Has the relationship between ionospheric behavior and geomagnetic activity changed over the past five solar cycles?

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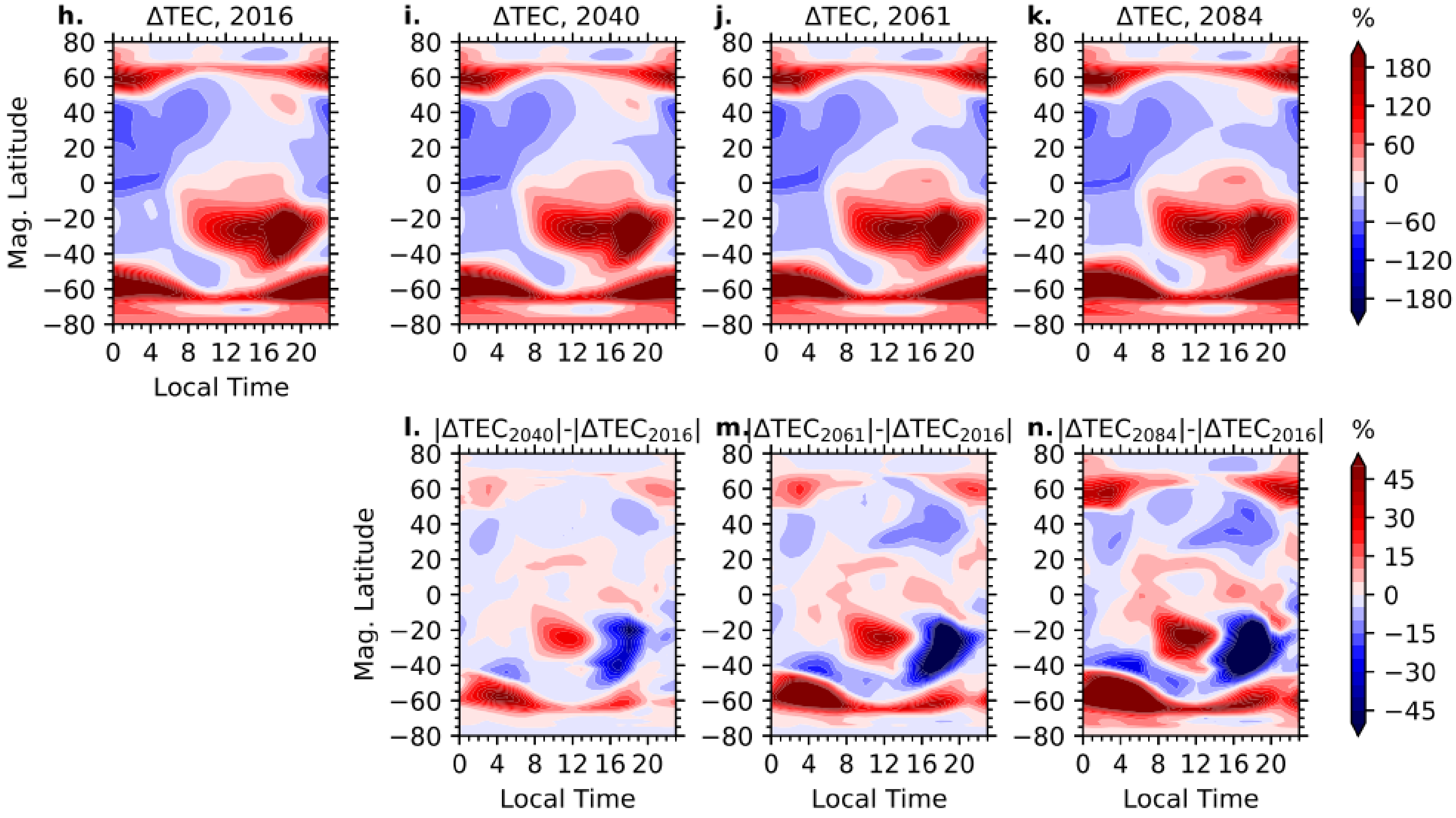
Introduction

- *Liu et al. 2021* - Geomagnetic activity (GA) can strengthen or weaken the CO_2 impacts on NmF2 (GAIA simulations).
- *Pedatella et al. 2025* - The impact of increasing CO_2 on the ionosphere's relationship with GA (WACCM-X simulation).



Pedatella et al. 2025

Research question

- Has the relationship between ionospheric behavior and geomagnetic activity changed over the past five solar cycles? (focus on midlatitude)

Data

- NmF2 hourly data from 6 midlatitude stations.

Name	URSI	LT (UT+)	Lat (°)	Lon (°)	GmLat 2015 (°)	Period and source of the ionosonde data		
						SWS*	GIRO*	CEDA / ukssdc
Boulder	BC840	- 7	40.00	−105.30	47.72	-	2002 - 2024	1958 – 2002
Port Stanley	PSJ5J	0	-51.60	−57.90	-42.21	-	2007 - 2019	1957 - 2007
Juliusruh	JR055	1	54.60	13.40	53.95	1957 - 2024	-	-
Slough/Chilton	RL052	3	51.50/ 51.70	−0.60/ −1.33	53.31/ 53.41	-	2007 - 2024	1931 - 2007
Moscow	MO155	- 4	55.47	37.30	51.05	1957 - 1995	2008 - 2022	-
Hobart	HO54K	11	-42.90	147.32	-49.77	1950 - 2015	2015 - 2024	-

SWS: Data taken from https://downloads.sws.bom.gov.au/wdc/iondata/wdc_display/ (in UT)
GIRO: Data taken from https://giro.uml.edu/didbase/scaled.php (autoscaled in UT)

- F30: the solar radio flux at the wavelength of 30 cm (1 GHz) https://spaceweather.cls.fr/services/radioflux/
- Geomagnetic indices from the GeoForschungsZentrum (GFZ)

Method

1) Filter solar activity in ionospheric data for each SC, each month and each LT

$$NmF2_{exp} = NmF2_{ionosonde} \text{ without days with } Kp \geq 3$$

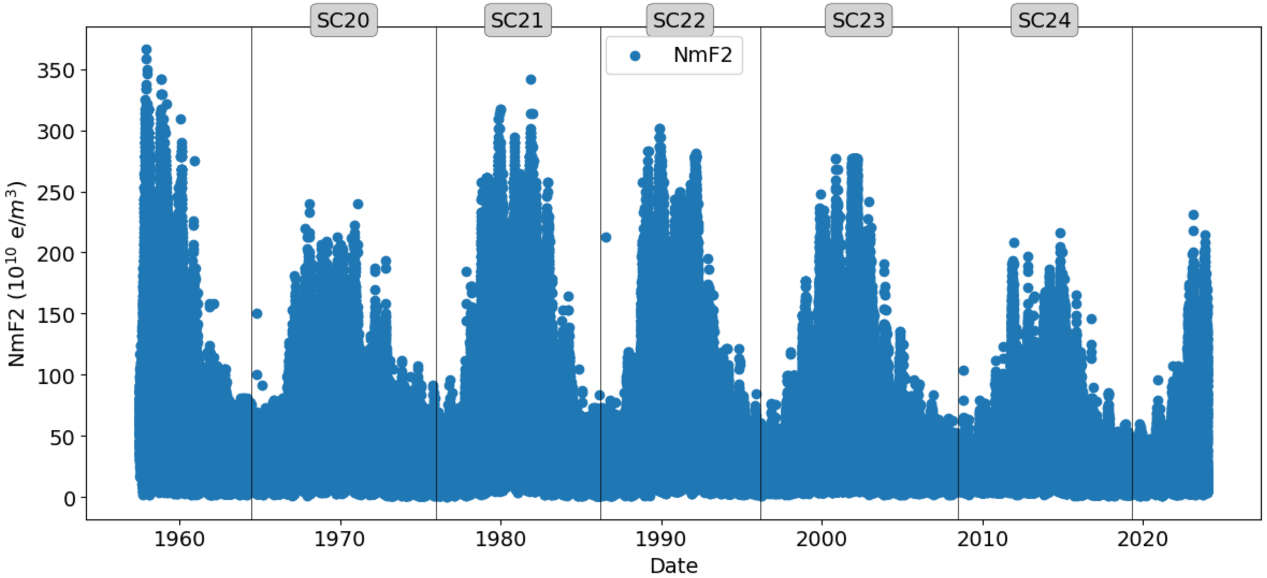
→ Used in the creation of the model.

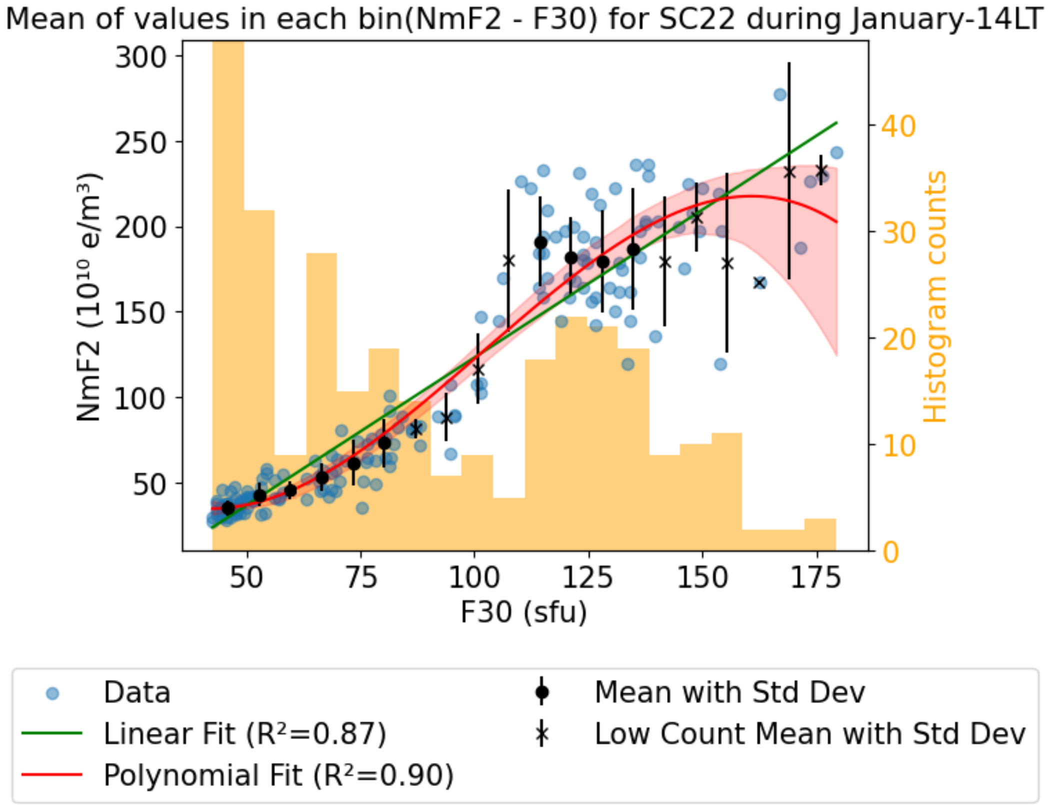
$$NmF2_{model} = a_1 E + a_2 E^2 + a_3 E^3 + a_4$$

Where E = EUV Solar proxy

$$NmF2_{perc} = \frac{NmF2_{ionosonde} - NmF2_{model}}{NmF2_{model}} * 100\%$$

Juliusruh Ionosonde data (54.6°N, 13.4°E)





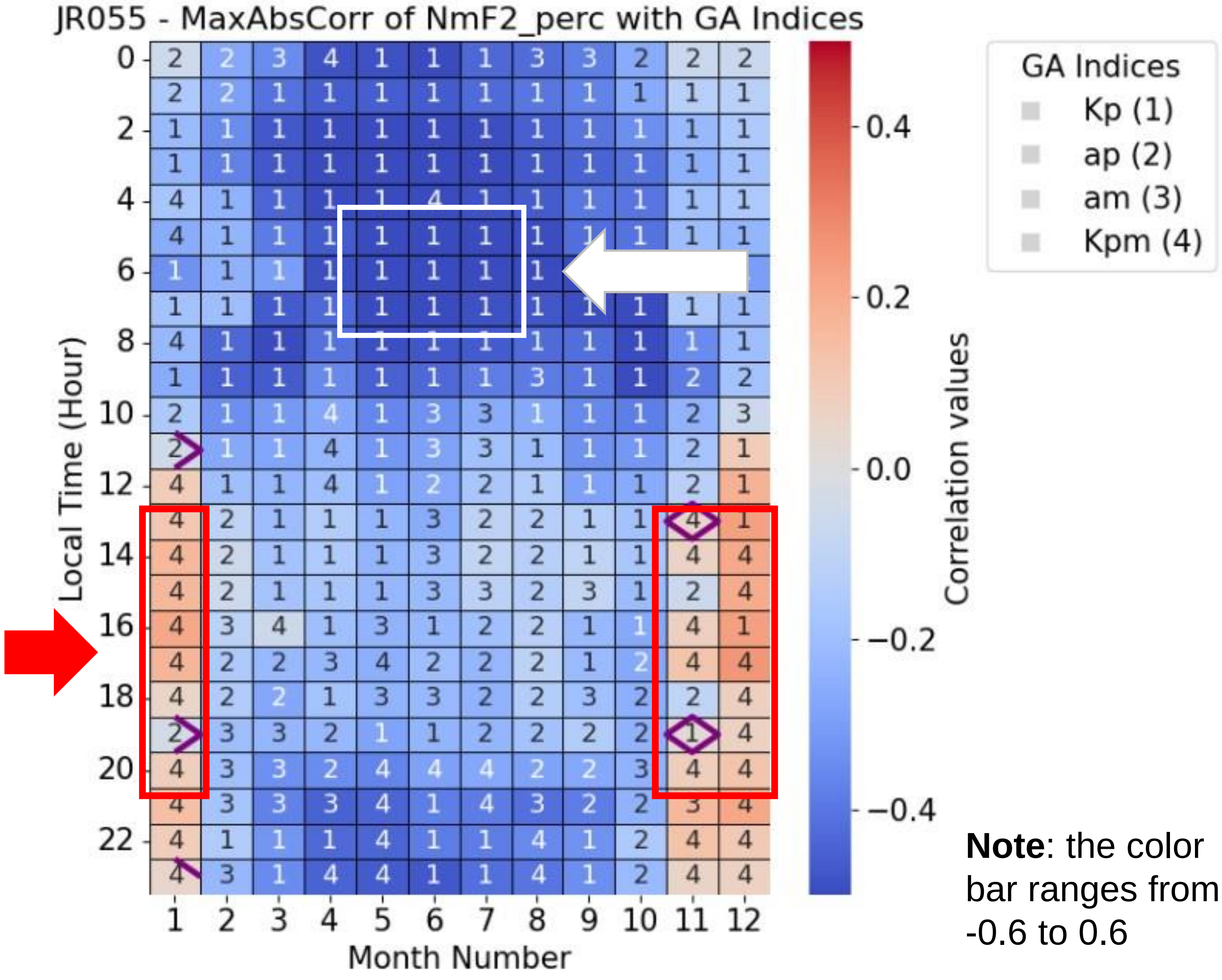
Tan Jun Rios et al. (2025)

2) Correlation between $NmF2_{perc}$ and GA Indices

Maximum absolute correlation between NmF2_perc and GA indexes

Juliusruh - Geomagnetic Lat: 54.2°

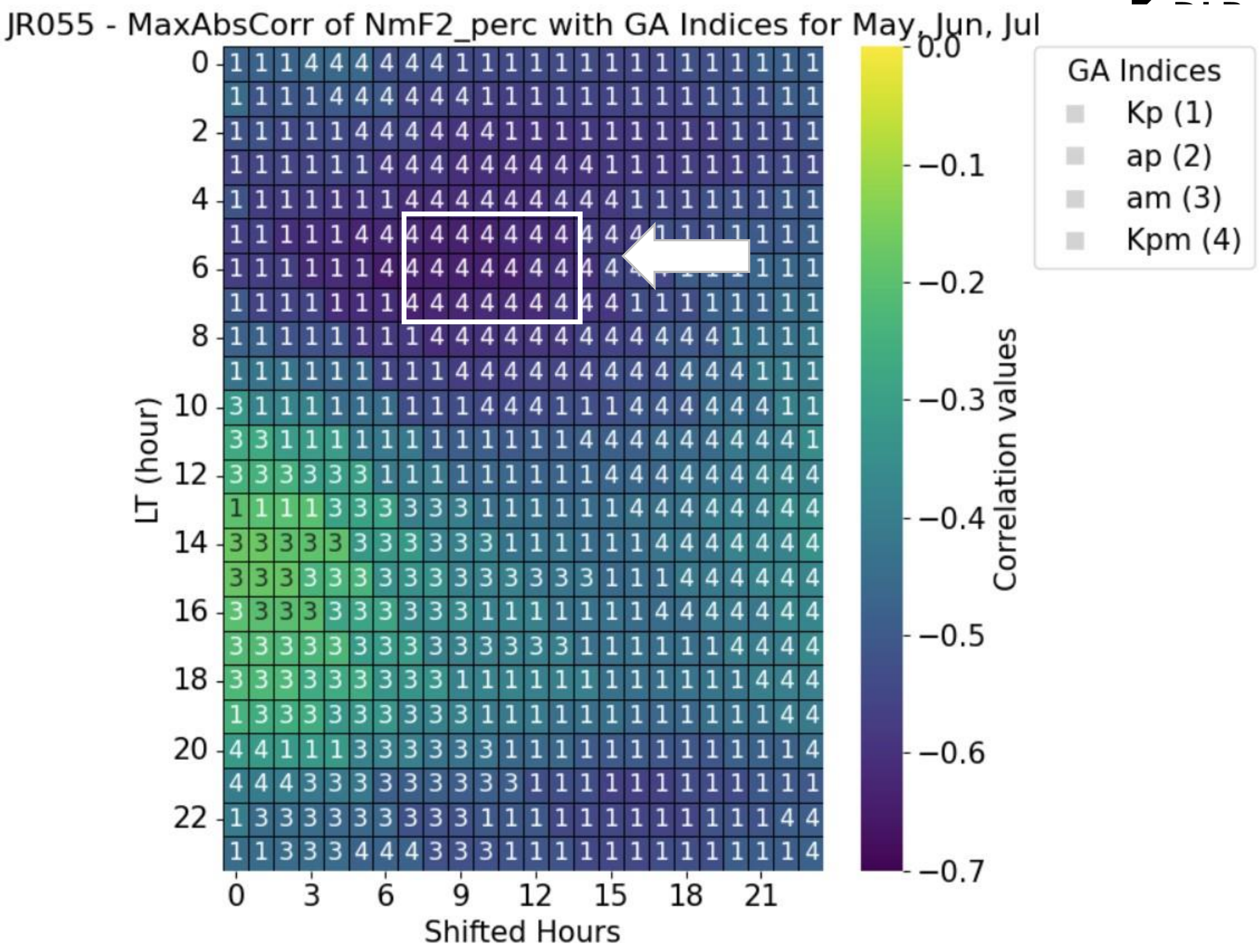
- Weak positive correlation during the winter afternoon.
- Negative correlation for the rest of the months and LT. Strong correlation in the morning summertime.



Note: the color bar ranges from -0.6 to 0.6

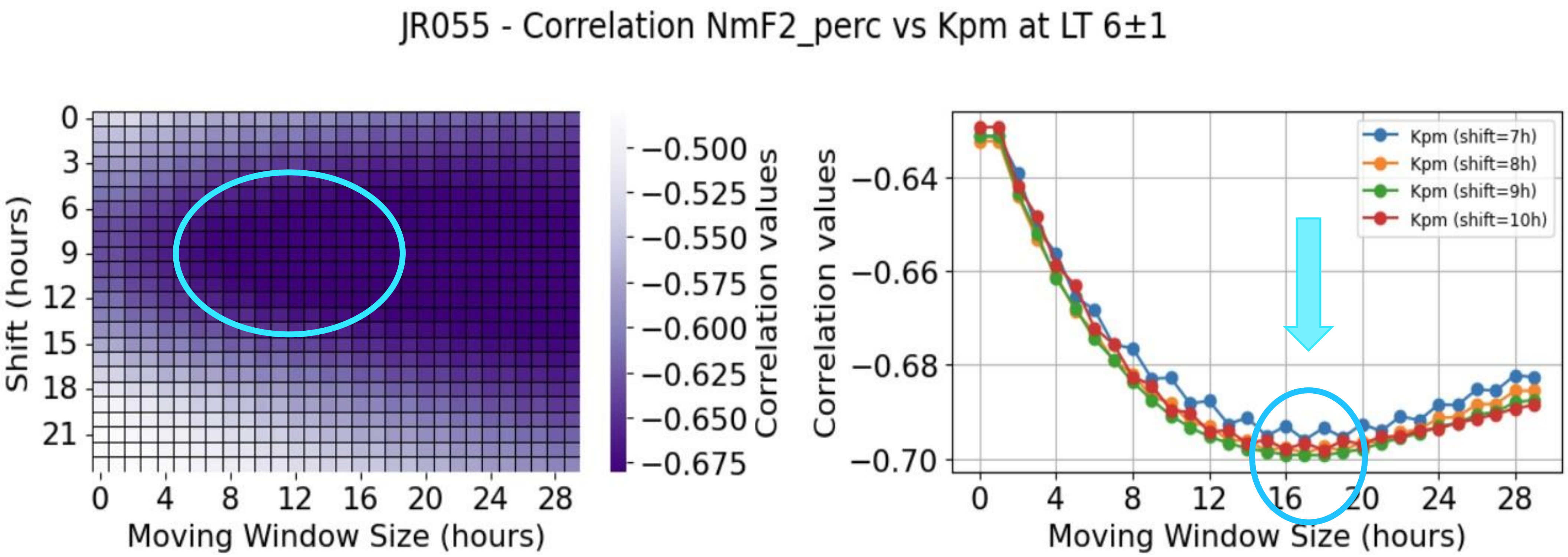
Correlation between NmF2_perc and GA indices

- Kpm index shifted between 6-12h produces a maximum absolute correlation around 6 LT.



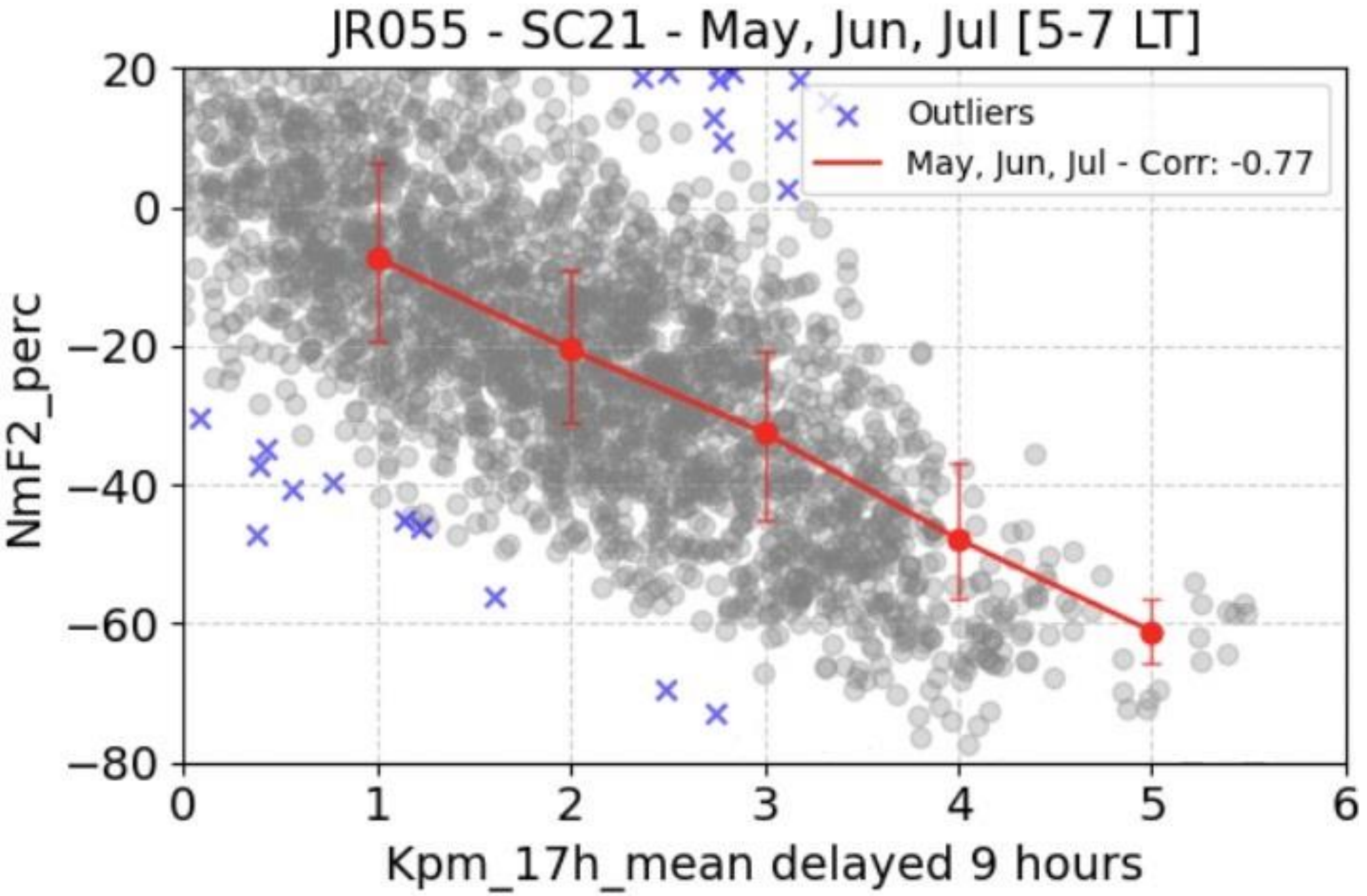
Correlation between NmF2_perc and GA indices

Juliusruh - Magnetic Latitude: 54.2°



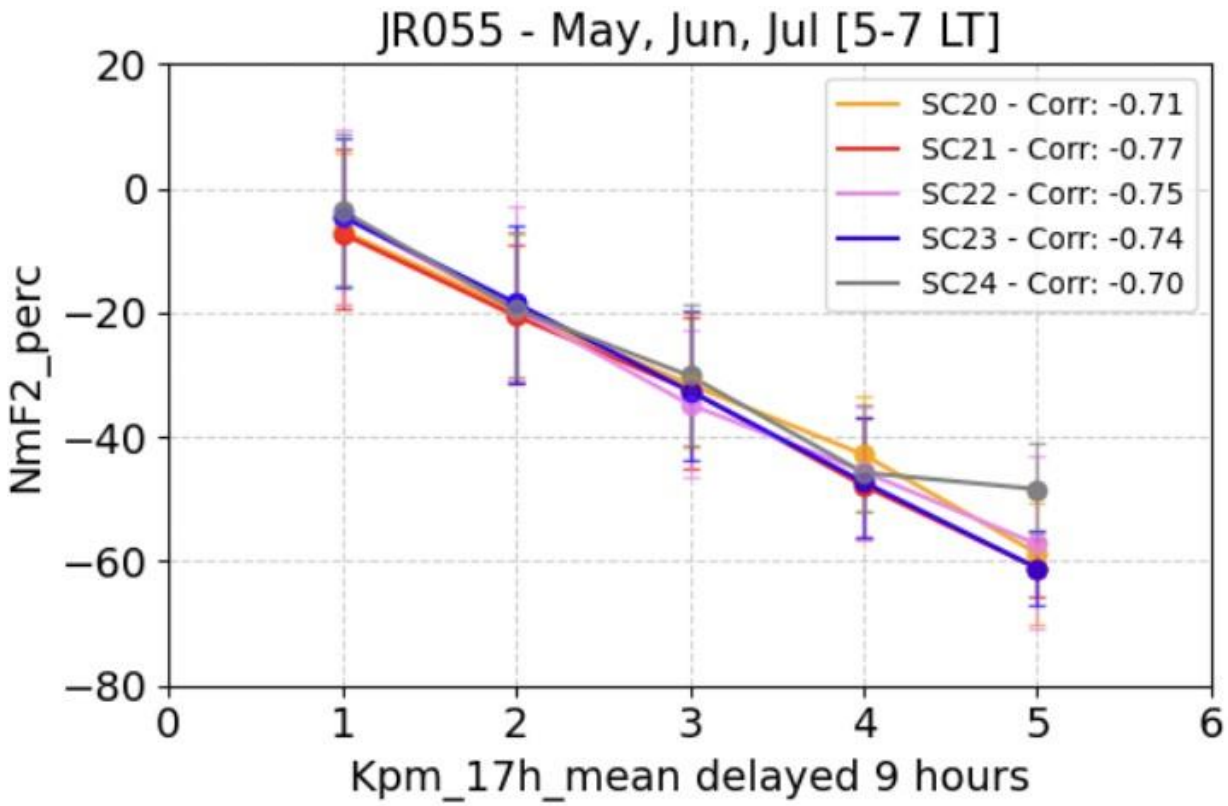
9h shifted Kpm index and 17-hour moving window average produces a maximum absolute correlation at 6 LT.

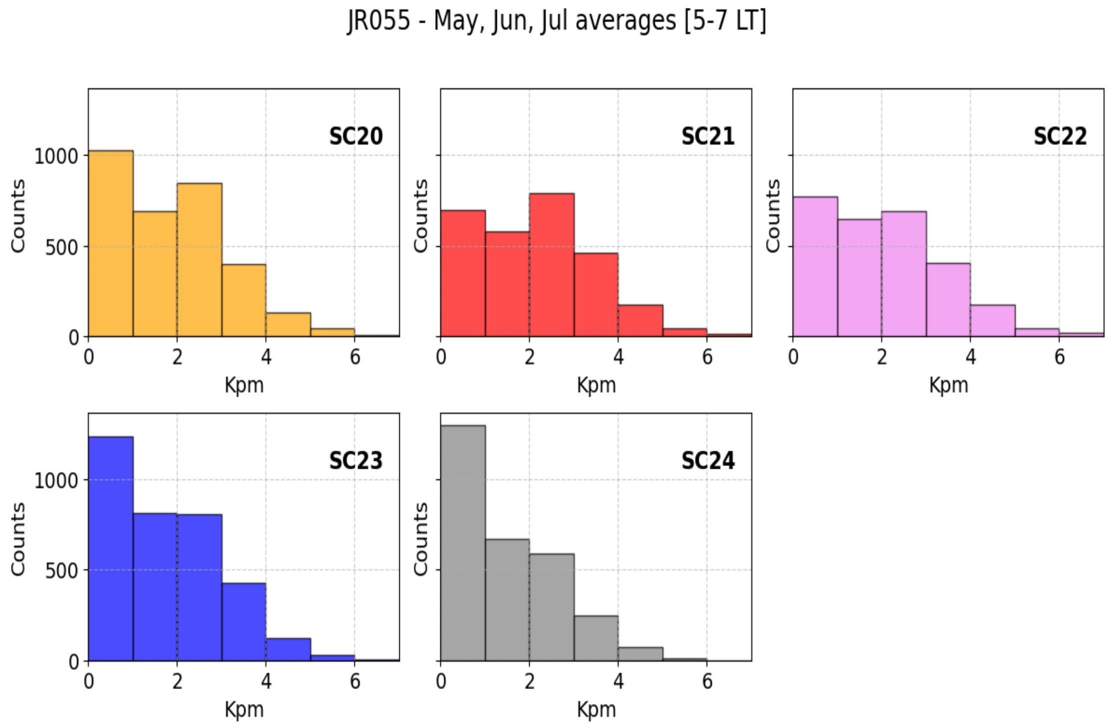
Visualization of the ionospheric response



- Red dots: mean values of NmF2_perc in each bin/window.
- Red error bars: quartiles of mean values.
- Bin/window size: 2 Kpm
- Step size: 1 Kpm
- Threshold = 10

Variation over time

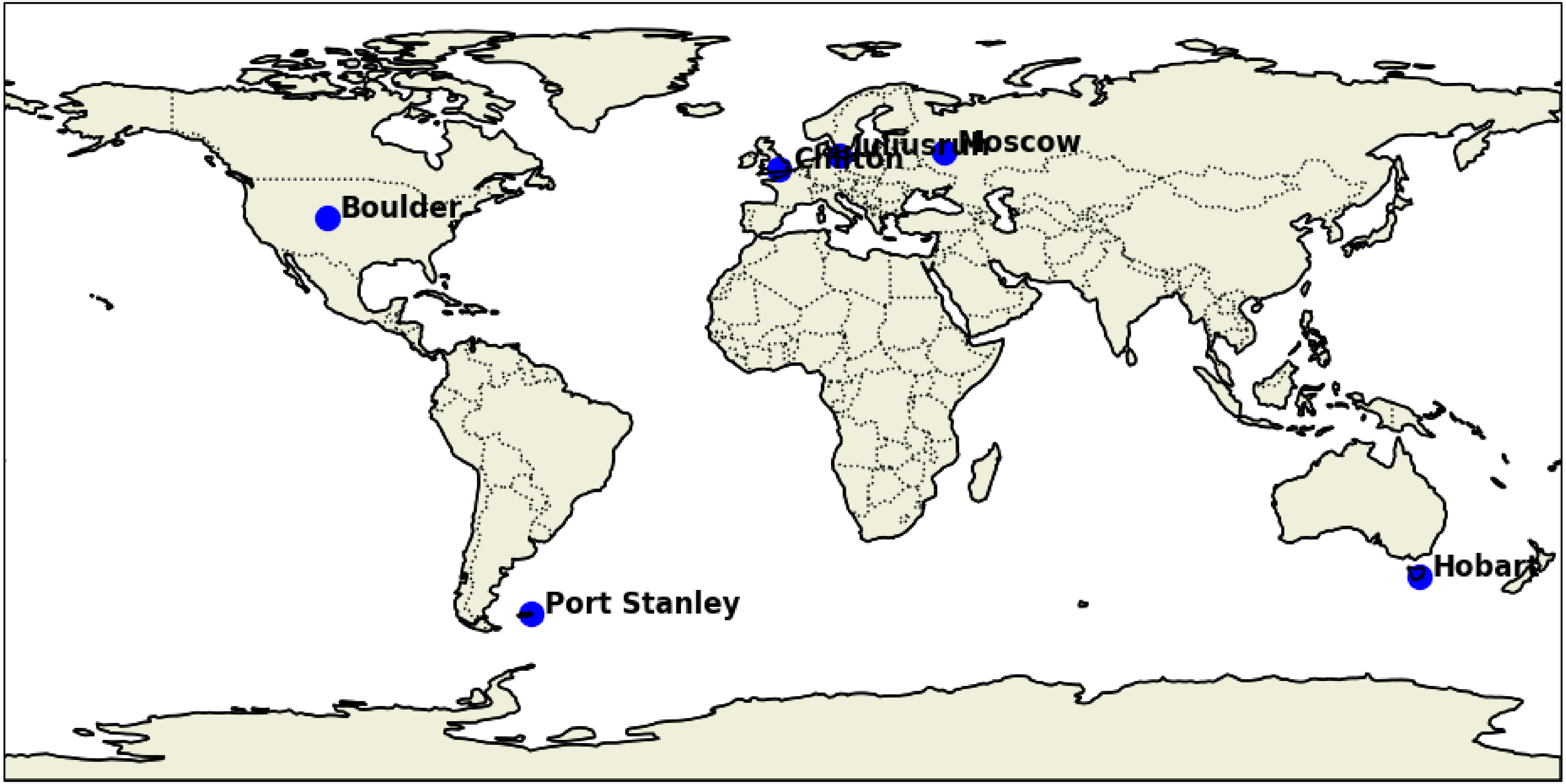




No noticeable variation in the relationship between the ionosphere and GA over the last five SCs.

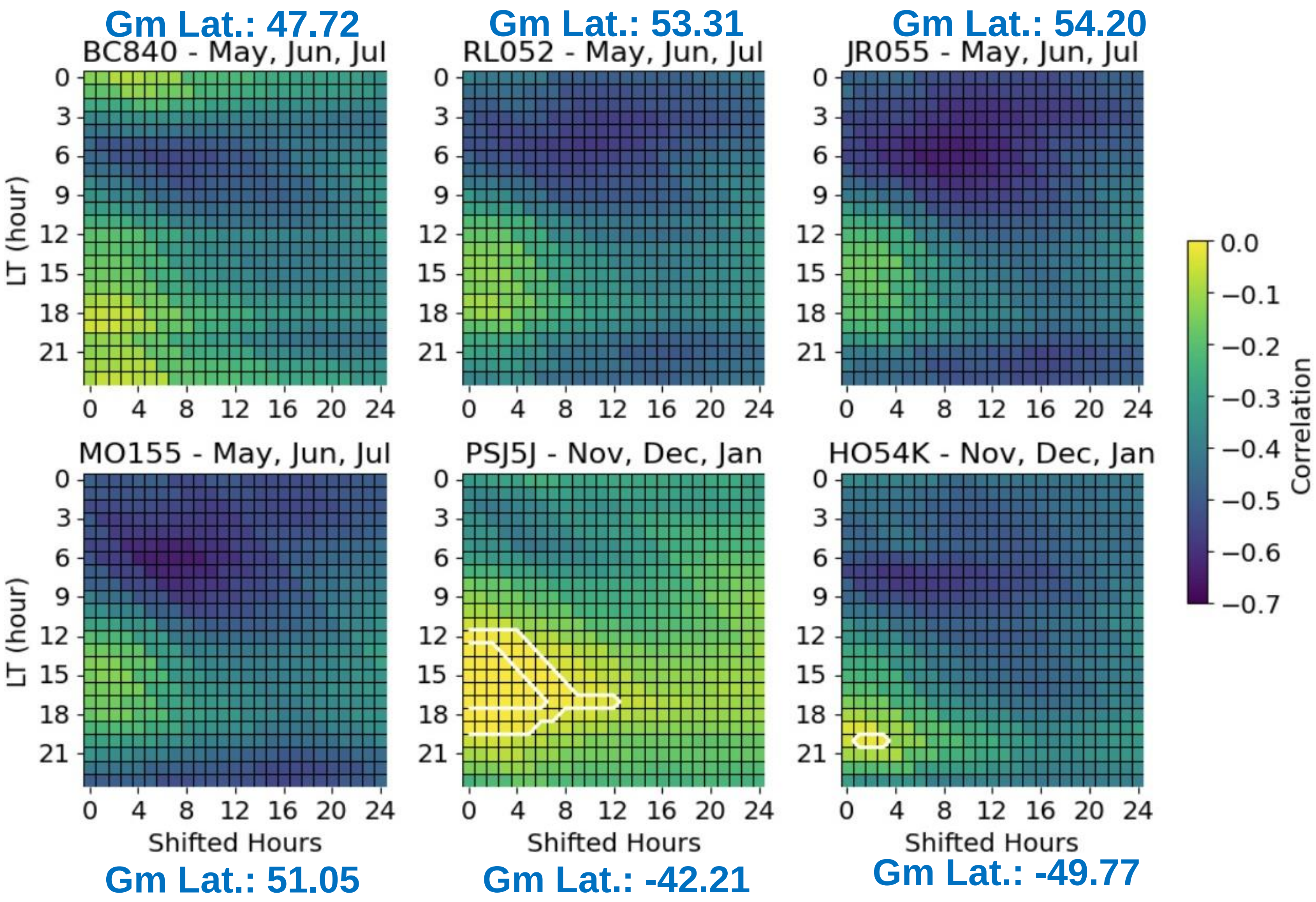
- 98% of the total data between Kpm 0-5.
- A strong geomagnetic disturbance (Kpm < 5) is unlikely.

Ionosonde stations

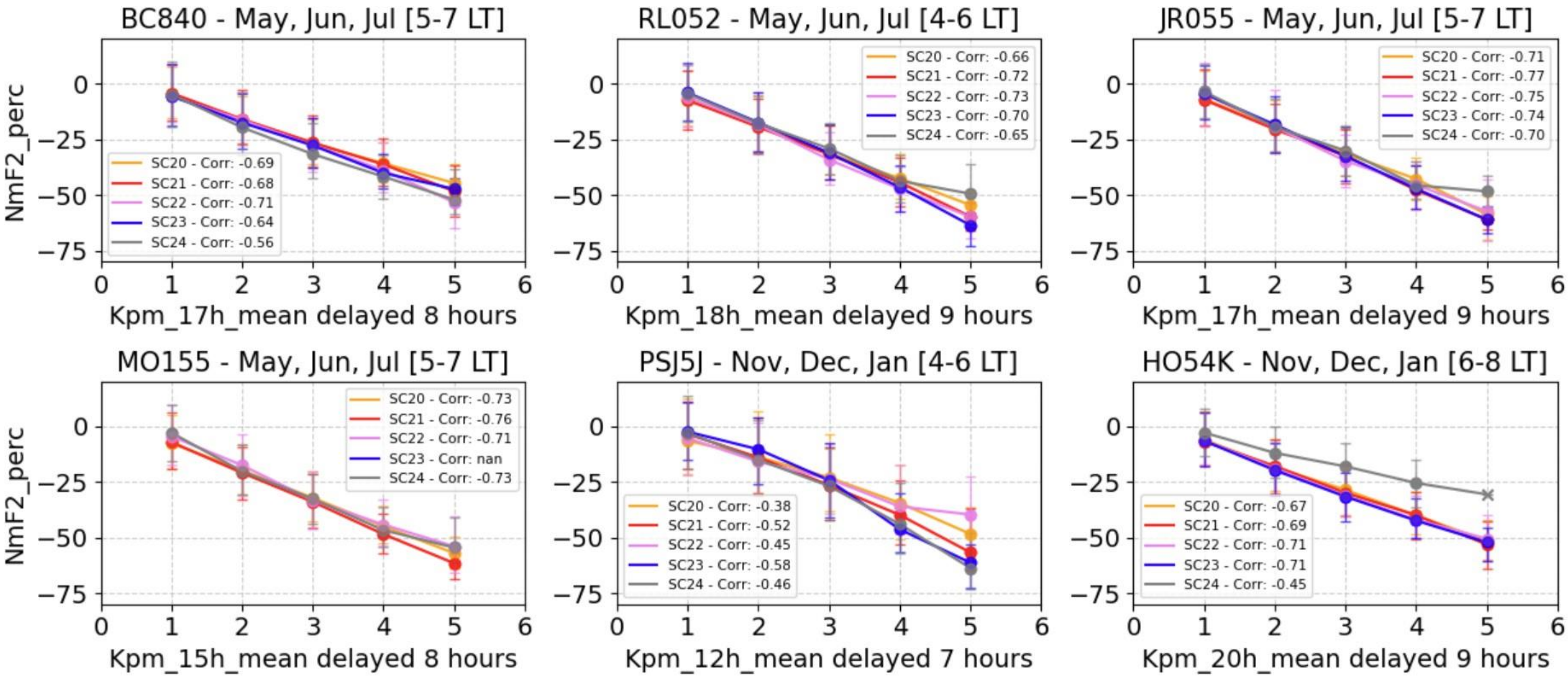


Correlation NmF2_perc and Kpm – Local Summer

- Similar pattern in all stations.
- Strong negative correlation during morning time.
- Delay 7-9 hours.



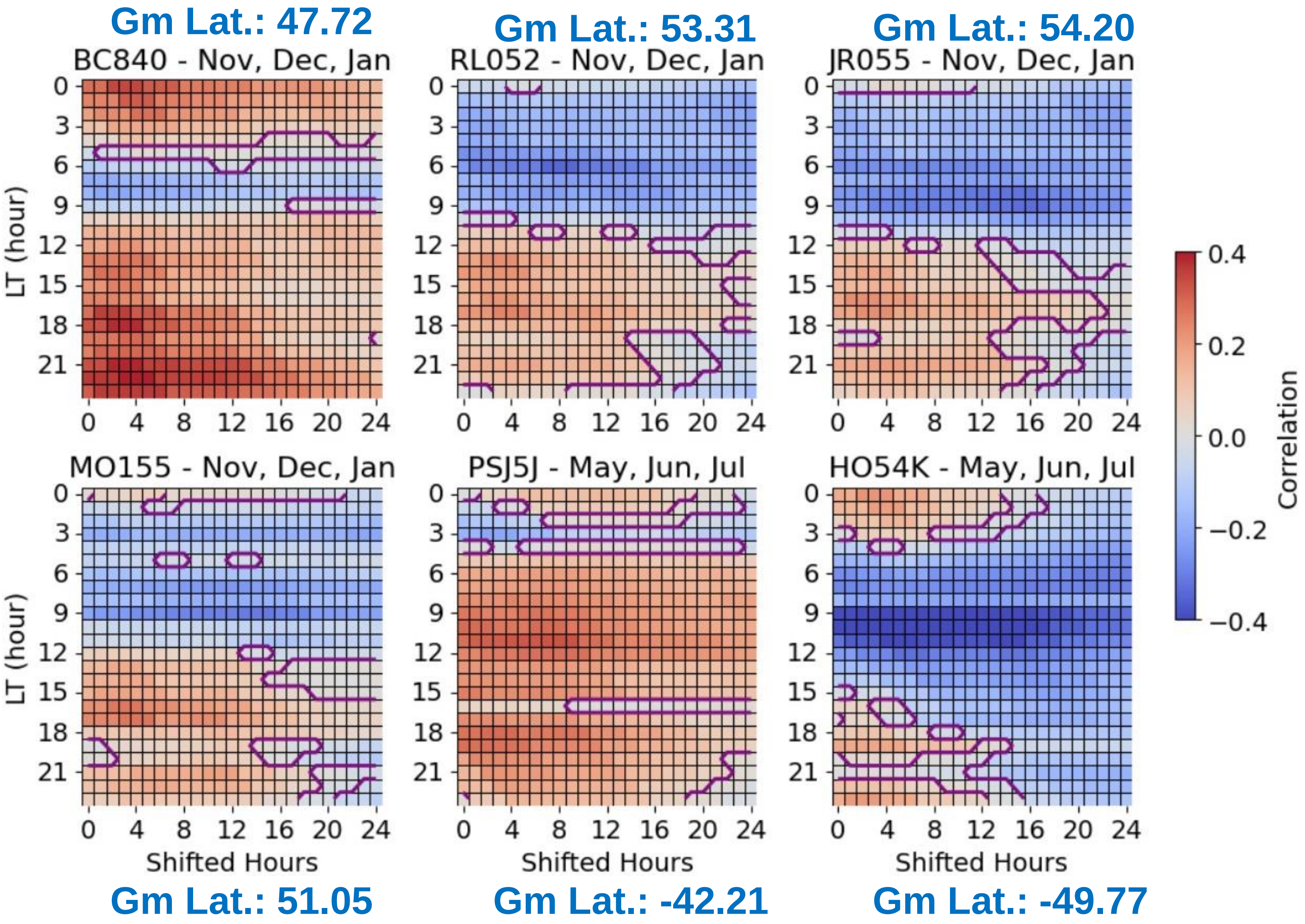
Variation over time for each SC



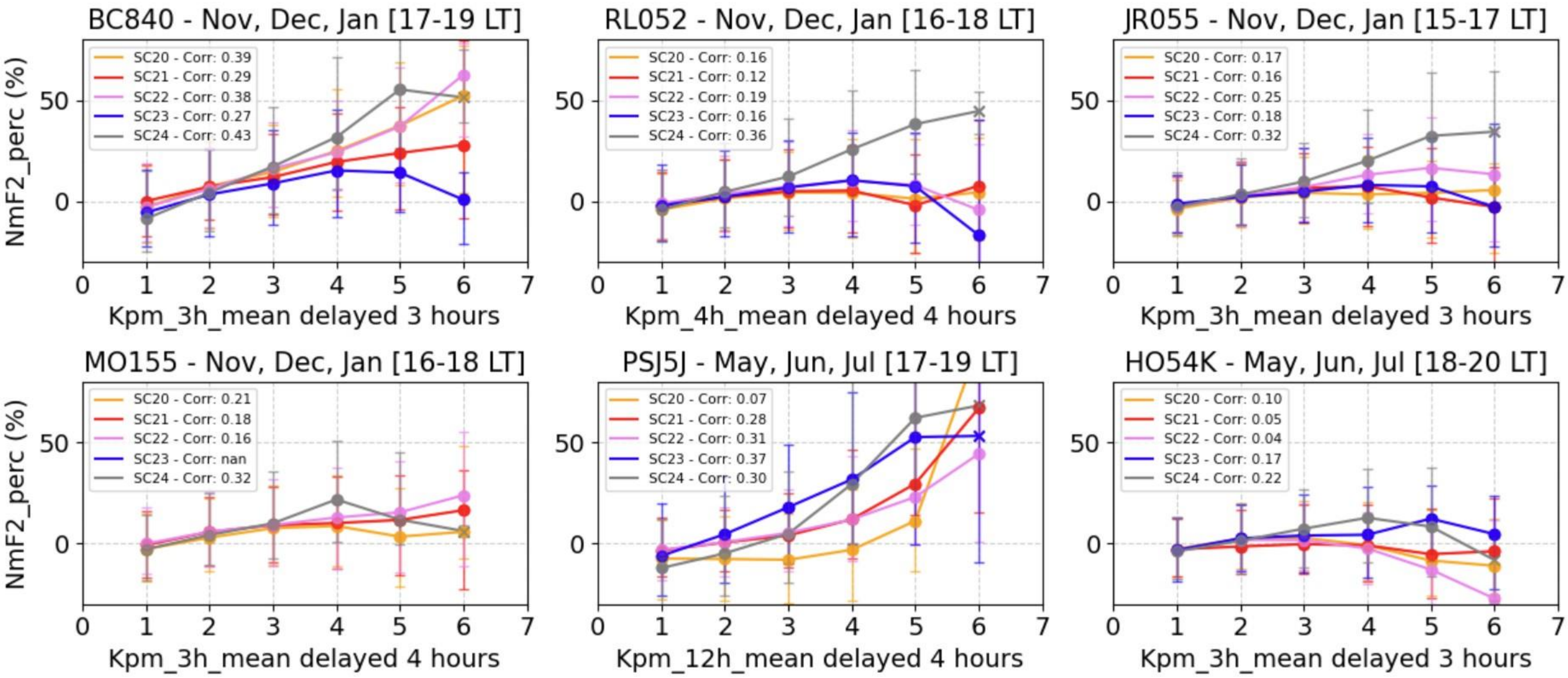
No noticeable variation over time in the relationship between the ionosphere and GA for morning summer time at midlatitudes.

Correlation NmF2_perc and Kpm – Local Winter

- The pattern varies for the different latitudes.
- Stronger positive correlation during the afternoon and night.
- Delay 3-4 hours.



Variation over time for each SC



The very strong variability and low correlation with GA indices during winter afternoons prevent the detection of long-term trends.

Summary for each station

Station Name	Local Summer			Local Winter		
	HCT(LT)	Delay (h)	WS (h)	HCT(LT)	Delay (h)	WS (h)
Boulder	(5 - 7)	8	17	(17 - 19)	3	3
Slough/Chilton	(4 – 6)	9	18	(16 - 18)	4	4
Juliusruh	(5 - 7)	9	17	(15 - 17)	3	3
Moscow	(5 - 7)	8	15	(16 - 18)	4	3
Port Stanley	(4 – 6)	7	12	(17 - 19)	4	12
Hobart	(6 - 8)	9	20	(18 -20)	3	3

HCT: Time for the highest correlation values
Delay hour: the number of hours delayed
WS: window size for the highest correlation

Discussion

- Our results show strong agreement with ionospheric storm patterns at midlatitudes.
- GA and ionospheric response are strongly linked and might change simultaneously.
- The variations in the ionospheric response to GA reported in the model results of Liu et al. (2021) and Pedatella et al. (2025) are not evident in our analysis.
  - → The actual CO_2 increment could be too small to cause noticeable impacts in the observations.
  - → Other long-term changes (not considered in the above model simulations) may compensate for the CO_2 increase.
- Limitations in the data and methods.

Conclusion

- The data from midlatitude ionosondes and geomagnetic proxies (used as proxies for solar wind energy input) do not yet allow for the detection of any long-term changes in the response to solar wind forcing.

References

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Thanks for your attention!

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