The response of field-aligned and horizontal ionospheric currents to HSS/SIR driven storms and comparison to ICME driven storms

M. N. Pedersen, H. Vanhamäki, A. T. Aikio
Space Physics and Astronomy Research Unit, University of Oulu, Finland

Correspondence:
marcus.pedersen@oulu.fi

Motivation and background

You watch the latest satellite measurements of the incoming solar wind and try to forecast when it will impact the ionosphere to let your friends see the aurora. How long do we need to wait to see it?
What if you know that the solar wind is coming from an interplanetary coronal mass ejection (ICME) that erupted a couple days ago, or from a coronal hole. Does that affect the time from L1 observation to auroral display?

The ionospheric and field-aligned currents (FAC) are closely related to the auroral display. Previous studies have shown that the AE index best correlate with the IMF Bz turning when lagged by ~40 min (e.g. Meng et al. 1973, McPherron et al., 2018). However, no study has previously distinguished between delay times for geomagnetic storms driven by high speed stream/stream interaction region (HSS/SIR), ICME sheath and magnetic clouds (MC).

It is also well known that the ionospheric currents are driven both directly and indirectly by the solar wind, for example by loading unloading-processes in the magnetosphere. However it has not been adequately quantified over how long time the solar wind affect the ionospheric currents at any one moment.

We try to answer two research questions:
1) What is the delay time from an interplanetary driver hits the magnetopause and the response observed in the ionospheric currents, and is it different for HSS/SIR, sheath and MC-driven storms?
2) What integration time of the solar wind yields the highest correlation with the ionospheric currents, and is it different for HSS/SIR, sheath and MC-driven storms?

Data

- This study considers 73 geomagnetic storms with $Dst_{min} \leq$ -50 nT from 2010 and 2017:
  28 are HSS/SIR-driven, 26 are ICME sheath-driven and 19 are MC-driven storms (for a list of storms see Pedersen et al. 2021 & 2022).
- The total northern hemispheric field-aligned current (FAC) was provided by the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE), the SME indices were provided by SuperMAG and the solar wind parameters (propagated to the Earth's bow shock nose), SYM-H and PCN indices were from OMNIWeb.
- The solar wind energy coupling to the magnetosphere-ionosphere system was estimated using the Newell coupling function (NCF, Newell et al., 2007):

$$\mathrm{NCF} = V_{SW}^{4/3} B_T^{2/3} \sin^{8/3}(\theta_c/2)$$

- Cross-correlation analysis was carried out for time series of the NCF and selected ionospheric parameters for all the geomagnetic storms.

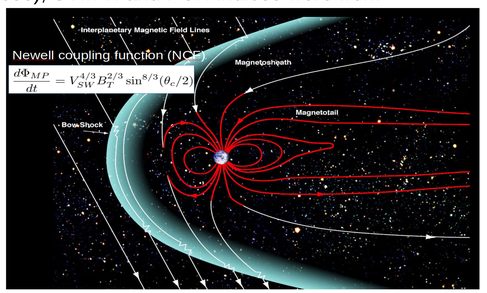

Figure 1. Illustration of solar wind, bow-shock nose and magnetosphere. Image credit: NASA/Goddard.

Research question 1) Delay time from the solar wind hitting the magnetopause to peak correlation with ionospheric currents

Analysis
- Cross-correlation was calculated for the NCF and total FAC for all storms using 10 min resolution.
- The time lag giving peak correlation was found for each storm, and the best lag reported for a category is the median of the lags.

Results
- The best lag between the NCF and total FAC is 40 min for HSS/SIR and sheath storms, and 60 min for MC-driven storms.
- The table shows that similar delays are found using the SME/U/L indices and by changing the coupling function to ε.

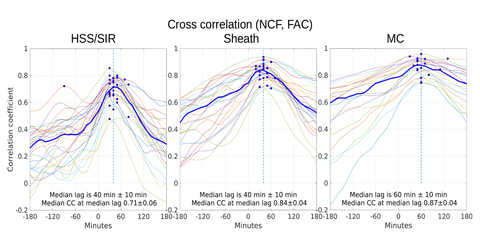

Figure 2. Cross-correlation between NCF and FAC**.** The dots show the peak correlation of individual storms, bold blue lines are median correlation at each time-step and dashed vertical lines show the median time lag

Time lag from cross-correlation

	Time lag (min)		
Parameters	HSS/SIR	Sheath	MC
NCF, FAC	40 ± 10	40 ± 10	60 ± 10
NCF, SME	40 ± 10	35 ± 15	50 ± 10
NCF, -SML	30 ± 10	40 ± 10	60 ± 20
NCF, SMU	30 ± 10	30 ± 20	60 ± 20
NCF, PCN	20 ± 0	20 ± 10	30 ± 10
ε, FAC	40 ± 10	40 ± 10	70 ± 10
ε, SME	30 ± 10	35 ± 15	60 ± 10
ε, -SML	35 ± 5	30 ± 20	60 ± 20
ε, SMU	40 ± 20	30 ± 45	60 ± 20
ε, PCN	20 ± 10	20 ± 20	50 ± 30
FAC, SME	0 ± 0	0 ± 0	0 ± 0
FAC, -SML	0 ± 0	0 ± 0	0 ± 0
FAC, SMU	0 ± 0	0 ± 0	0 ± 10
FAC, PCN	0 ± 0	0 ± 0	0 ± 10

Table 1. Best time lag and median absolute deviations. The time lag is the time the second parameter lags behind the first one

Research question 2) Solar wind integration time that gives peak correlation with total FAC

Analysis
- We calculated the Pearson correlation coefficient for the total FAC (10 min resolution) and NCF for increasing NCF integration times (10 – 300 min).
- NCF is only integrated using data preceding the FAC.

Results
- The integration time that best correlates with the total FAC is:
  - 80 min for sheath storms
  - 90 min for HSS/SIR storms
  - 140 min for MC storms

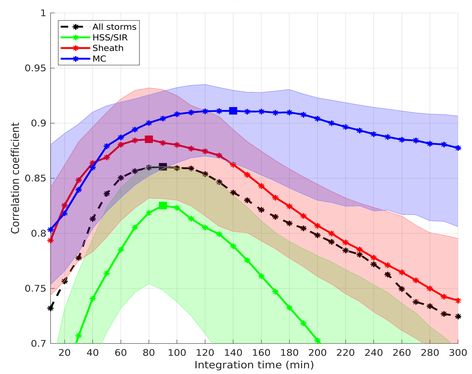

Figure 3. Correlation between total FAC and NCF for increasing NCF integration time. The solid lines show the median correlation in each storm category and the shaded area shows the span covering the 25th to 75th percentile. The maxima of each curve are shown by a solid square.

Summary and conclusions

We have carried out a cross-correlation analysis of the solar wind-magnetosphere coupling (Newell coupling function, NCF) at the Earth bow shock nose and ionospheric currents (total FAC and SME indices) to answer the two research questions posed in the top left window.

1)Yes, there are differences between the different geomagnetic storm drivers. The total field-aligned current (FAC) have peak correlation with the Newell coupling function (NCF) when it is lagged by 40 ± 10 min for HSS/SIR and sheath storms, and 60 ± 10 min for MC storms. Similar lags are found for the electrojet indices.

2)Yes, the best integration time depends on the storm driver. Highest correlation between the FAC and integrated NCF is achieved by integrating the NCF by the preceding 80 min for sheath, 90 min for HSS/SIR and 140 min for MC storms.

A manuscript of this work has been submitted to GRL.

References
Meng, C.-I. et al., (1973). "Cross-correlation analysis of the AE index and the interplanetary magnetic field bz component.", JGR https://doi.org/10.1029/JA078i004p00617
McPherron, et al., (2018). "Relation of field-aligned currents measured by the network of Iridium® spacecraft to solar wind and substorms." JGR, https://doi.org/10.1002/2017GL076741
Pedersen, M. N., et al. (2021) "Field-aligned and ionospheric currents by AMPERE and SuperMAG during HSS/SIR-driven storms." JGR, https://doi.org/10.1029/2021JA029437
Pedersen, M. N., et al. (2022) "Effect of ICME-driven storms on field-aligned and ionospheric currents from AMPERE and SuperMAG." JGR, https://doi.org/10.1029/2022JA030423

Acknowledgement:
This work was supported by the Academy of Finland projects 314664 and 348782, and the Vilho, Yrjö and Kalle Väisälä Foundation. We also thank AMPERE, SuperMAG and NASA/GSFC's Space Physics Data Facility's OMNIWeb for providing the data for this study.