cdaweb.gsfc.nasa.gov/index.html/. The authors also acknowledge World Data Center for Geomagnetism (Kyoto) for the use of the geomagnetic indices data.

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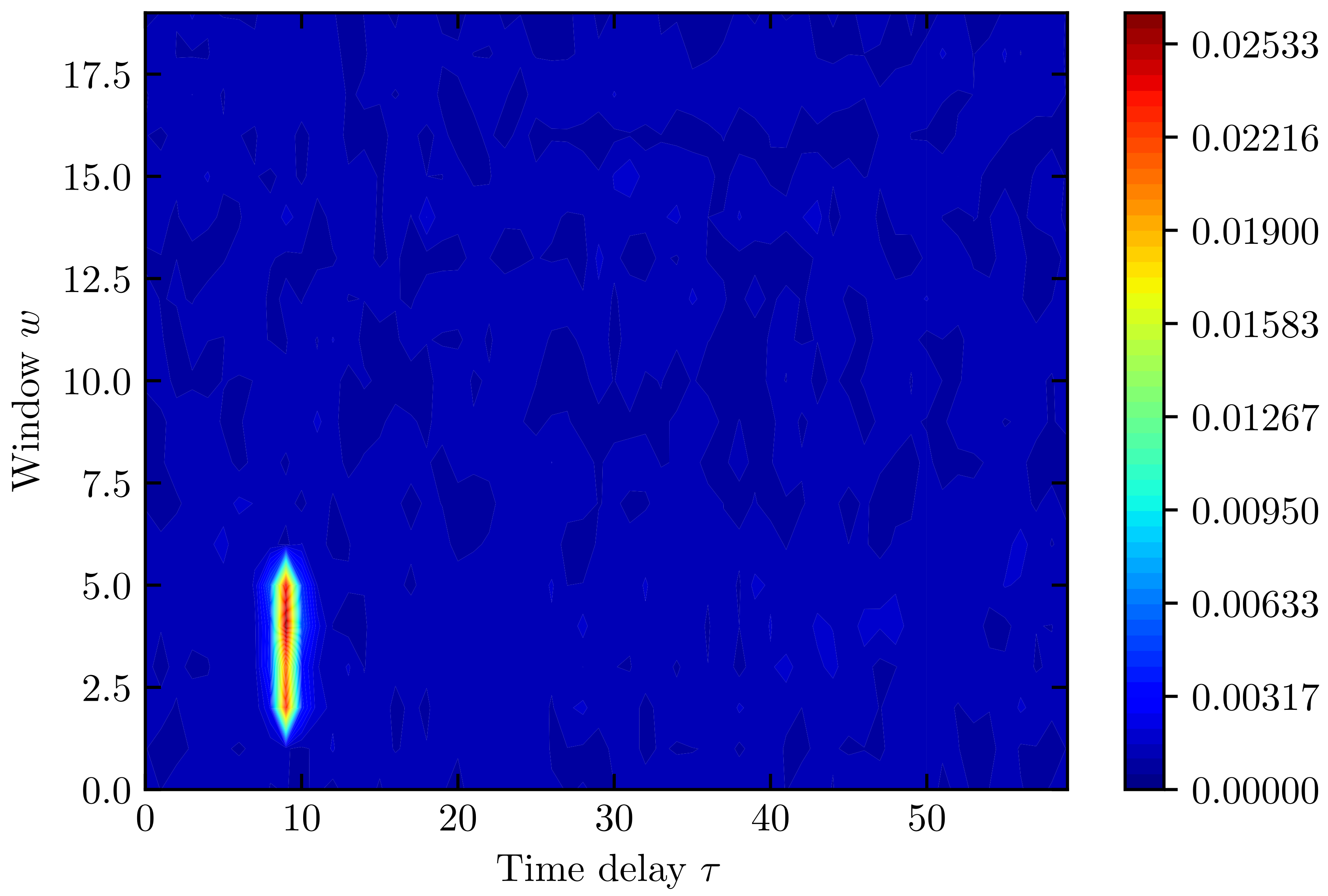
Appendix — An example (localized event)

if $i \in [t, t+dt]$

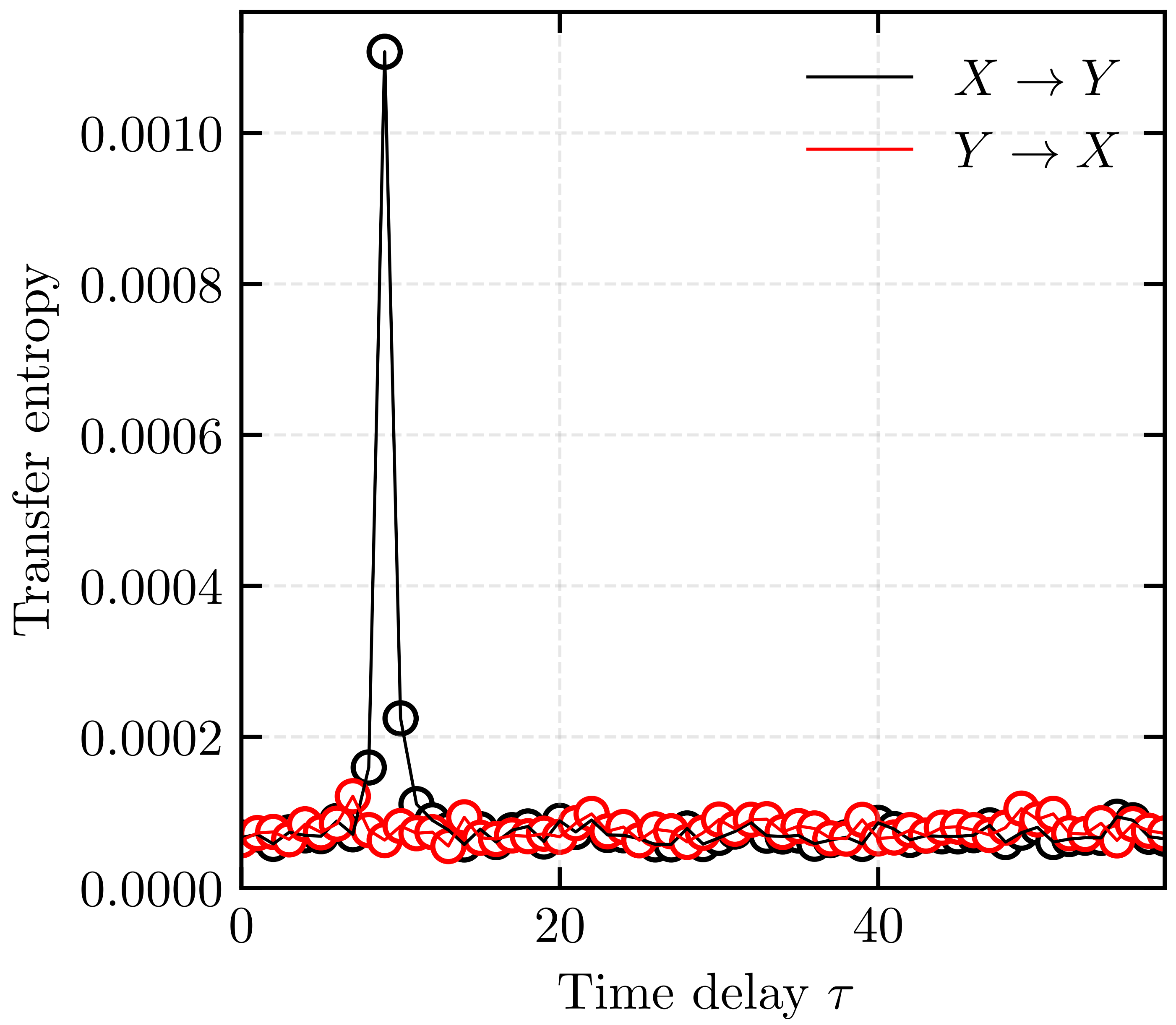
$$\begin{cases} x_{i+1} = a \cdot x_i + \mathcal{N}(0,\sigma) \\ y_{i+1} = b \cdot y_i + a \cdot x_{i-8} + \mathcal{N}(0,\sigma) \end{cases}$$

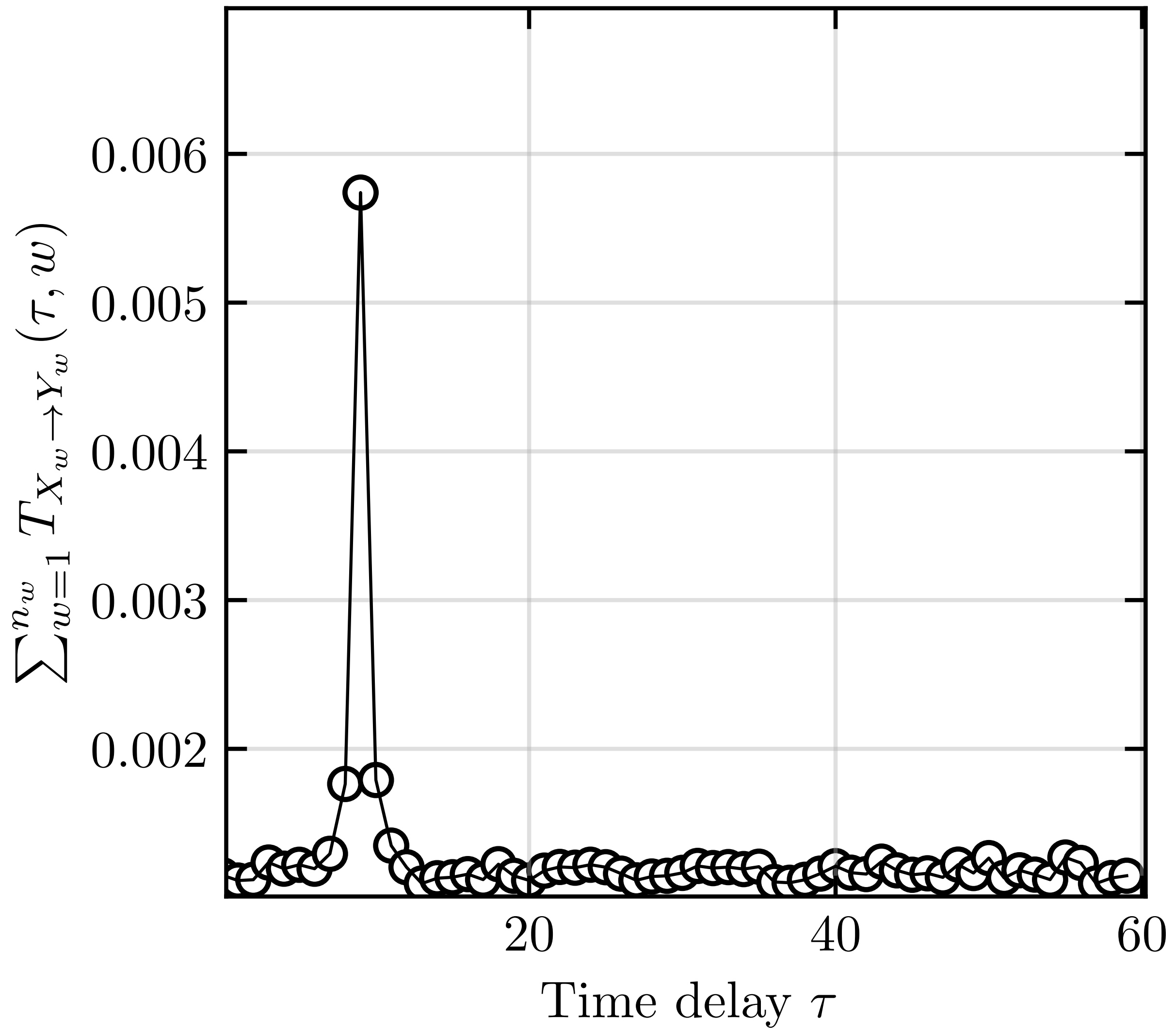
if $i \notin [t, t+dt]$

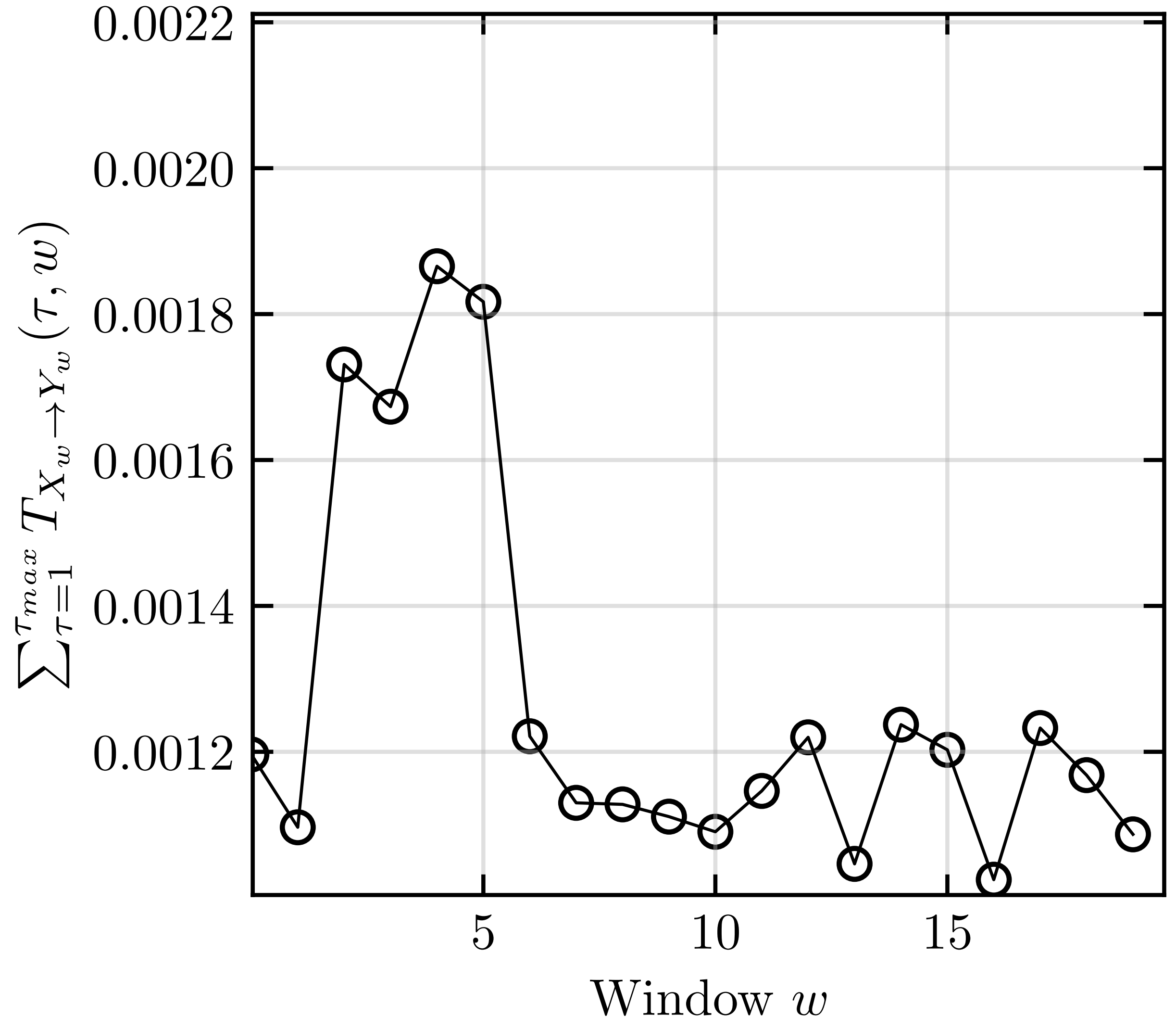
$$\begin{cases} x_{i+1} = a \cdot x_i + \mathcal{N}(0,\sigma) \\ y_{i+1} = b \cdot y_i + \mathcal{N}(0,\sigma) \end{cases}$$



Total averaged information flow







The paper written by De Michelis et al. (2011), which supports this idea, is also one of the first application of the information theory to storm-substorm relationship

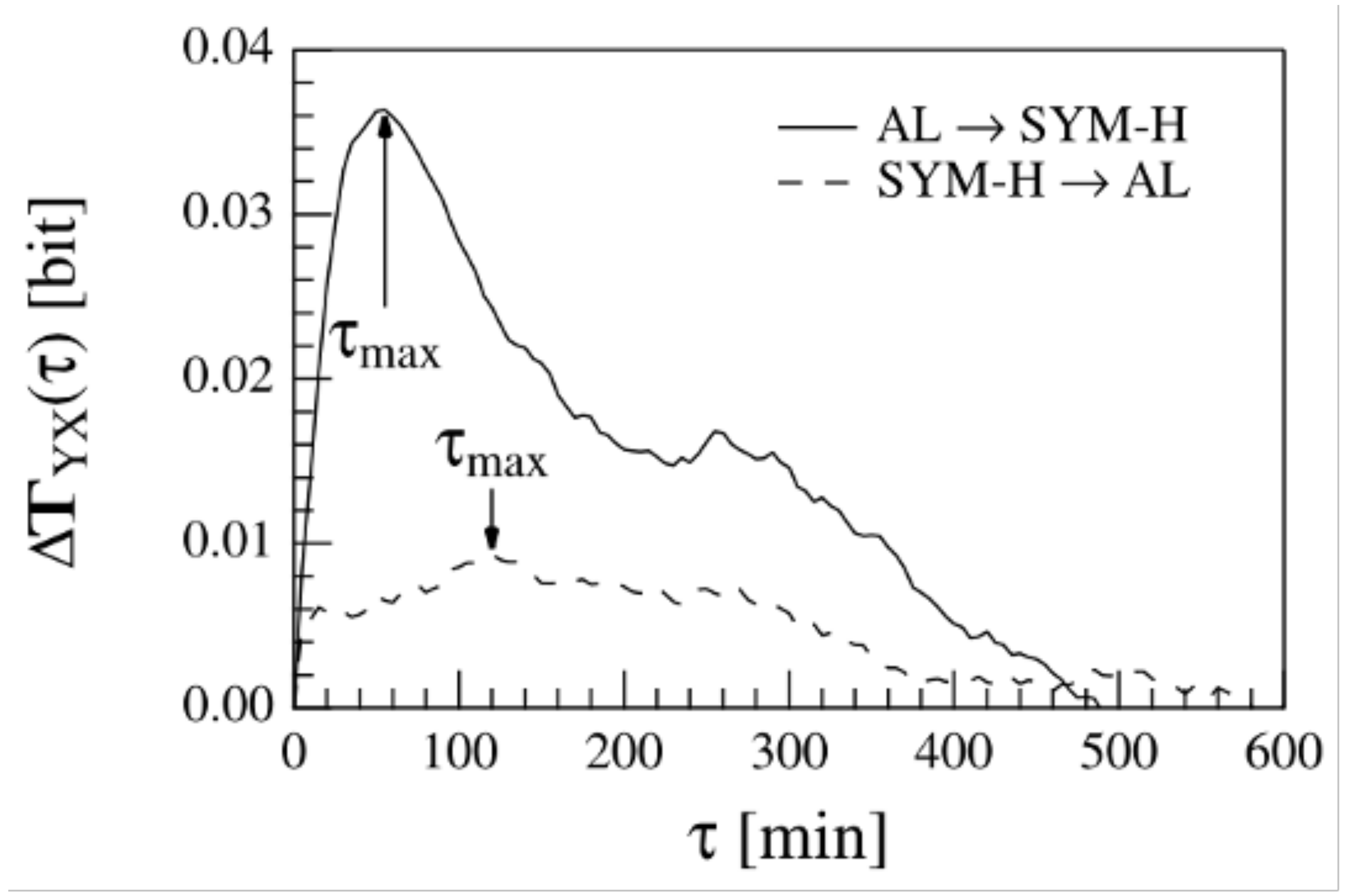
An information theory approach to the storm-substorm relationship

P. De Michelis,[1,2] G. Consolini,[3] M. Materassi,[4] and R. Tozzi[1]

Received 7 February 2011; revised 21 April 2011; accepted 23 May 2011; published 27 August 2011.

[1] One of the most interesting aspects of the global magnetospheric response to solar wind changes is the relationship between storms and substorms. Here we present new results on the relationship between these two different classes of magnetospheric phenomena by approaching the problem on the side of information theory. Using the Auroral Electrojet *AL* and *SYM-H* indices as representative proxies of magnetic substorms and storms, we investigate the transfer of information by means of transfer entropy analysis (Schreiber, 2000). The obtained results seem, on average, to indicate the presence of a net transfer of information from *AL* to *SYM-H* on time scales shorter than 10 h. On the basis of this result, geomagnetic substorms may act as a driver for the occurrence of geomagnetic storms. However, carrying out a more careful analysis which takes into account the global geomagnetic daily activity, we suggest that the direction of information flow between substorms and storms depends on the global activity level. Indeed, if it is true that a sequence of magnetospheric substorms may drive a moderate storm, it is also true that very large storms may dominate and drive the occurrence of magnetospheric substorms.

Their results suggest that there exists a dominant information flow from AL to Sym-H. But the information flow from Sym-H to AL is not zero.



[De Michelis et al. 2011]