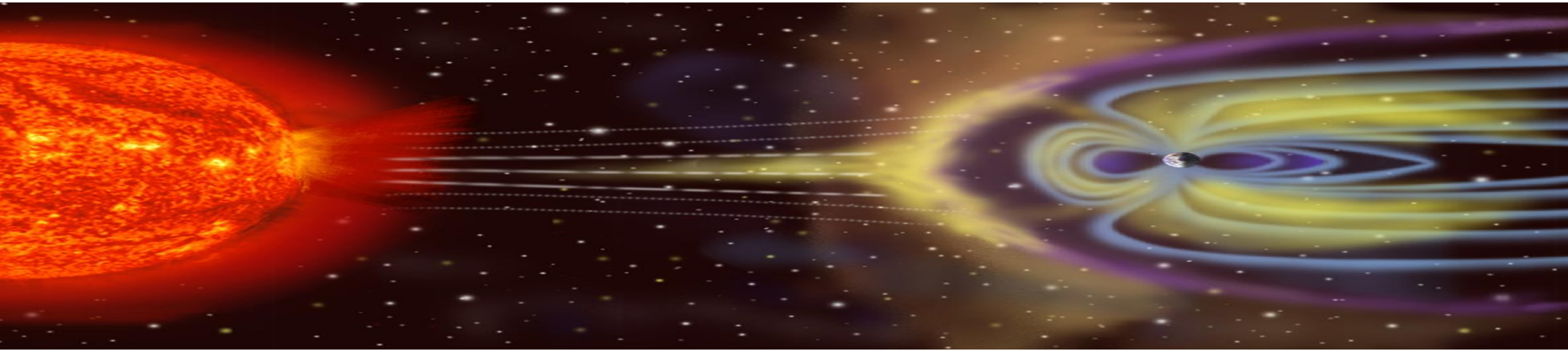

Impact of F10.7 Flux and Proton Intensity on Delayed Ionospheric TEC Responses at Low Latitudes During Geomagnetic Storms Across Solar Cycles 23–25

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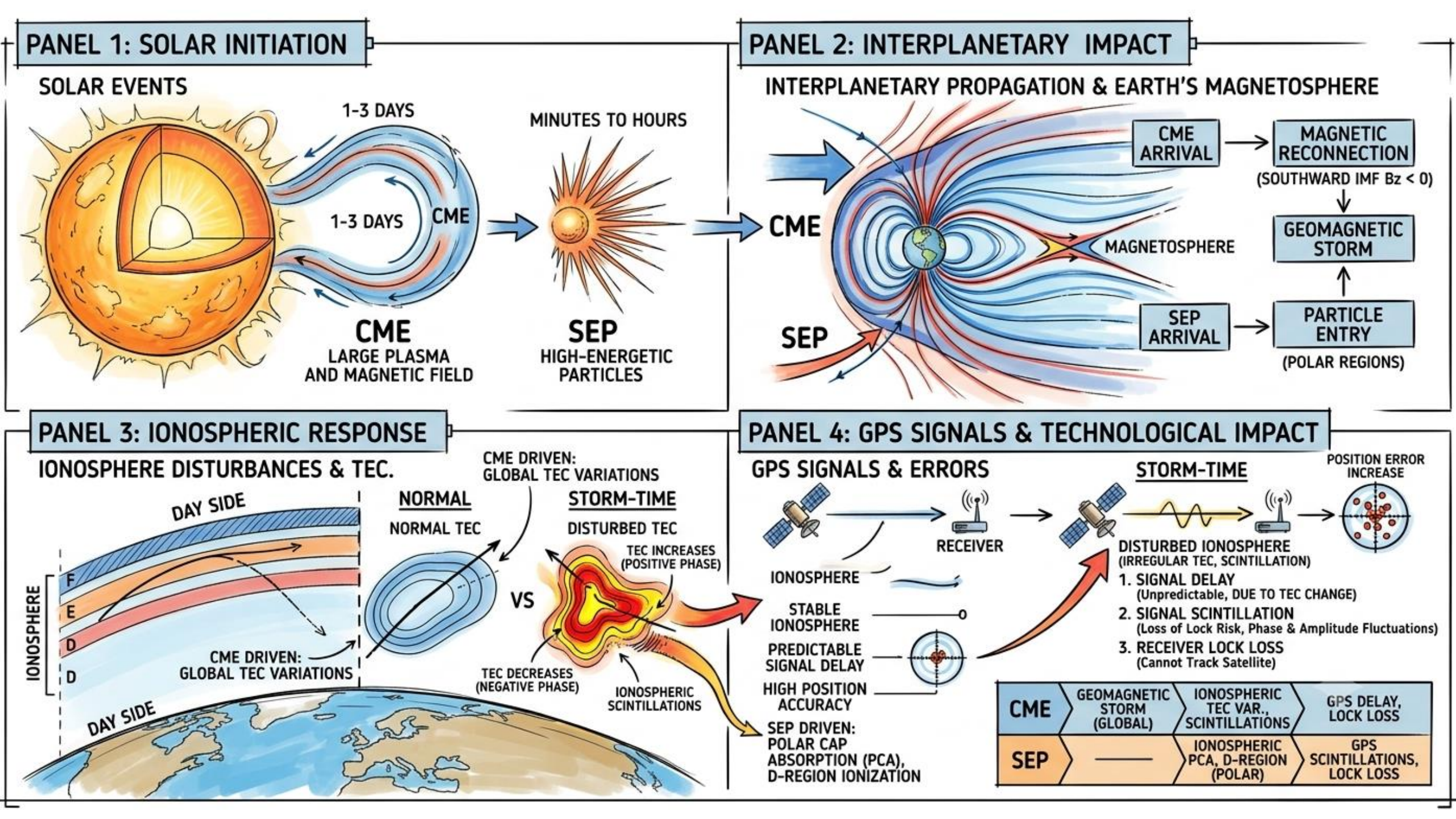
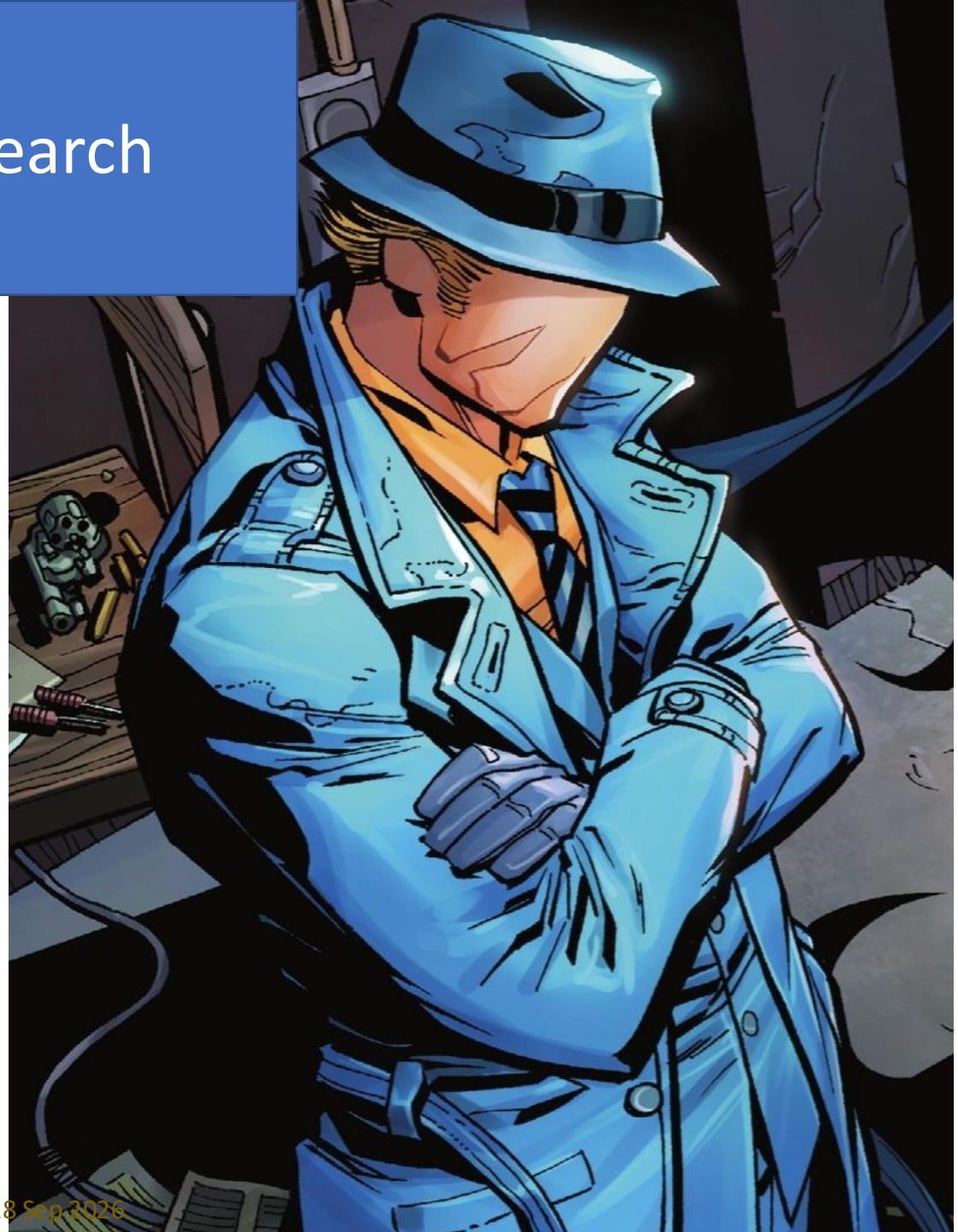
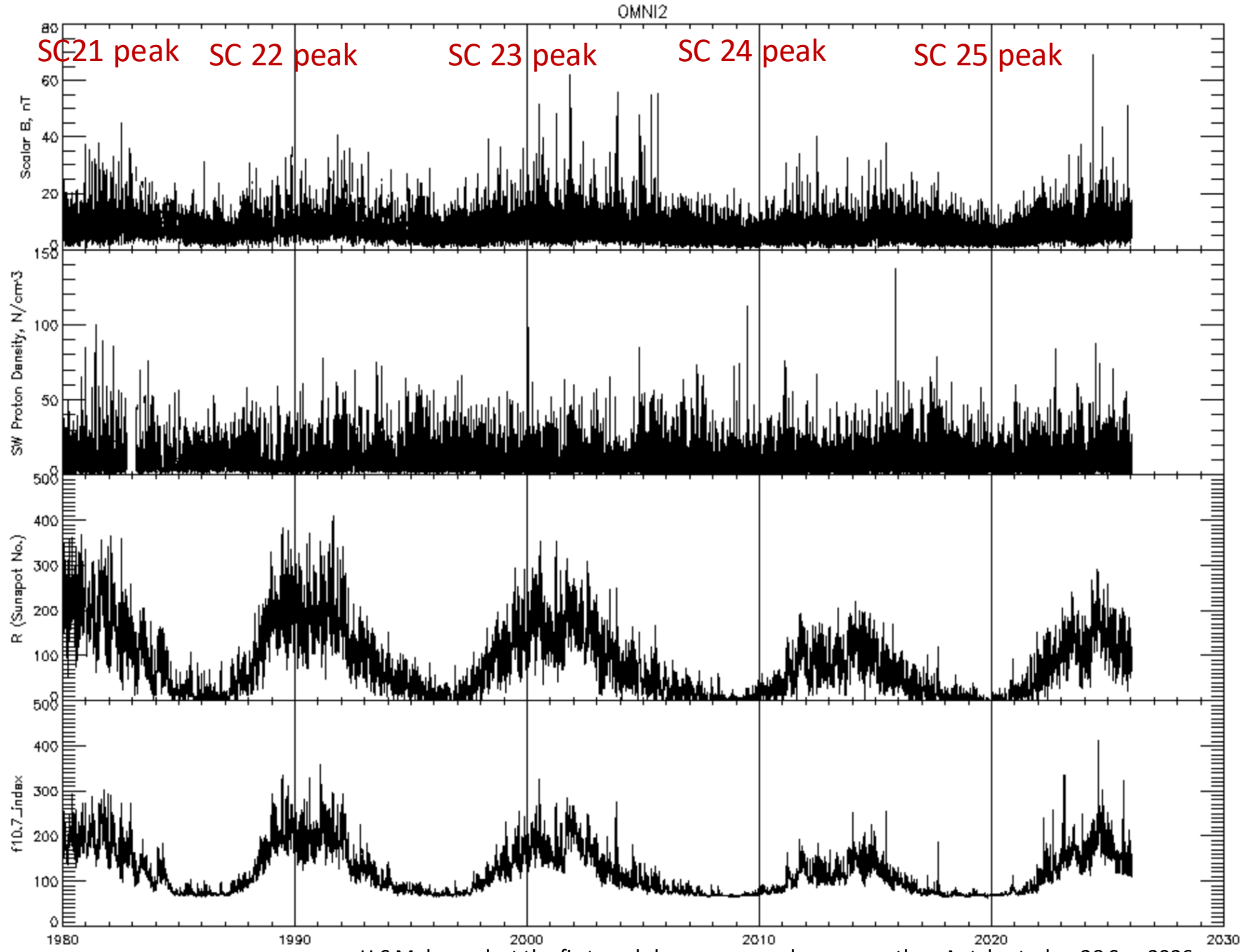

PANEL 1: SOLAR INITIATION
SOLAR EVENTS
1-3 DAYS
1-3 DAYS
CME
MINUTES TO HOURS
CME
LARGE PLASMA AND MAGNETIC FIELD
SEP
HIGH-ENERGETIC PARTICLES
PANEL 2: INTERPLANETARY IMPACT
INTERPLANETARY PROPAGATION & EARTH'S MAGNETOSPHERE
CME
SEP
MAGNETOSPHERE
CME ARRIVAL
MAGNETIC RECONNECTION
(SOUTHWARD IMF Bz < 0)
GEOMAGNETIC STORM
SEP ARRIVAL
PARTICLE ENTRY
(POLAR REGIONS)
PANEL 3: IONOSPHERIC RESPONSE
IONOSPHERE DISTURBANCES & TEC.
DAY SIDE
IONOSPHERE
F
E
D
D
CME DRIVEN: GLOBAL TEC VARIATIONS
DAY SIDE
CME DRIVEN: GLOBAL TEC VARIATIONS
NORMAL
NORMAL TEC
VS
STORM-TIME
DISTURBED TEC
TEC INCREASES (POSITIVE PHASE)
TEC DECREASES (NEGATIVE PHASE)
IONOSPHERIC SCINTILLATIONS
PANEL 4: GPS SIGNALS & TECHNOLOGICAL IMPACT
GPS SIGNALS & ERRORS
RECEIVER
IONOSPHERE
STABLE IONOSPHERE
PREDICTABLE SIGNAL DELAY
HIGH POSITION ACCURACY
SEP DRIVEN: POLAR CAP ABSORPTION (PCA), D-REGION IONIZATION
STORM-TIME
POSITION ERROR INCREASE
DISTURBED IONOSPHERE
(IRREGULAR TEC, SCINTILLATION)
1. SIGNAL DELAY
(Unpredictable, DUE TO TEC CHANGE)
2. SIGNAL SCINTILLATION
(Loss of Lock Risk, Phase & Amplitude Fluctuations)
3. RECEIVER LOCK LOSS
(Cannot Track Satellite)
CME | GEOMAGNETIC STORM (GLOBAL) | IONOSPHERIC TEC VAR., SCINTILLATIONS | GPS DELAY, LOCK LOSS
SEP | —— | IONOSPHERIC PCA, D-REGION (POLAR) | GPS SCINTILLATIONS, LOCK LOSS

Triggers for this research



Plot omni2 data from 19800101 to 20260110



1. Interplanetary Magnetic Field Strength |B| nT: high-amplitude spikes represent transient interplanetary disturbances (primarily CMEs and fast solar wind streams). The frequency of magnetic spikes directly tracks the ~11-year solar cycle activity, peaking near solar maxima when eruptive events are frequent.

2. SW Proton Density : proton density spikes highlight shock fronts driven by CMEs and CIRs , density spikes occur throughout all solar cycle phases, though compressed plasma structures are more severe during active solar years.

3. Sunspot Number R: SC 21 (~1980 peak), SC 22 (~1990 peak), SC 23 (~2000 peak), SC 24 (~2011/2014 weak peak), and ongoing SC 25 (~2024–2025 peak). An observed declining trend from SC 21 -24. followed by a clear resurgence in SC 25.

4. F 10.7 Solar Flux : measures radio emissions from the upper chromosphere and lower corona. Highly correlated with R

The long-term observation of solar parameters—such as Sunspot Number, F10.7 solar flux, and interplanetary magnetic field strength—demonstrates that while solar activity follows a well-established ~11-year periodicity, each individual solar cycle exhibits unique structural features and intensity variations

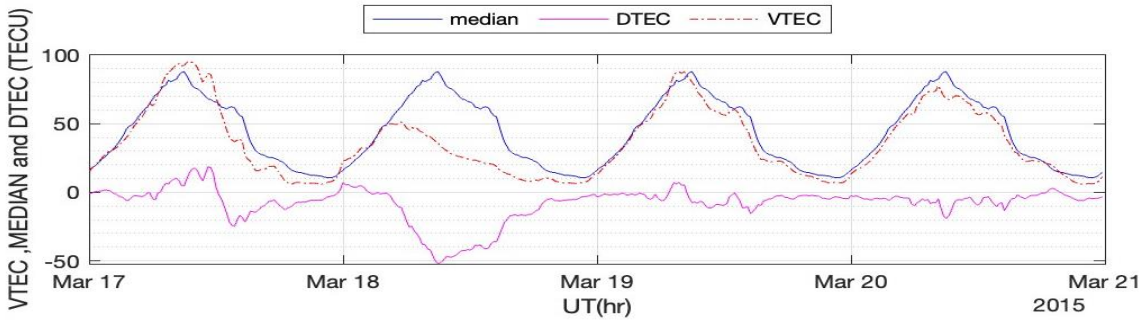
Solar Cycle	Epoch / Status	Weak Storms (-50 < Dst -30nT)	Moderate Storms (-100 < Dst -50 nT)	Strong/Extreme Storms (Dst -100 nT)	Primary Driver
SC 20	1964–1976	~1,100	~ 420	~ 75	CME & HSS Streams
SC 21	1976–1986	**~1,600**	**~ 580**	**~ 115**	Frequent CMEs (Solar Max)
SC 22	1986–1996	~1,500	~ 530	~ 110	Fast CMEs & Major SEPs
SC 23	1996–2008	~1,250	159- 191	84- 110	CMEs (Max) / HSS (Declining)
SC 24	2008–2019	~850	127	22	Reduced CMEs, dominant HSS
SC 25	2019–Present (**Active**)	~650 to date	~ 180 to date	~ 35 - 40 to date	Resurgent CMEs & Strong CIRs

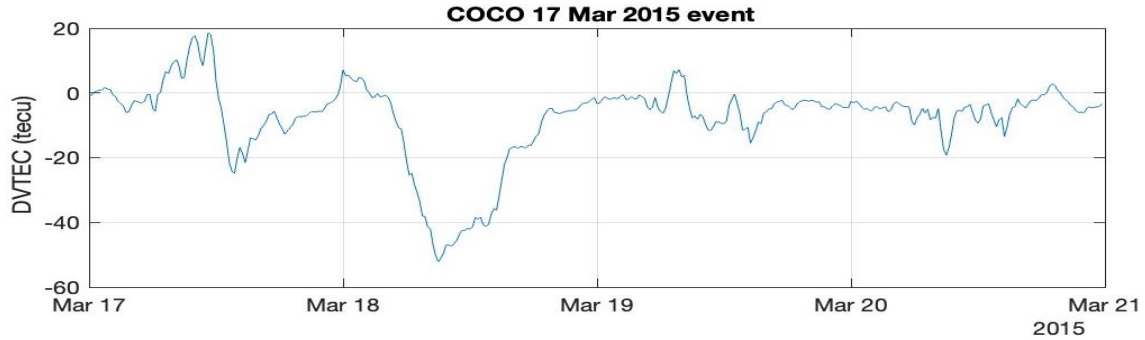
This table established from data ISGI and previous research work

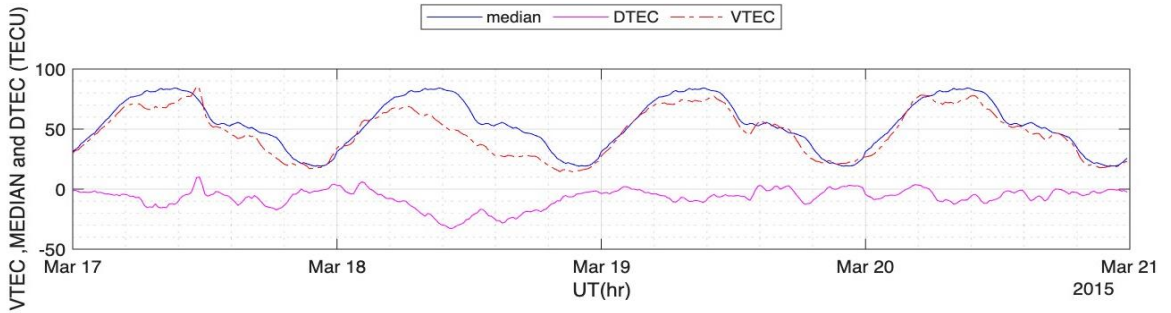
Ionosphere

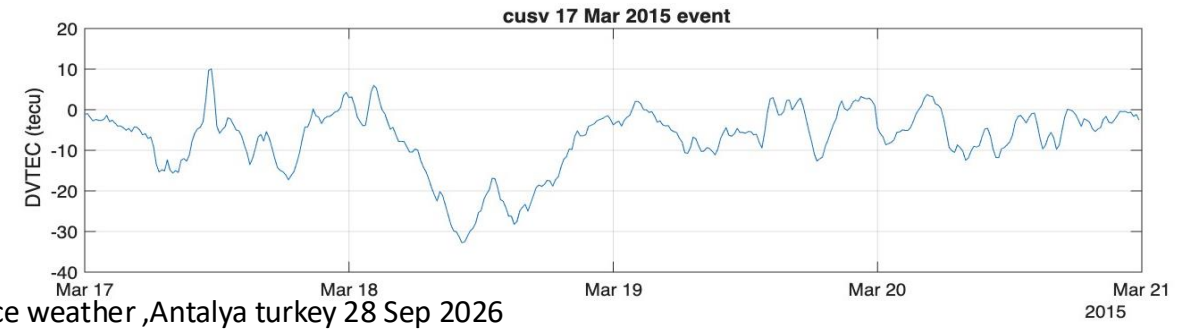
- Both stations show negative values for DVTEC with different amplitude.
- The stations are offset in longitude and Latitude

So the question here for how much the difference in longitude and latitude (low – equatorial) can change the DVTEC in Ionosphere ?





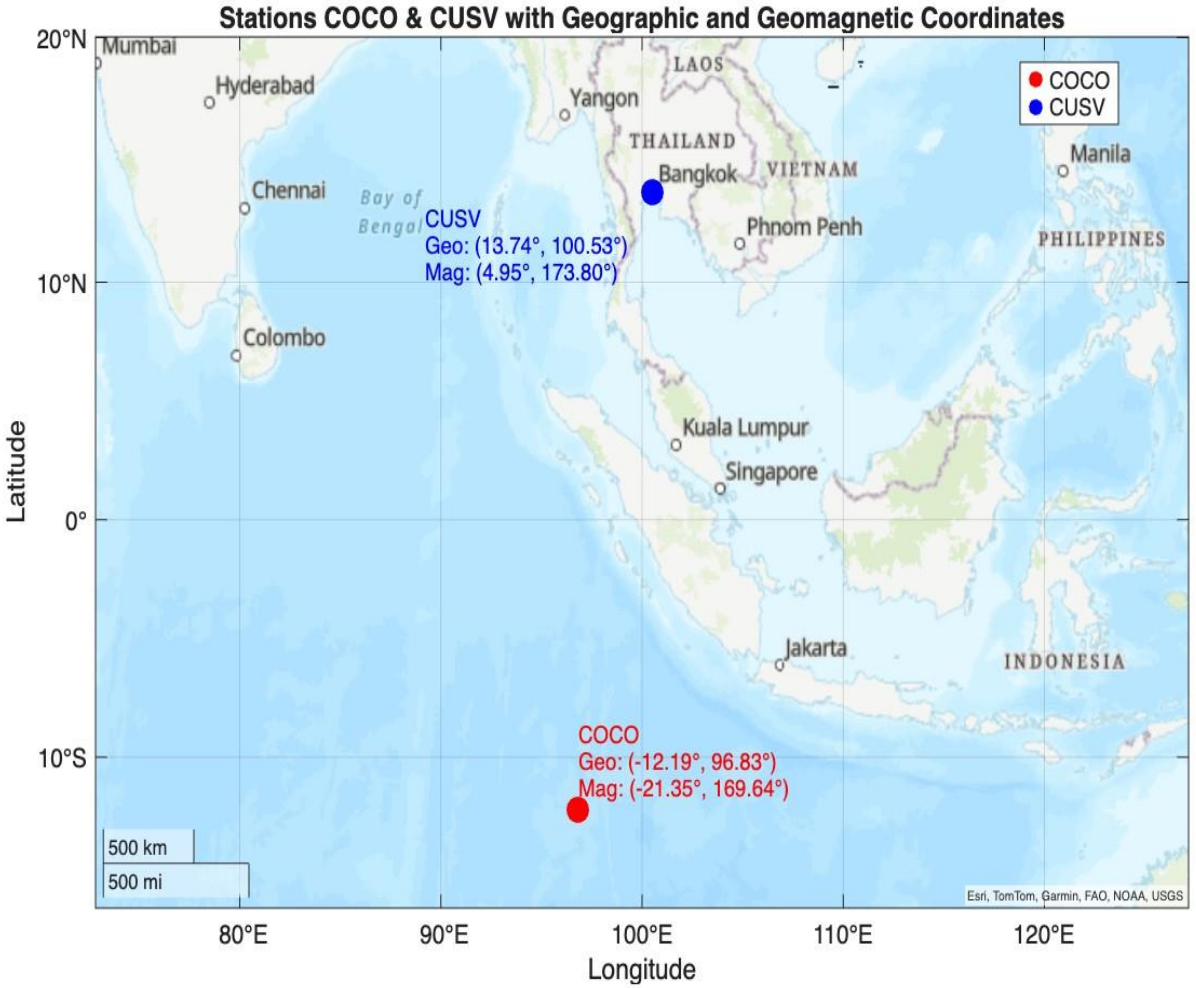




Main objective of this research

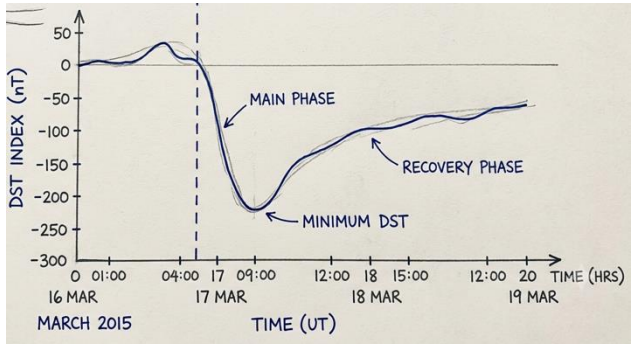
- 1- Monitor all magnetic storm origin during different phases of SC
- 2- Find all parameters that play a role in the enhancement of the magnetic storm(Sun- Earth).
- Investigate the position of the GPs stations at the Low – equatorial latitude
- Find physical and statistical correlations that affect the ionosphere TEC. Specially DTEC.
- Finally, monitor the delay time during the discussed SCs.

Stations used



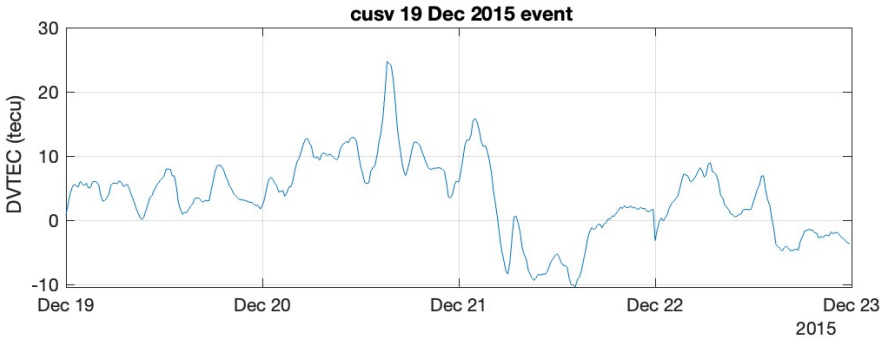
S. No.	Station code	Country	Geographic Latitude (°N)	Geographic longitude (°E)
1.	COCO	Kneeling Island	-12.19	96.83
2.	CUSV	Thailand	13.74	100.53

Selection criteria for event discussed

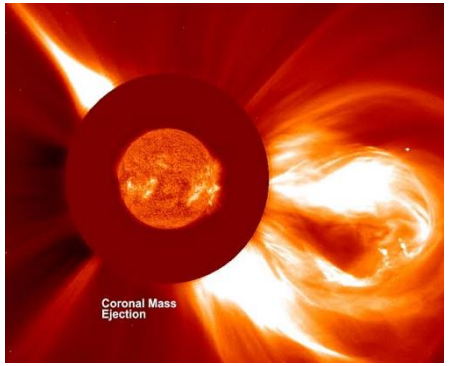


- A rigorous multi-filtering stage was used to select magnetic storms for analysis for a 4-day time window around each event to select optimal geomagnetic storms.

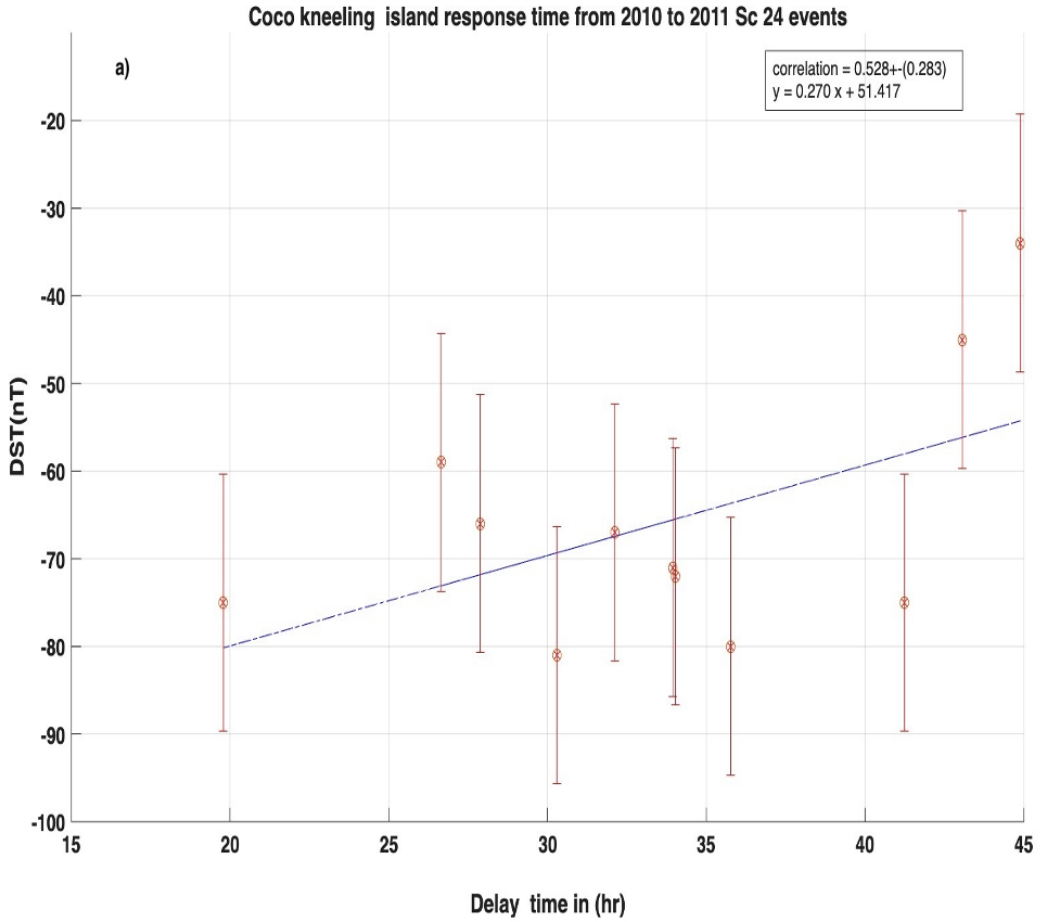
1. **Intensity and Profile:** The storm must display a single, well-defined main phase peak with a minimum Dst threshold of ≤−20 nT.
2. **Local Time Constraints:** The SSC should ta
   period between 22 LT and 3 LT is considered
3. **Solar Origin Verification:** The solar origin o
   limb or not coincide with a far-sided event, as
   suddenly.
4. **Boundary Limits:** There is no cap on the DTEC values during the entire range of periods under discussion, whether at the maximum or minimum, allowing various mechanisms (such as PPEF and DDEF) to contribute to this correlation. However, considering earlier studies, we restricted the delay period to 10 h or more.

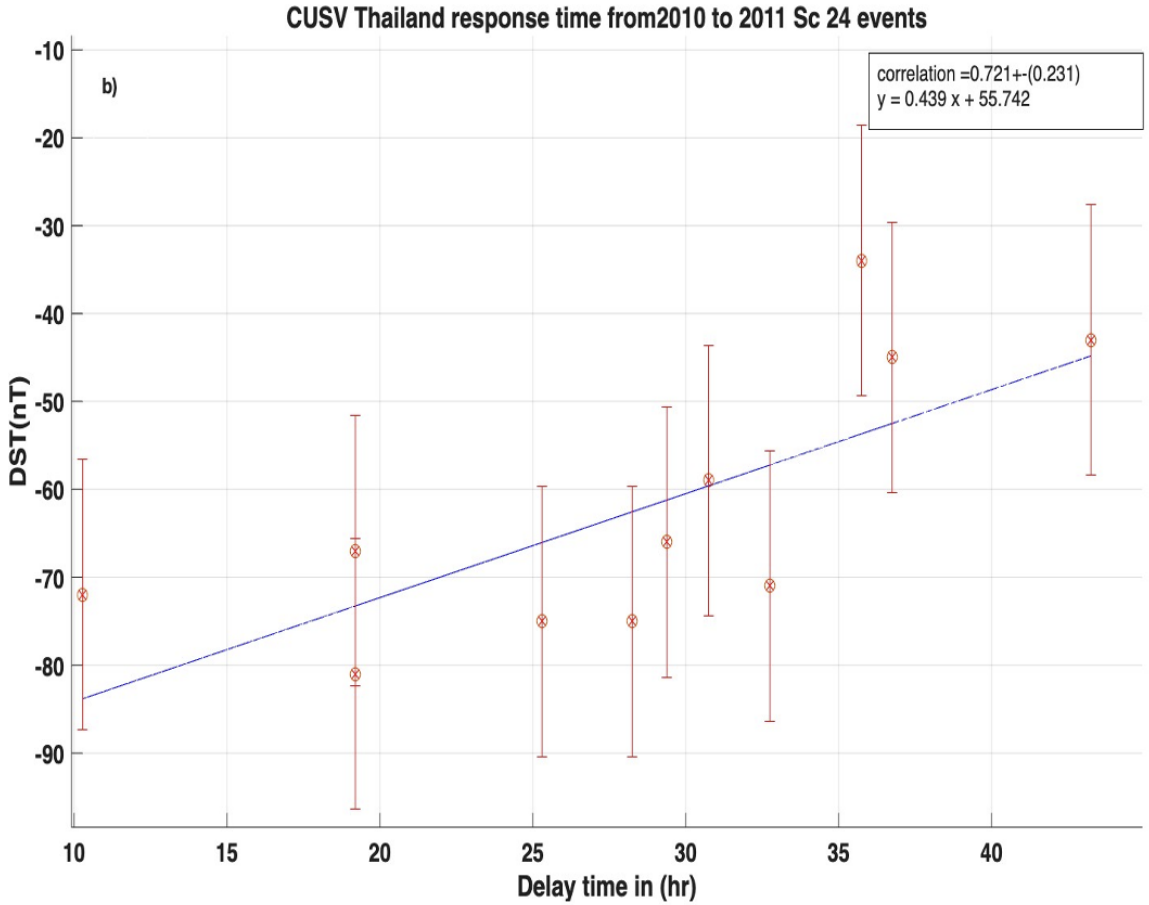






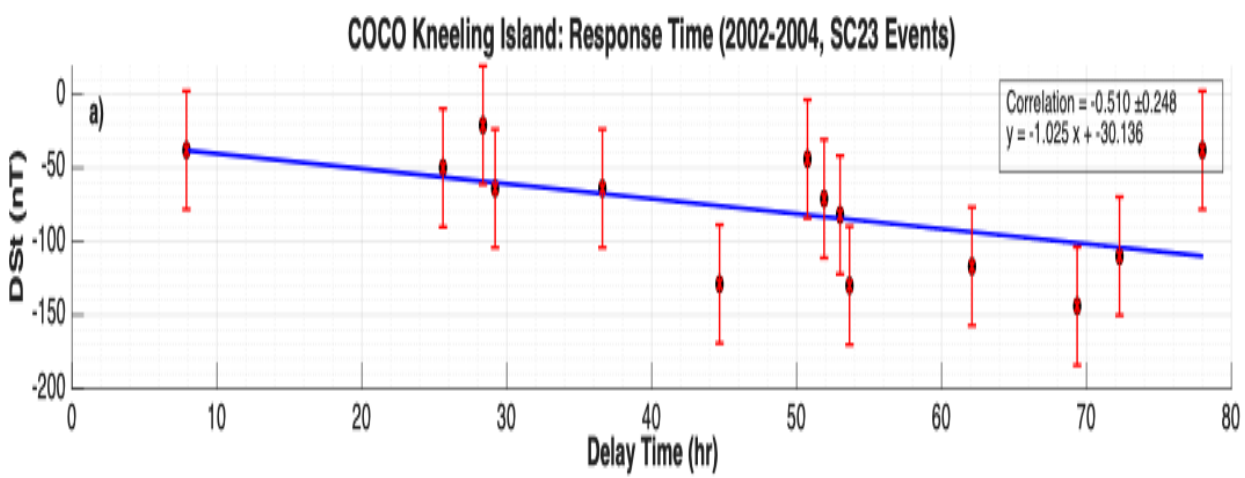
Comparing the two stations correlation's

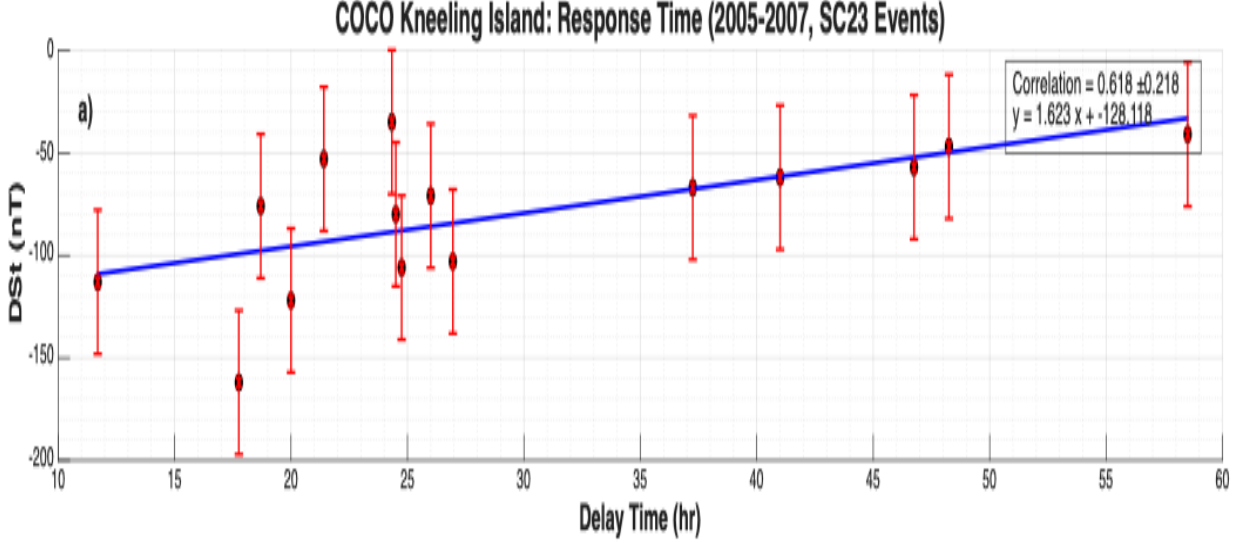


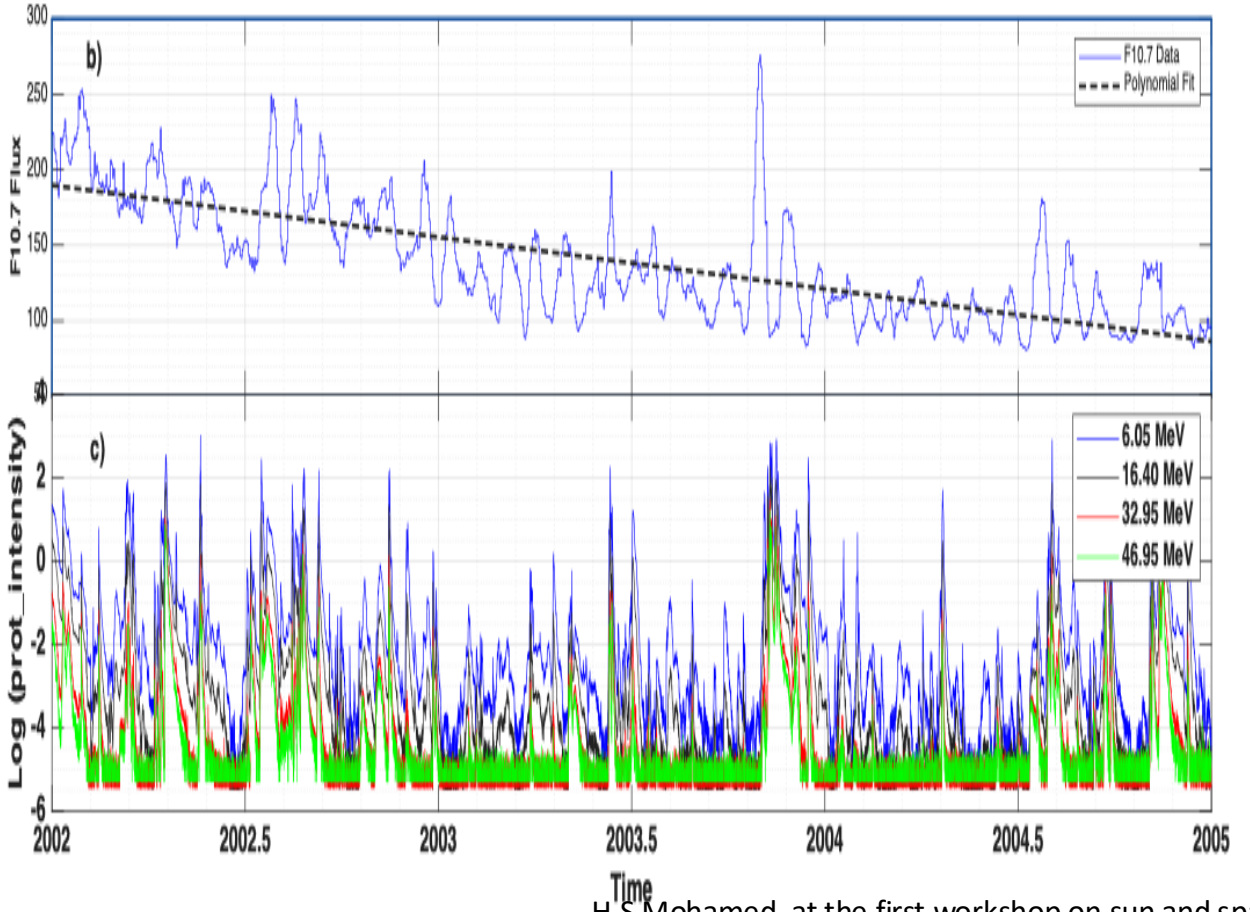


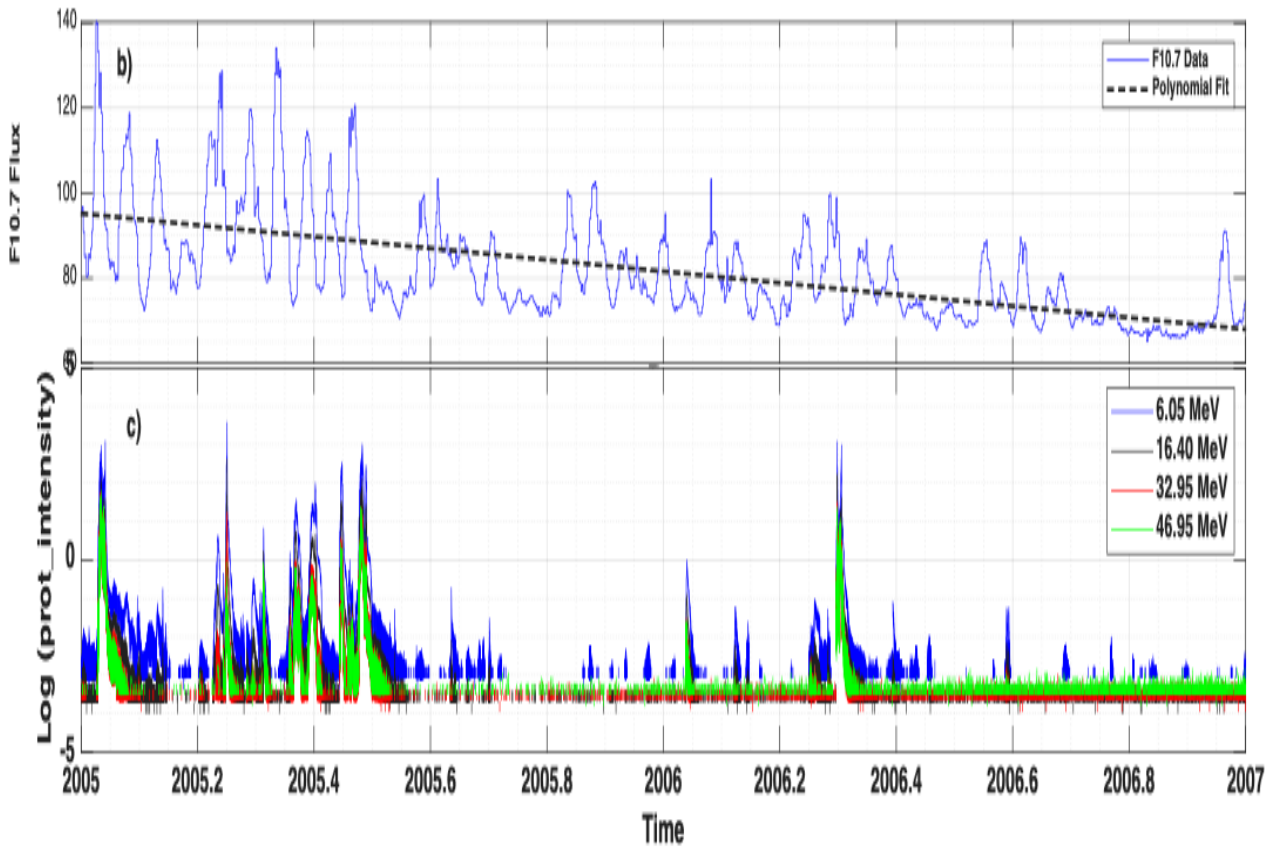
Number of selected geomagnetic storms per year according to the phases of Solar Cycles 23, 24, and 25

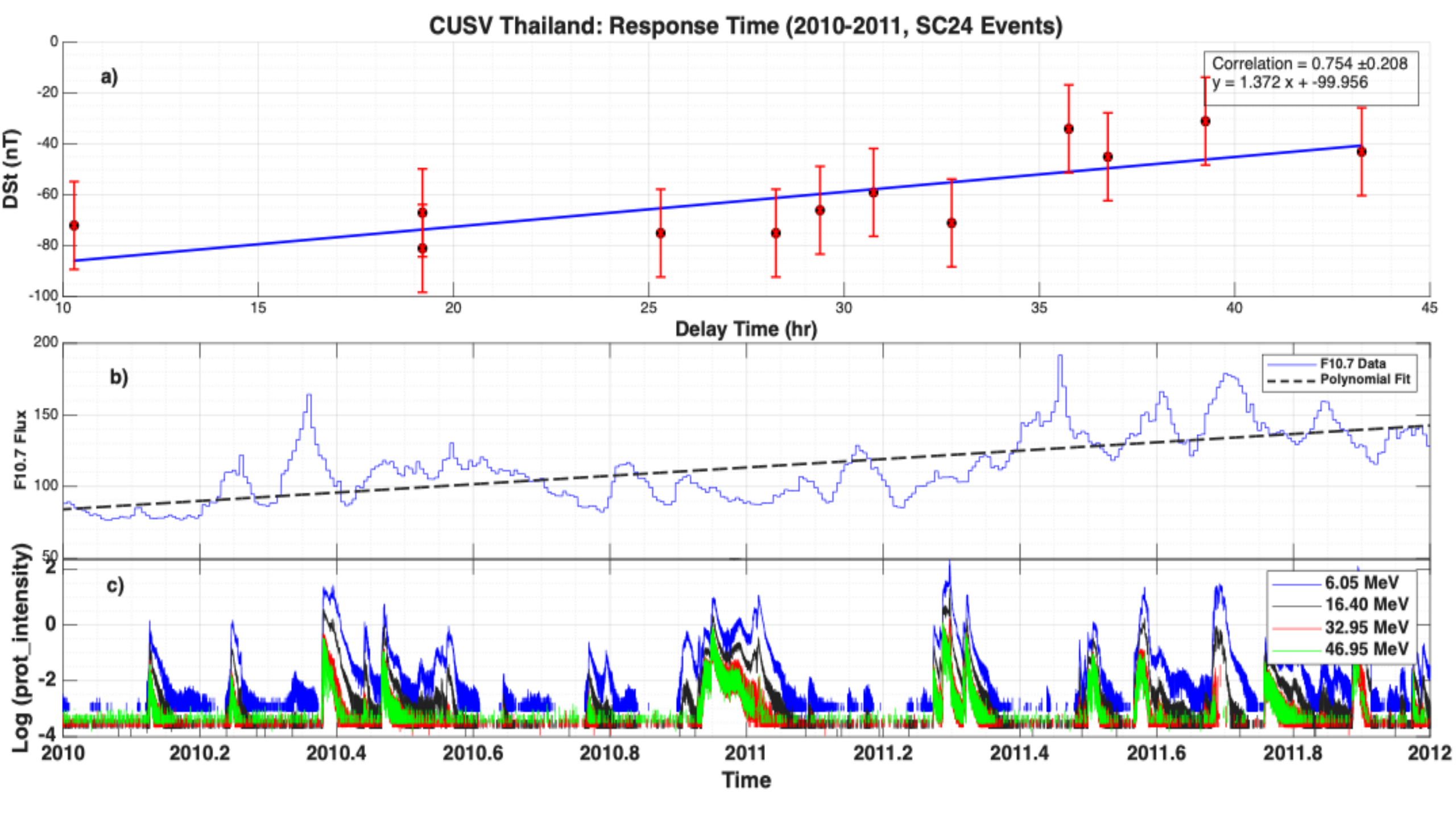
Years	Phases of the Sunspot cycle	Selected events/year	Selected events/ period
2002	Maximum SC23	5	2002-2004 □ 14 events
2003	Decreasing SC 23	4	
2004	Decreasing SC23	5	
2005	Decreasing SC 24	11	2005-2007 □ 15 events
2006	Deep solar minimum	2	
2007	Deep solar minimum	2	
2010	Increasing SC 24	9	2010-2011 □ 12 events
2011	Increasing SC 24	3	
2014	Maximum SC 24	1	2014-2017 □ 10 events
2015	Decreasing SC24	3	
2016	Decreasing SC24	3	
2017	Decreasing SC24	3	
2020	Increasing SC 24	0	2020-2021 □ 6 events
2021	Increasing SC 24	6	

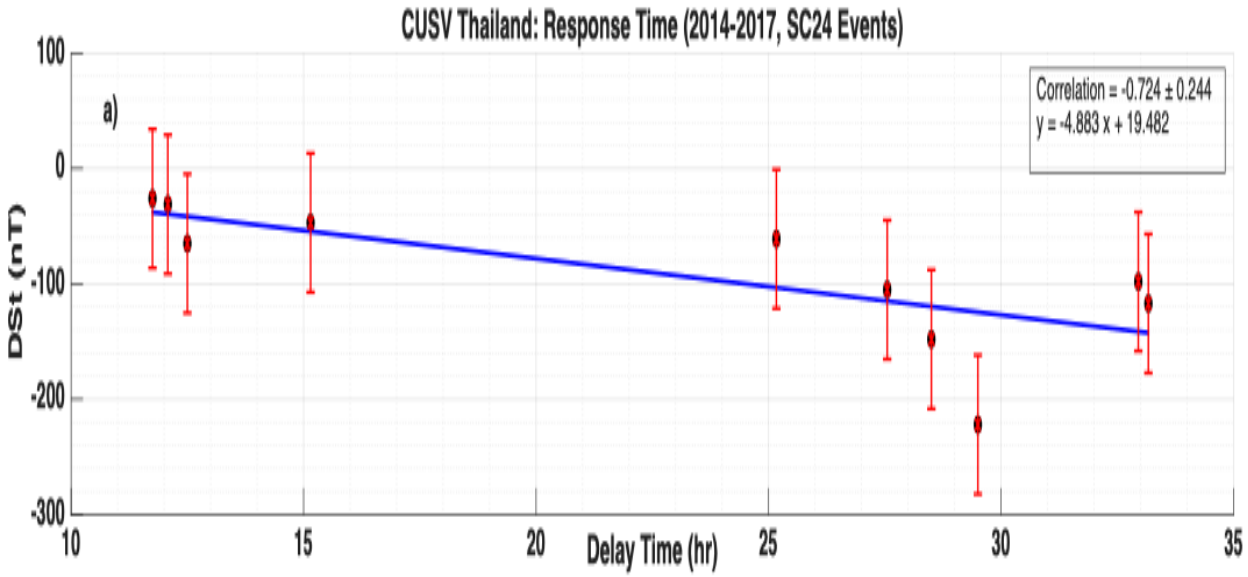

COCO Kneeling Island: Response Time (2002-2004, SC23 Events)
a)
Correlation = -0.510 ±0.248
y = -1.025 x + -30.136
DSt (nT)
Delay Time (hr)

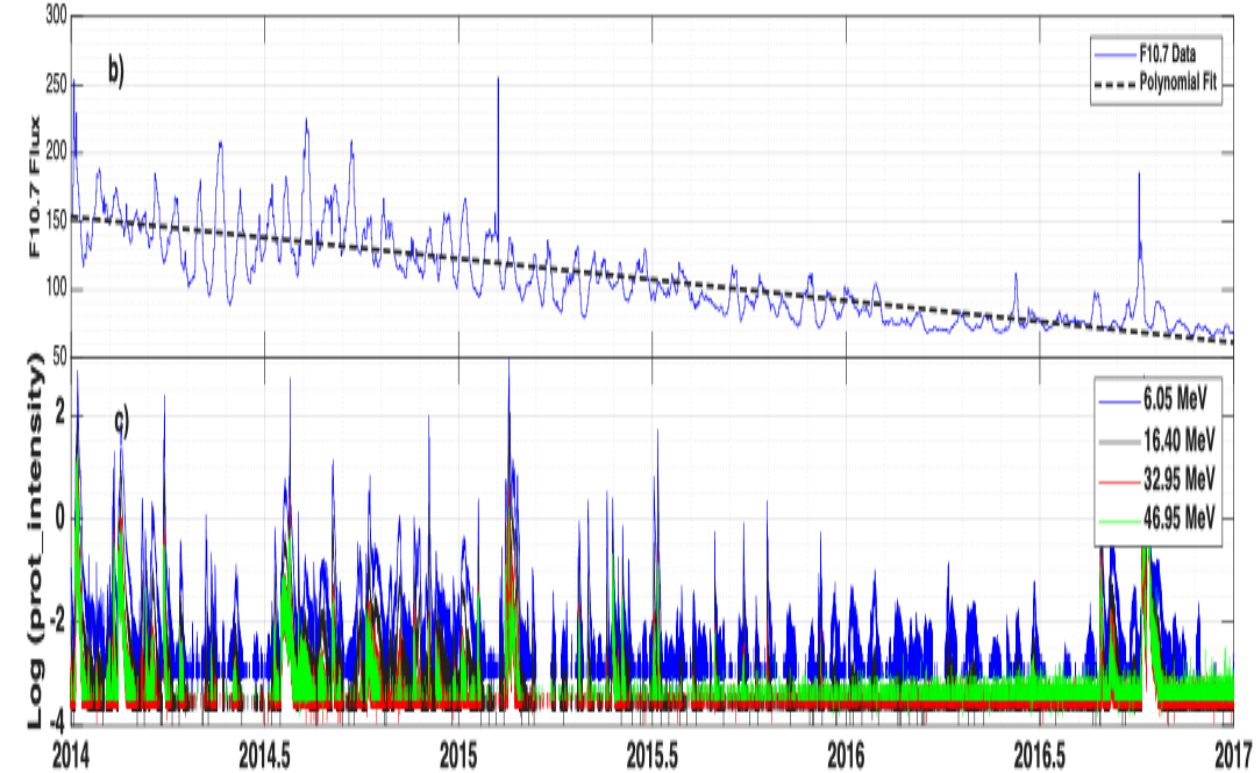

COCO Kneeling Island: Response Time (2005-2007, SC23 Events)
a)
Correlation = 0.618 ±0.218
y = 1.623 x + -128.118
DSt (nT)
Delay Time (hr)

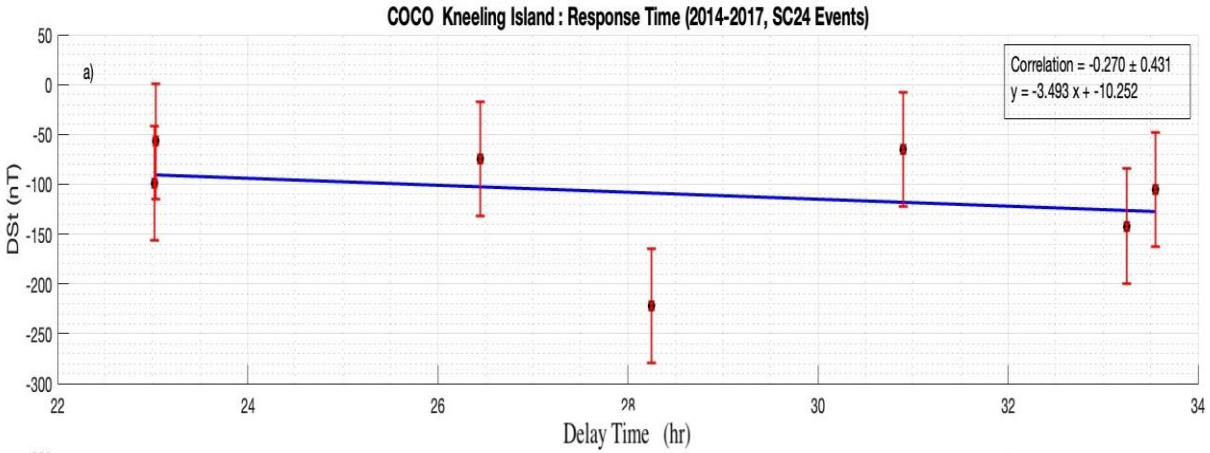

b)
F10.7 Data
Polynomial Fit
F10.7 Flux
c)
6.05 MeV
16.40 MeV
32.95 MeV
46.95 MeV
Log (prot_intensity)
Time

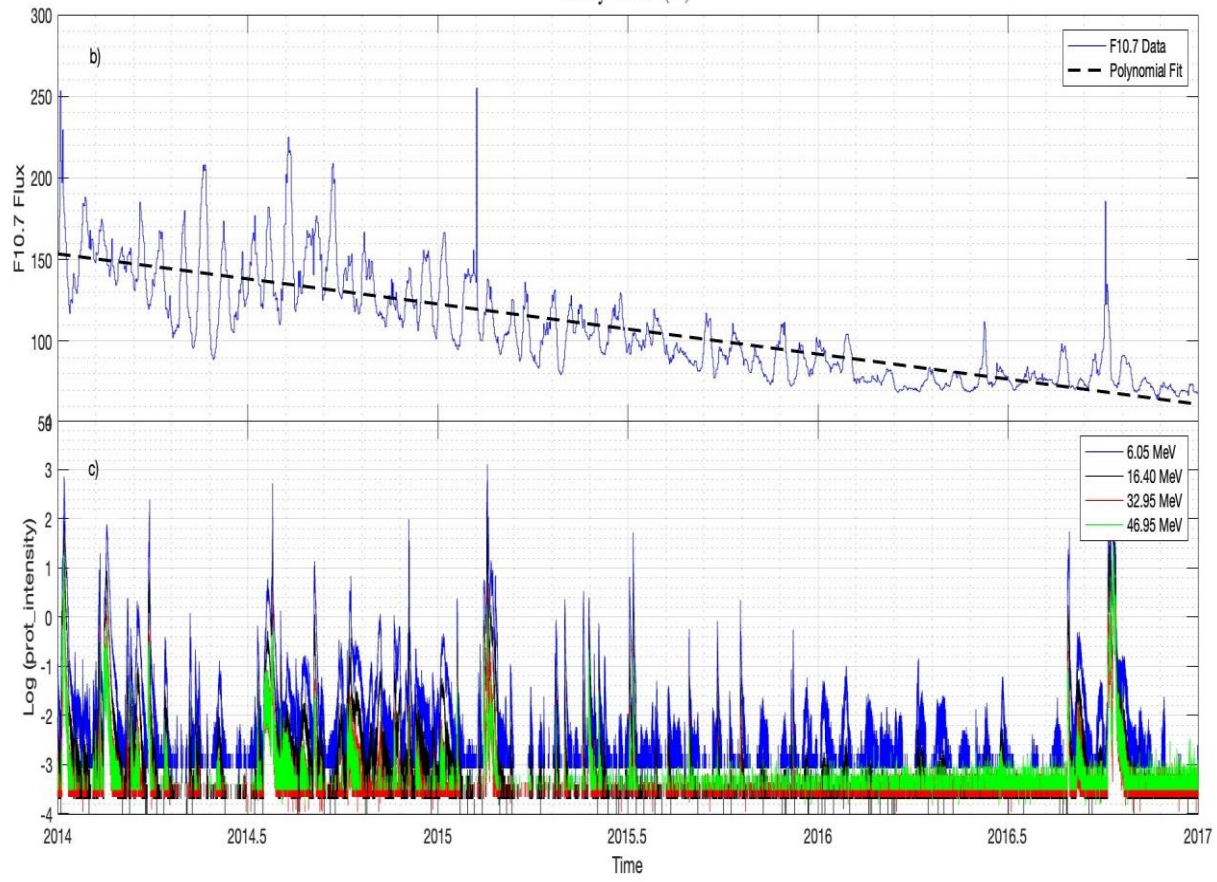

b)
F10.7 Data
Polynomial Fit
F10.7 Flux
c)
6.05 MeV
16.40 MeV
32.95 MeV
46.95 MeV
Log (prot_intensity)
Time

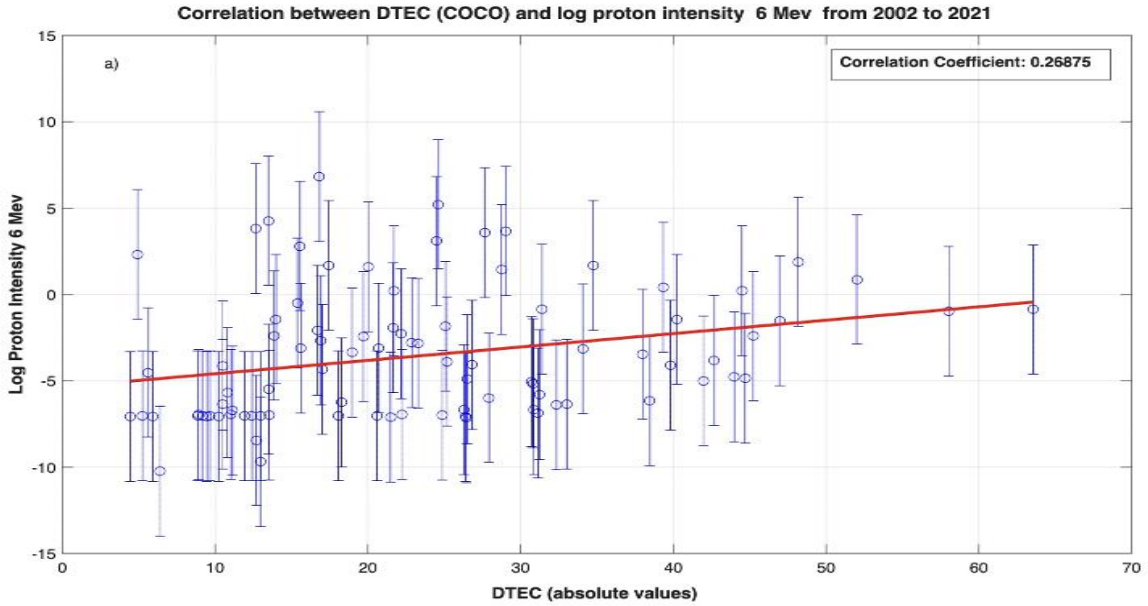

CUSV Thailand: Response Time (2010-2011, SC24 Events)
a)
Correlation = 0.754 ±0.208
y = 1.372 x + -99.956
DSt (nT)
Delay Time (hr)
b)
F10.7 Data
Polynomial Fit
F10.7 Flux
c)
6.05 MeV
16.40 MeV
32.95 MeV
46.95 MeV
Log (prot_intensity)
Time

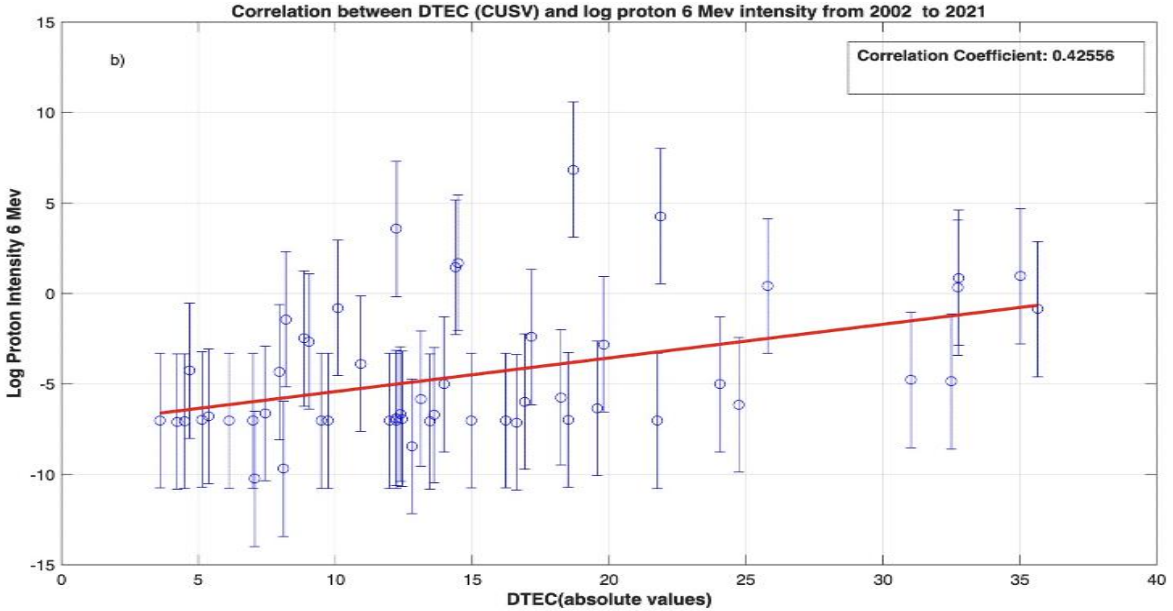

CUSV Thailand: Response Time (2014-2017, SC24 Events)
a)
Correlation = -0.724 ± 0.244
y = -4.883 x + 19.482
DSt (nT)
Delay Time (hr)

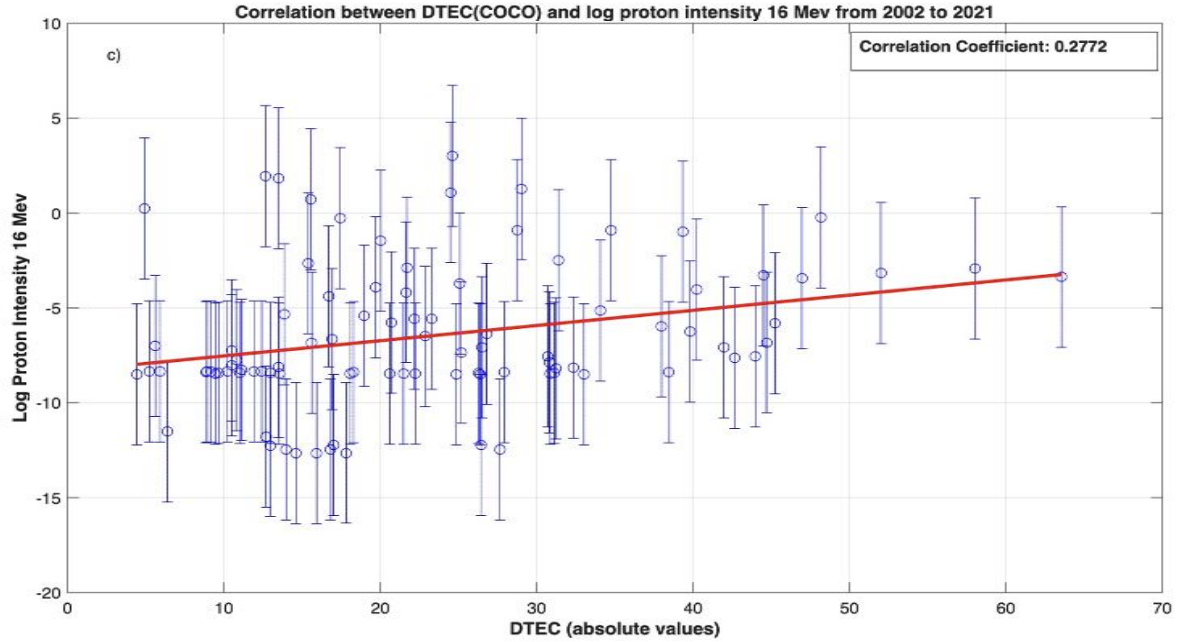

b)
F10.7 Data
Polynomial Fit
F10.7 Flux
c)
6.05 MeV
16.40 MeV
32.95 MeV
46.95 MeV
Log (prot_intensity)
Time

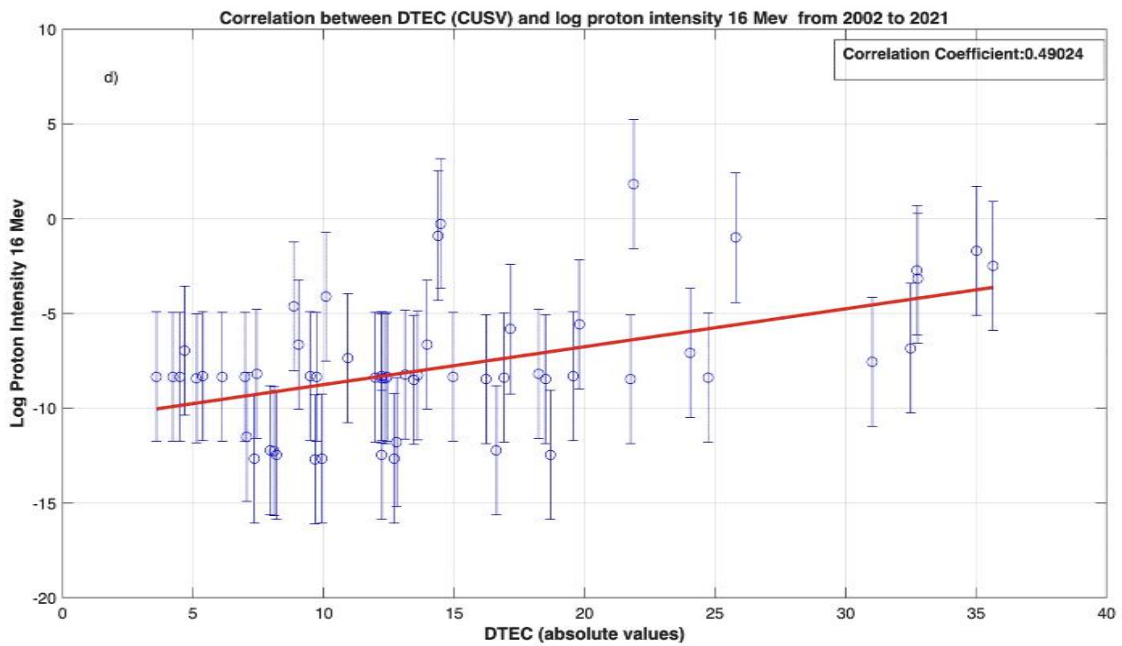

COCO Kneeling Island : Response Time (2014-2017, SC24 Events)
a)
Correlation = -0.270 ± 0.431
y = -3.493 x + -10.252
DSt (nT)
Delay Time (hr)


b)
F10.7 Data
Polynomial Fit
F10.7 Flux
c)
6.05 MeV
16.40 MeV
32.95 MeV
46.95 MeV
Log (prot_intensity)
Time

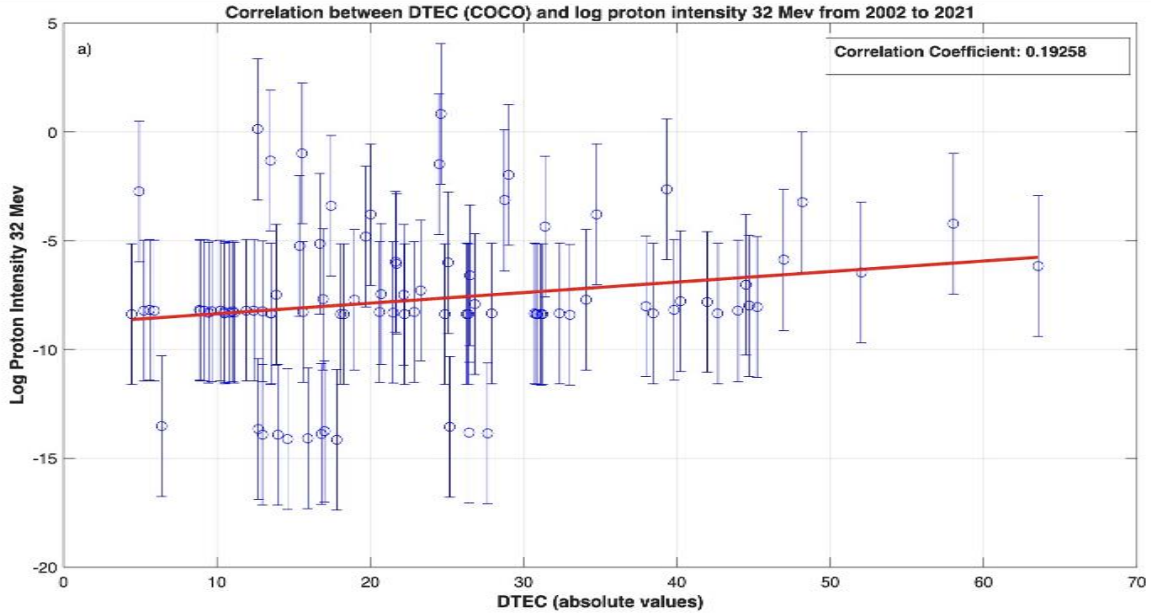


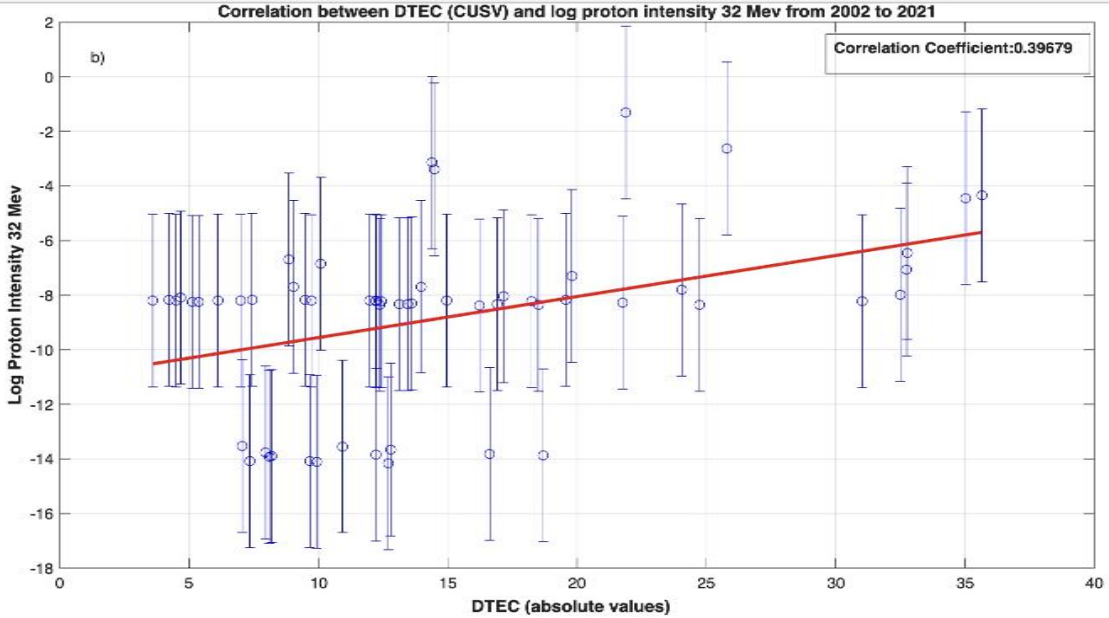


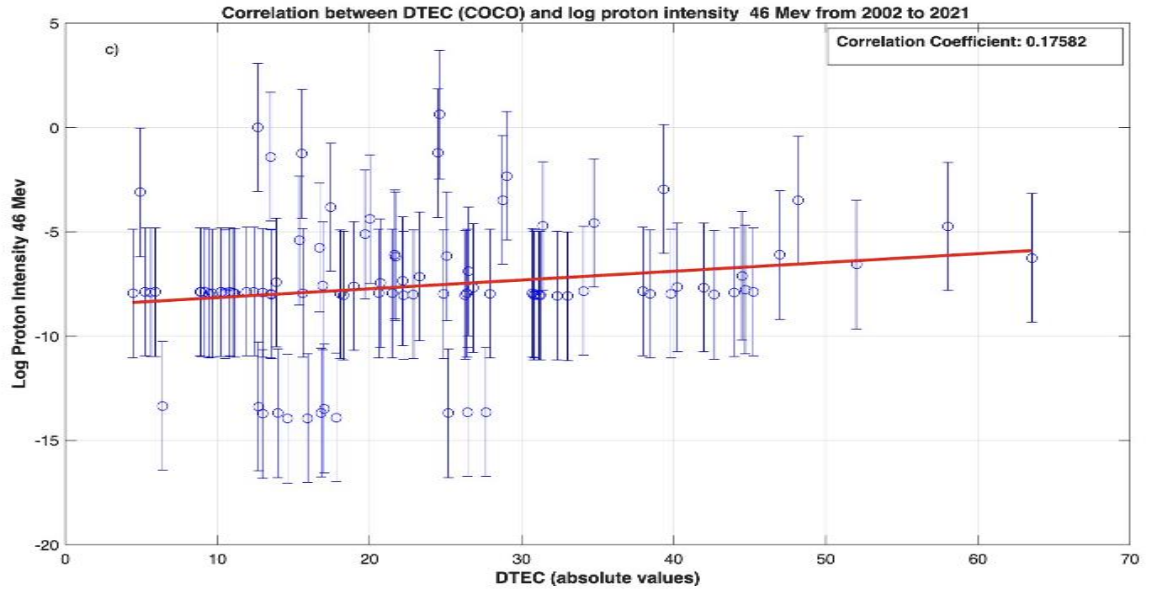


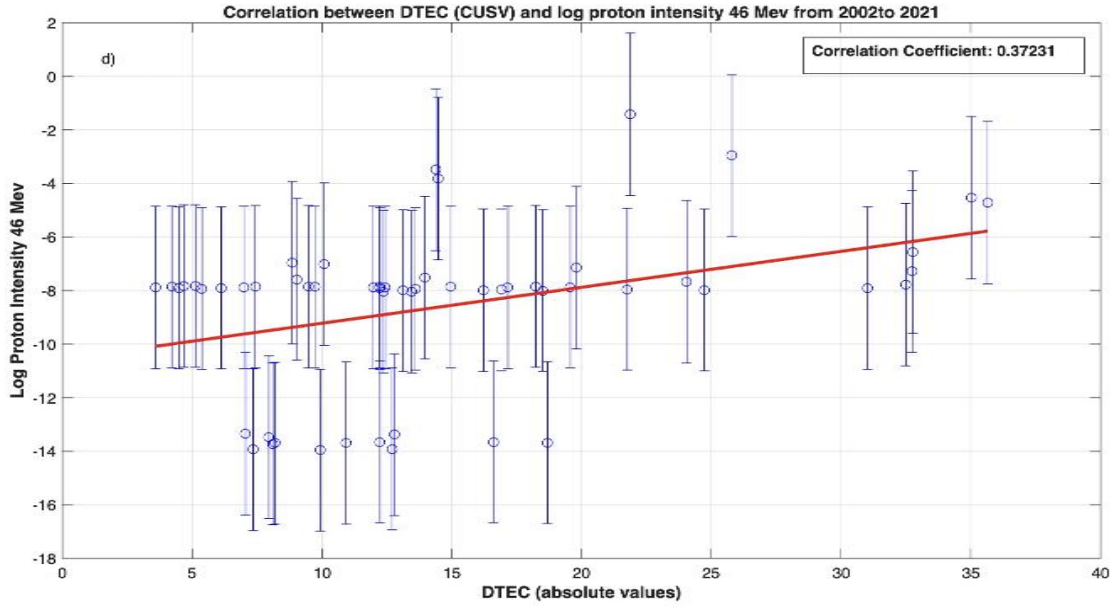


Low-energy protons (6–16 MeV) exhibited significant correlations with DTEC at both stations, confirming the influence of Energetic Storm Particles (ESPs) on low-latitude ionization.

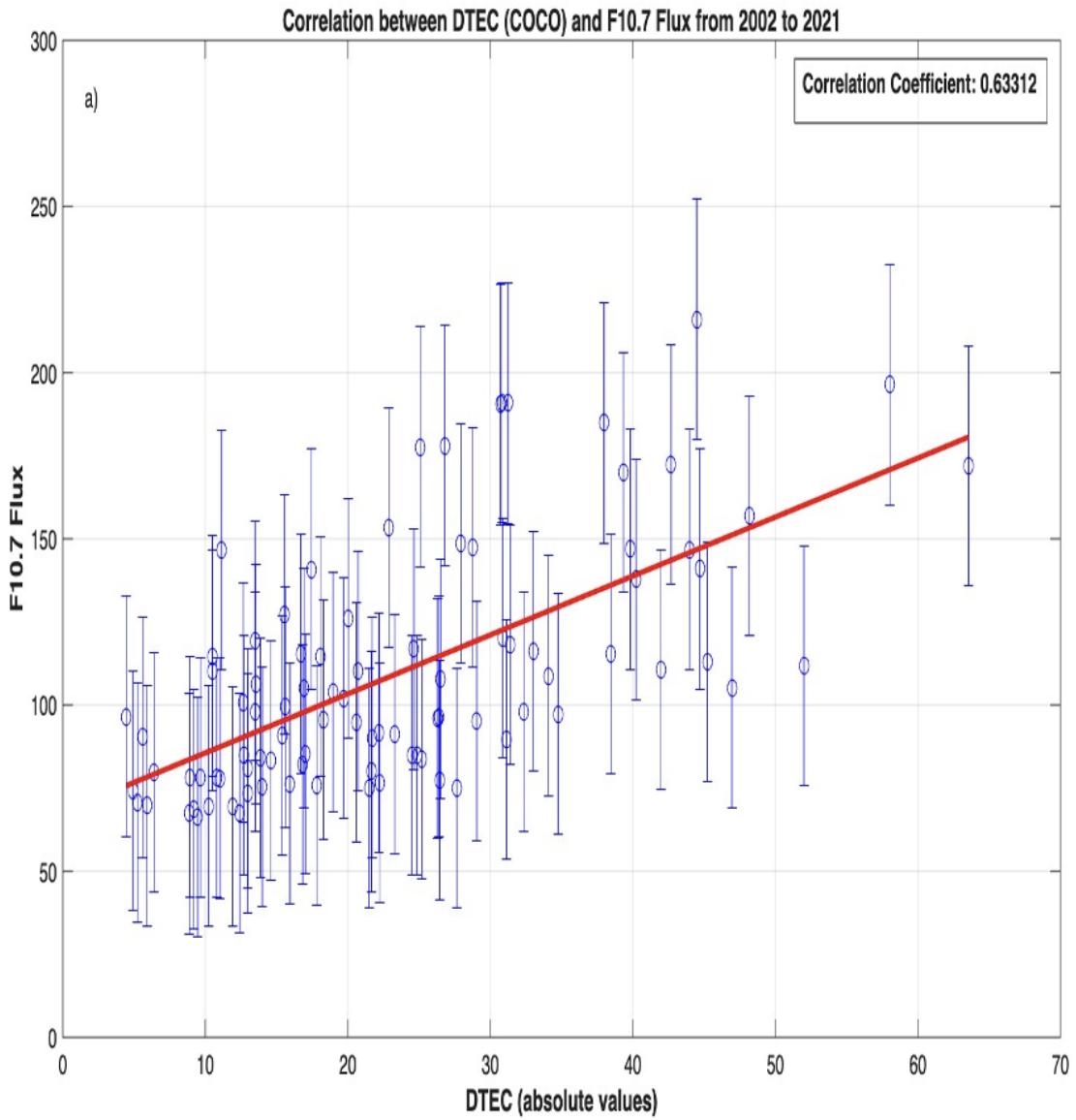


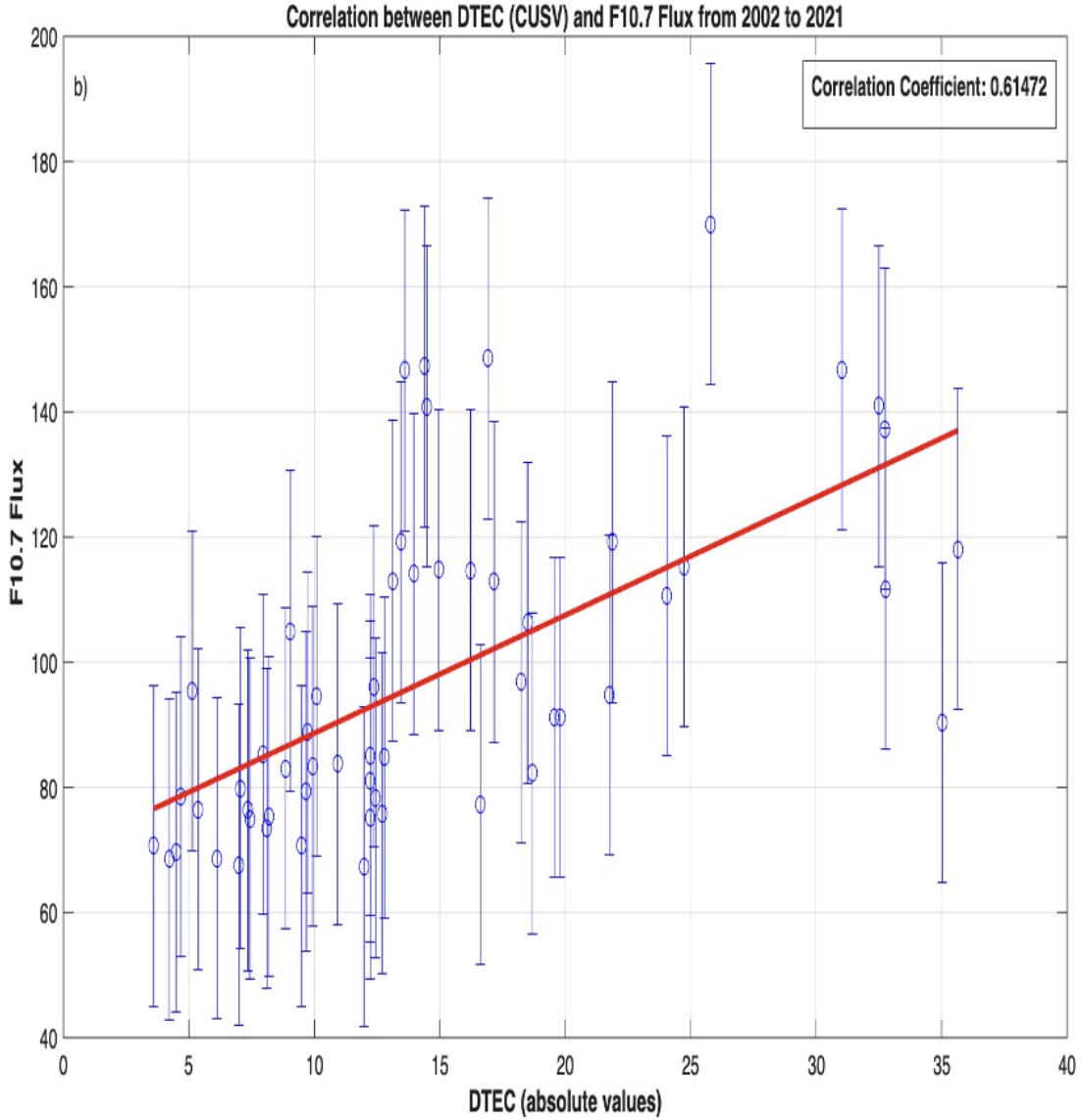


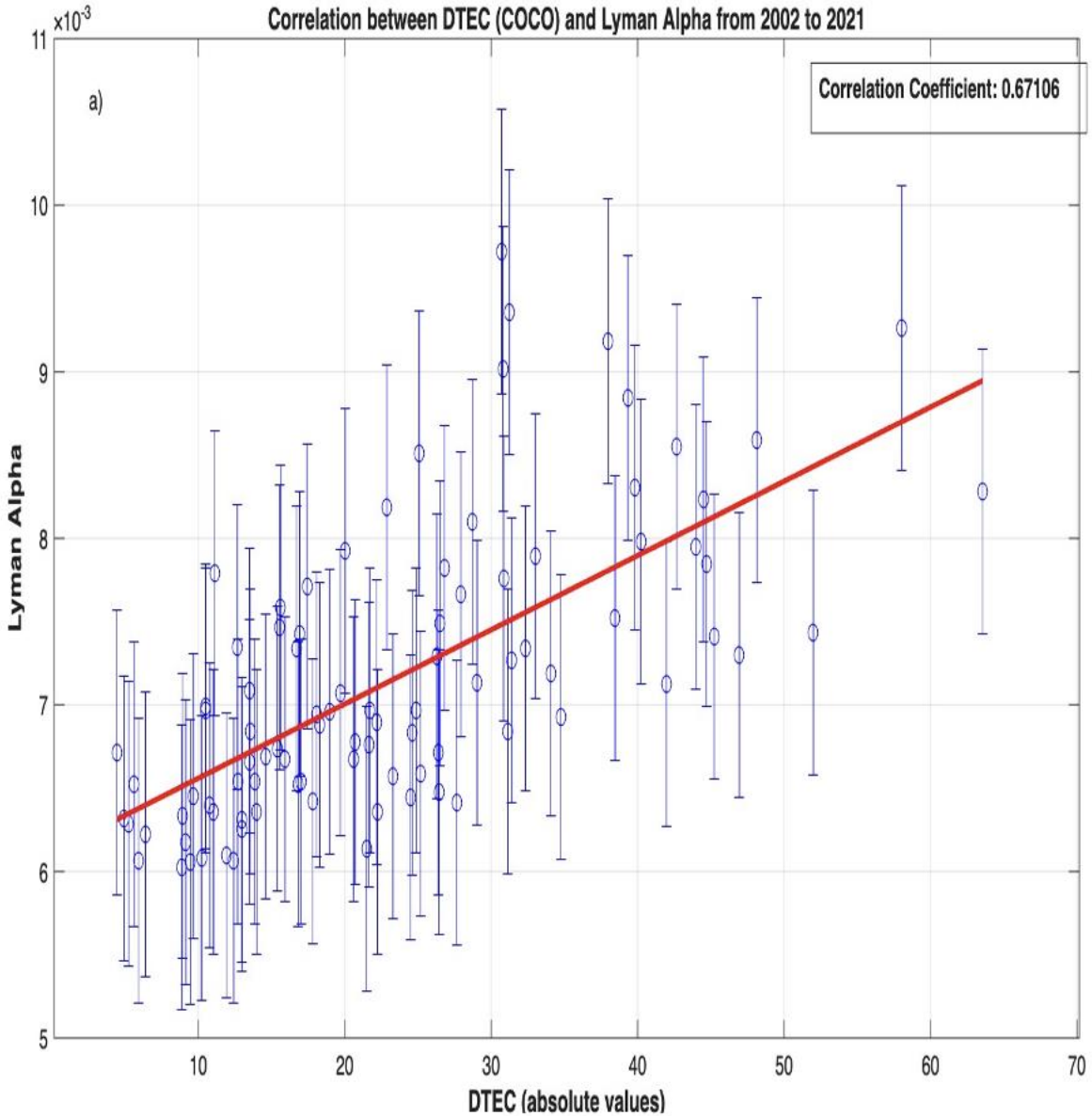


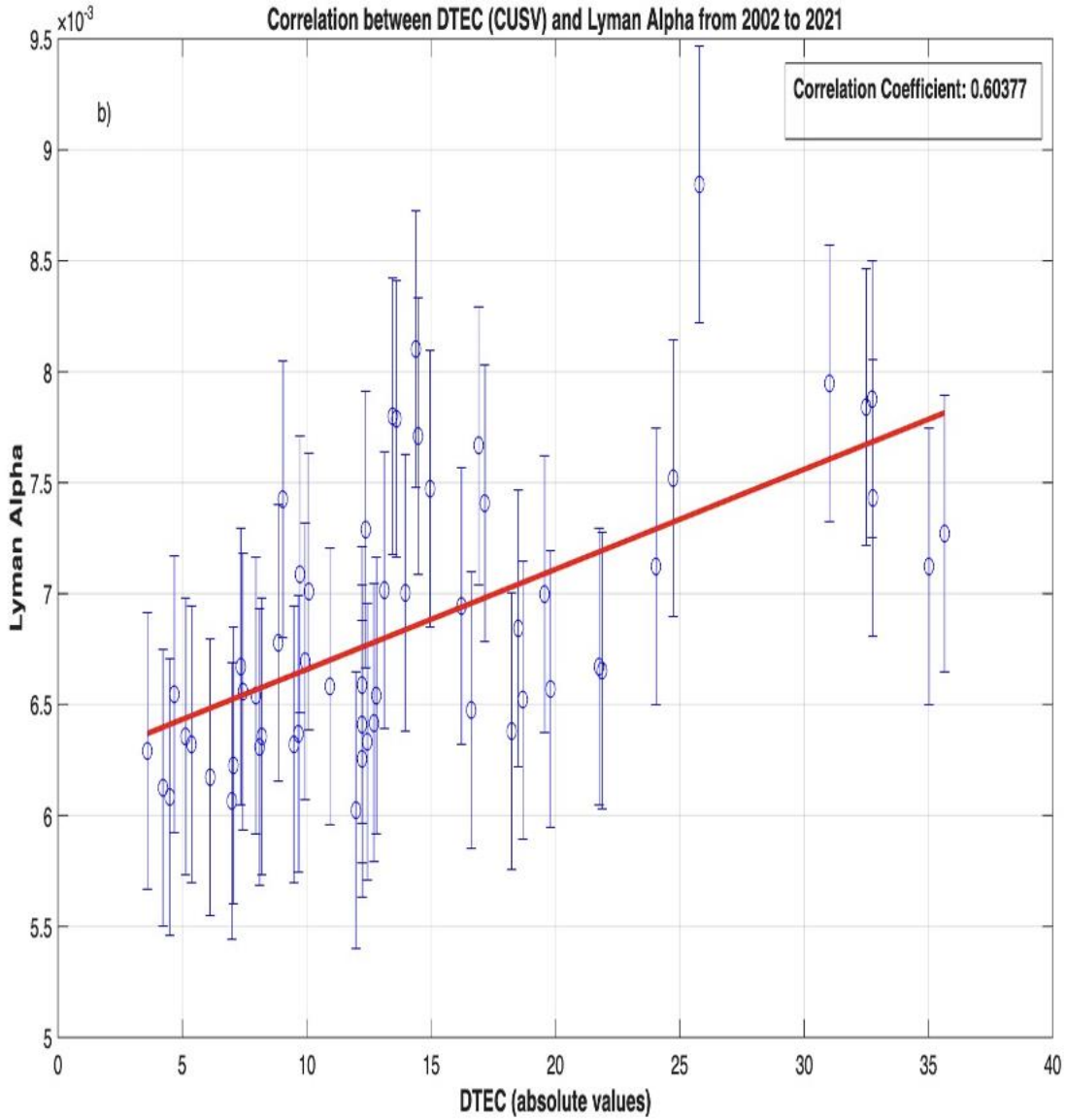


At higher energies (32–46 MeV), a latitudinal divergence emerged: correlations remained significant at the dip equator (CUSV) but weakened at the EIA crest (COCO site). This discrepancy highlights the role of the EIA, where transport and diffusive processes at the crest obscure the prompt signatures of high-energy forcing preserved at the equator.


Correlation between DTEC (COCO) and F10.7 Flux from 2002 to 2021
a)
Correlation Coefficient: 0.63312
F10.7 Flux
DTEC (absolute values)
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70


Correlation between DTEC (CUSV) and F10.7 Flux from 2002 to 2021
b)
Correlation Coefficient: 0.61472
F10.7 Flux
DTEC (absolute values)
40
60
80
100
120
140
160
180
200
0
5
10
15
20
25
30
35
40


Correlation between DTEC (COCO) and Lyman Alpha from 2002 to 2021
x10-3
a)
Correlation Coefficient: 0.67106
Lyman Alpha
DTEC (absolute values)


Correlation between DTEC (CUSV) and Lyman Alpha from 2002 to 2021
x10-3
b)
Correlation Coefficient: 0.60377
Lyman Alpha
DTEC (absolute values)

The correlation used :

- The correlation used is Pearson correlation
- $$r = \frac{\sum(xi-\bar{x})(yi-\bar{y})}{\sum(xi-\bar{x})^2\sum(yi-\bar{y})^2}$$
- where x_i and y_i are the individual sample points. where $\bar{x}$ and $\bar{y}$ are the mean values of the respective variables. In this study, **x** is considered for the parameter **delay time or DTEC**, whereas **y** denotes Dst, F10.7, Lyman alpha, or log proton intensity, based on the analysis undertaken.

Correlations	COCO	Number of events	CUSV	Number of events
SC23 (2002-2004)	0.510	14	NA	NA
SC23 (2005-2007)	0.618	15	NA	NA
Ascending phase Sc24 (2010-2011)	0.528	11	0.754	12
Phase SC24 (2014-2017)	0.27	7	0.724	10
Ascending phase Sc25 (2021)	NA	NA	0.891	6
Log proton int (6 MEV) with DTEC	0.2687	93	0.425	57
Log proton int (16 MEV) with DTEC	0.2772	93	0.4902	57
Log proton int (32 MEV) with DTEC	0.19258	93	0.396	57
Log proton int (46 MEV) with DTEC	0.17582	93	0.372	57
F10.7 with DTEC	0.633	93	0.6147	57
Lyman Alpha and DTEC	0.671	93	0.6037	57

Conclusion :

- this study confirms the critical role of the solar radiative background in modulating storm-time delays. Both F10.7 flux and Lyman-alpha (Lyα) irradiance showed strong positive correlations with DTEC ($r>0.60$) at both stations.
- The divergence in high-energy proton correlations between CUSV and COCO validates the physical distinction between the "source" (equator) and "sink" (crest) of the equatorial plasma fountain.
- The study established a consistent statistical relationship between the Dst index and ionospheric delay time ($r=0.50$ to 0.89), validating the use of Dst as a proxy for forecasting low-latitude ionospheric disturbances.
- The delay time differ according to the phase of the Solar cycle
- During the ascending phases of SC 24 and SC 25, the delay times stabilized within 31–34 hr.
- During the declining phase of SC 24 (Weak Cycle Dynamics), the shortest delay times (~27 hr) were observed.
- During the SC 23 Early Declining phase (Compound Events), the longest delay times (~48 hr) occurred during strong solar activity.
- Difference with 4 degree longitude does not affect the correlation direction (direct- inverse) for both stations.
- The Correlation usually follow the direction of mean F10.7 unless the log proton intensity lack emission like

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