Impact of CMEs on the magnetosphere and thermosphere system during the May 2024 Gannon Storm

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CONTENT

The Dynamic Sun

08 May 2024

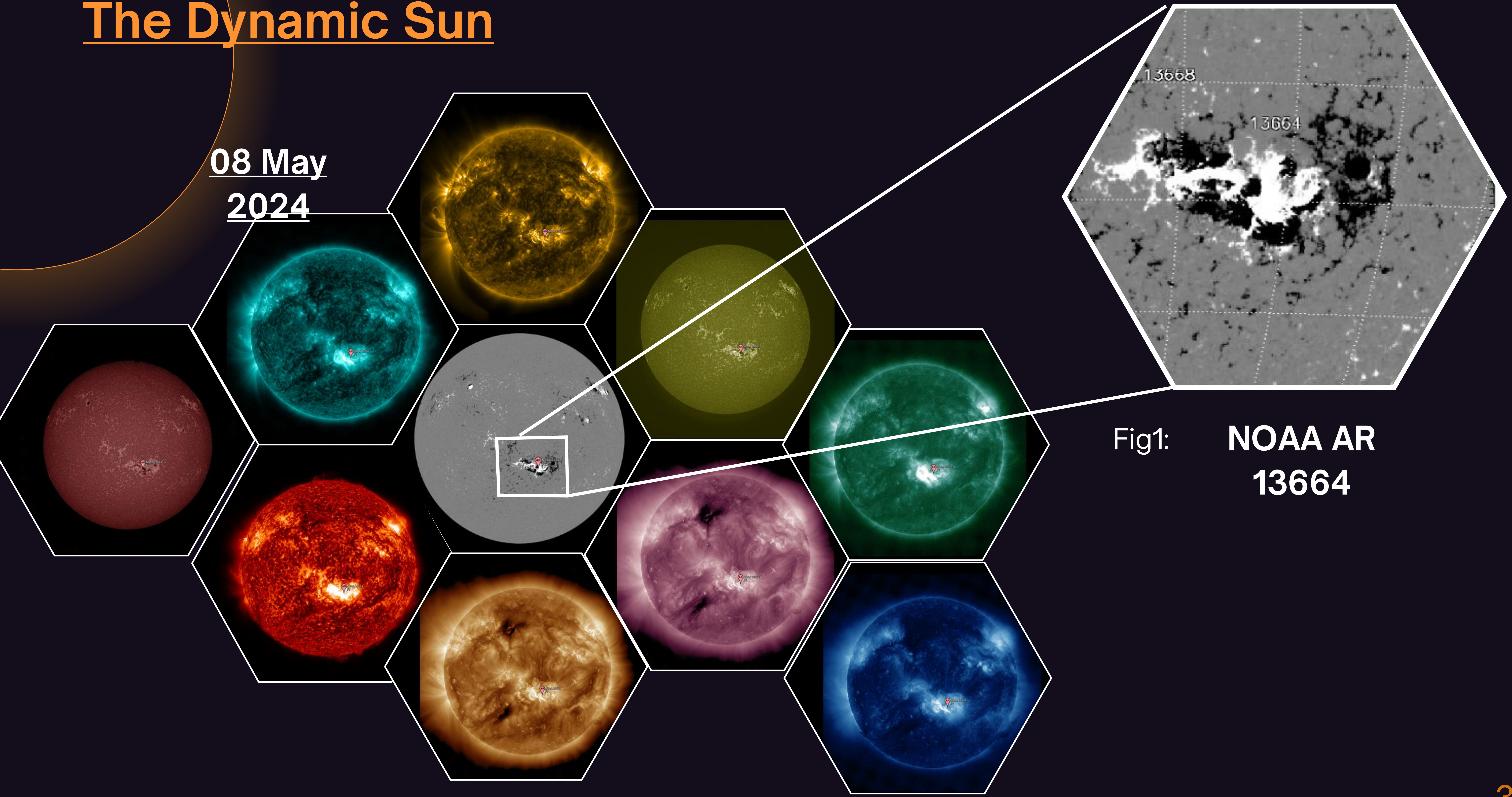
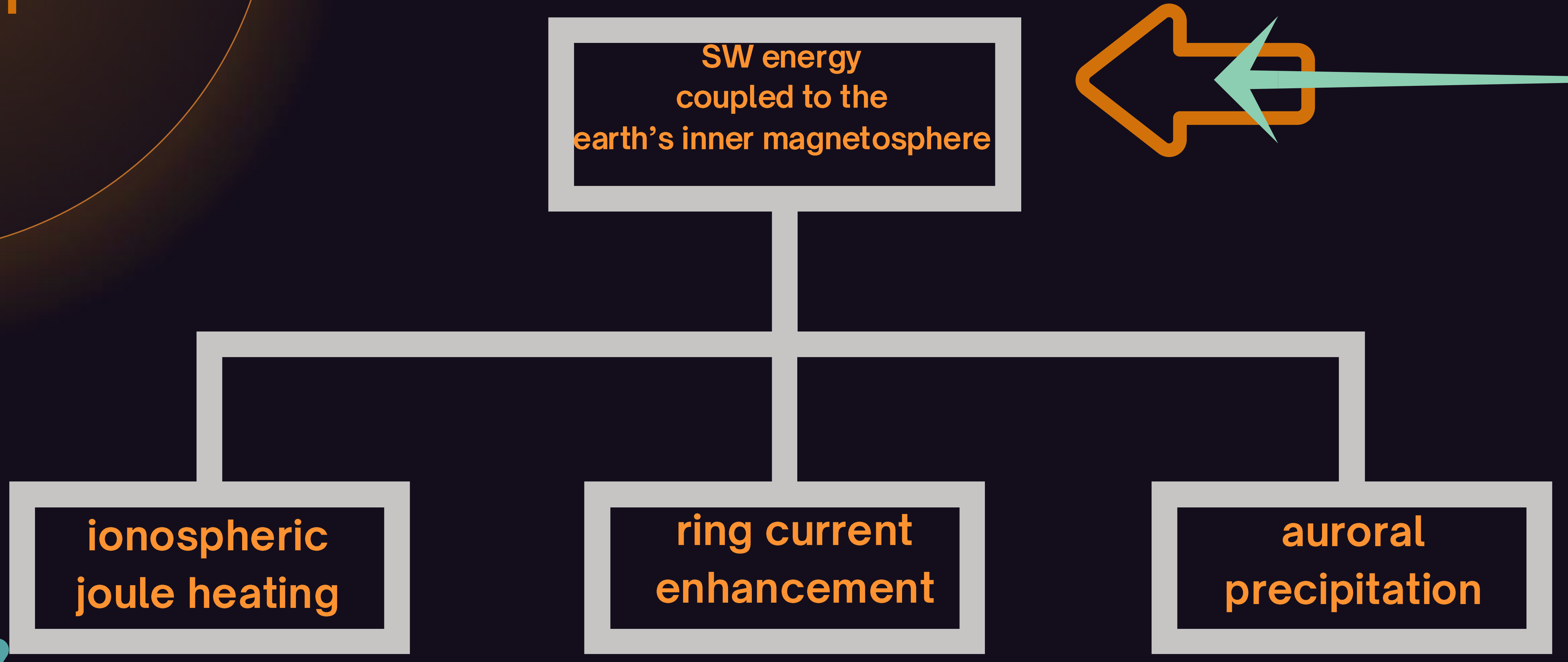


Fig1: **NOAA AR 13664**

Solar Wind Energy dissipation through Ionospheric Joule heating during the storm



Energy carried by space weather drivers
EFLARE + ECME

primary pathway
through which magnetospheric energy is thermalized in the high-latitude thermosphere

drives heating

expansion

increased satellite drag

changes in composition (eg: NO)

Motivation for Study

- To study the most intense geomagnetic disturbances in modern history : May 2024
- Exploring the multi realm aspect of heating effect in SUN-EARTH connection
- Multi-thermal diagnostics → understand heating/energy release during eruption → heat dissipation mechanism via Joule Heating
- Combined observations from EUV channels (AIA/SDO), model based and emperical study to know heat dissipation mechanism
- The study will further extend to investigate propagation of the space weather drivers and its impact in earth’s lower atmosphere

Geomagnetic superstorm of May 2024

- The Gannon storm: most intense storm since Halloween storms of November 2003
- Class: G5 rating, Kp Index=9
- Triggered by multiple coronal mass ejections from NOAA AR 13664
- Peak SYMH -518nT
- southward IMF reaching -50 nT

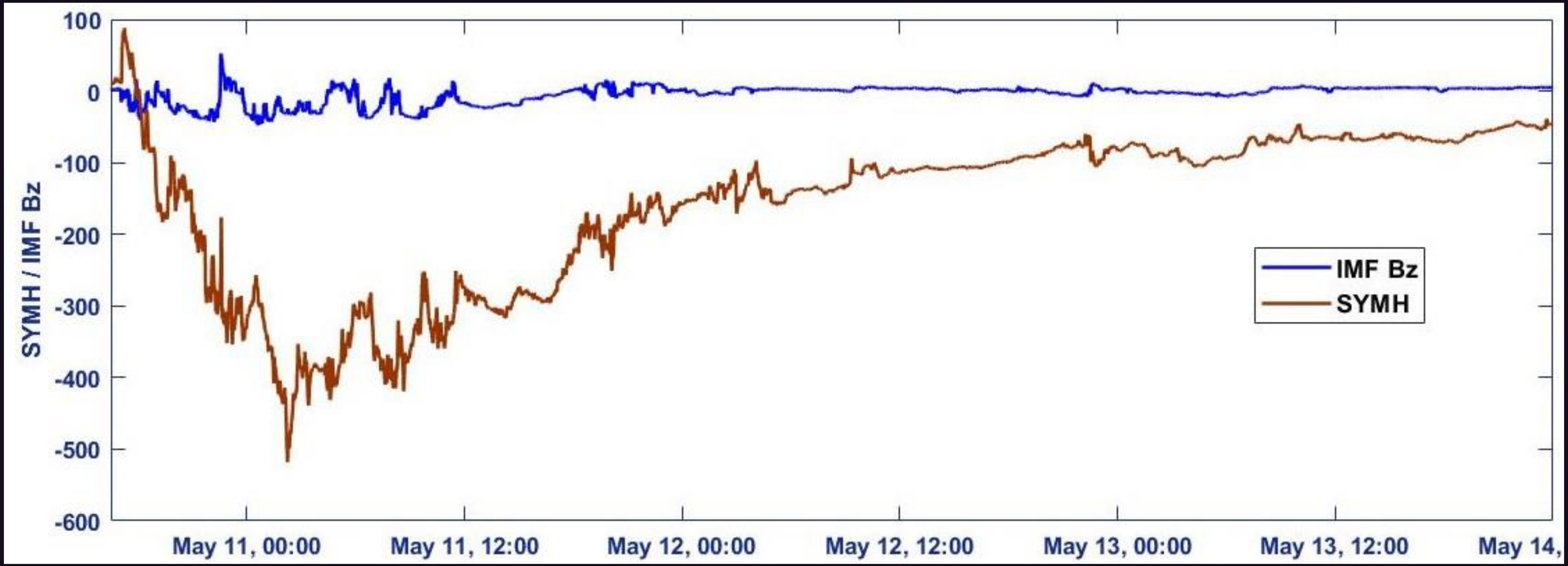

100
0
-100
-200
-300
-400
-500
-600
SYMH / IMF Bz
May 11, 00:00
May 11, 12:00
May 12, 00:00
May 12, 12:00
May 13, 00:00
May 13, 12:00
May 14,
IMF Bz
SYMH

Fig2

Geomagnetic superstorm of May 2024 : Magnetospheric effects

HF radio blackouts (2-12 MHz) occurred due to D/E-region ionization from preceding flares

boosted dayside TEC by over 100%, disrupting GPS signals

Aurorae were visible at unusually low latitudes worldwide, including mid-latitudes like Hawke's Bay and Cannon Falls

In India, aurorae was visible at high latitude northern region like Ladakh, which was one one the rarest low-latitude sightings in the space era for the Indian subcontinent

Observations and Analysis

DATA/RESOURCES

- AIA/SDO
- LASCO/SOHO
- WIND
- ACE
- Omniweb data
- SABER/TIMED

Observation 1 : The CME + Flare analysis

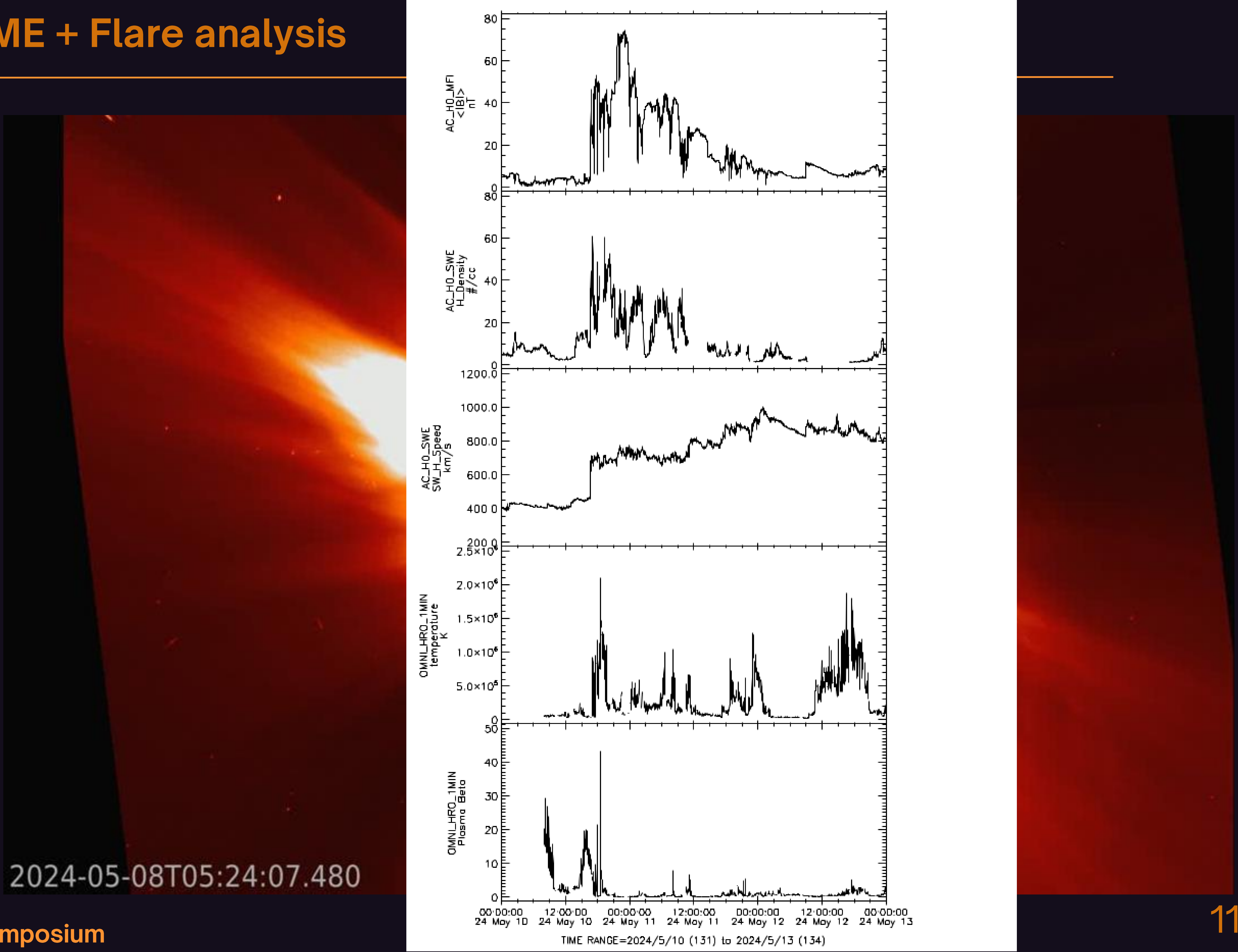
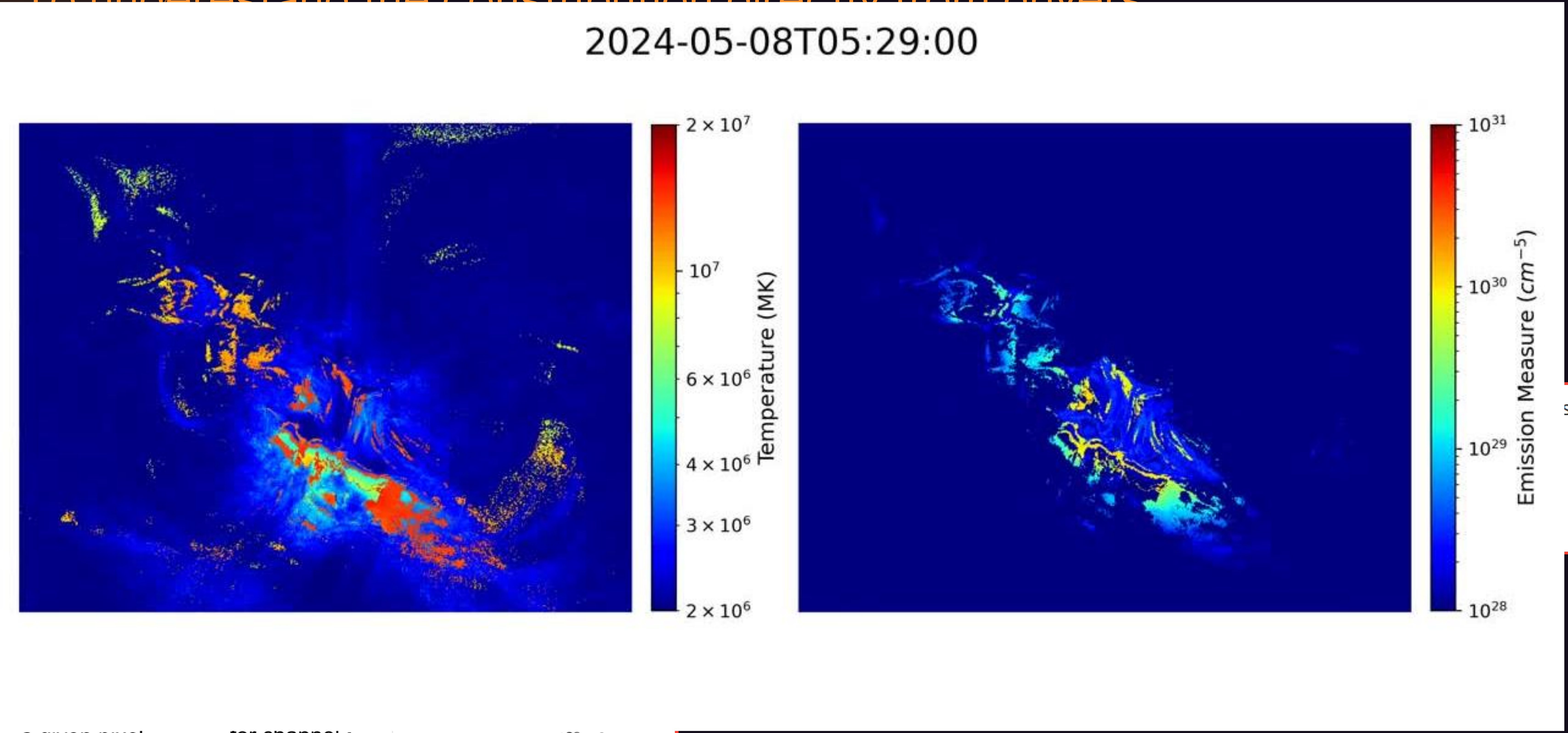


Fig3: credits JH (LASCO/SOHO)

Observation 1 : The CME + Flare analysis

- To underestand the constribution directly from drivers



a given pixel   for channel i $\mathrm{DEM}(T)dT = \int_0^\infty n_e^2(T)dz,$

Fig4: TEM, EM Maps

Observation 2: Energetics of SW

- SW couple energy to the magnetosphere is estimated using Coupling Function by *Tenfjord and Østgaard (2013)*

$$P_{\text{storm}}\,(W) = \frac{B_T^2 V_x}{\mu_0} M_A \sin^4\left(\frac{\theta}{2}\right) \frac{135}{5 \times 10^{22} |B_z|^3 + 1} R_E^2$$

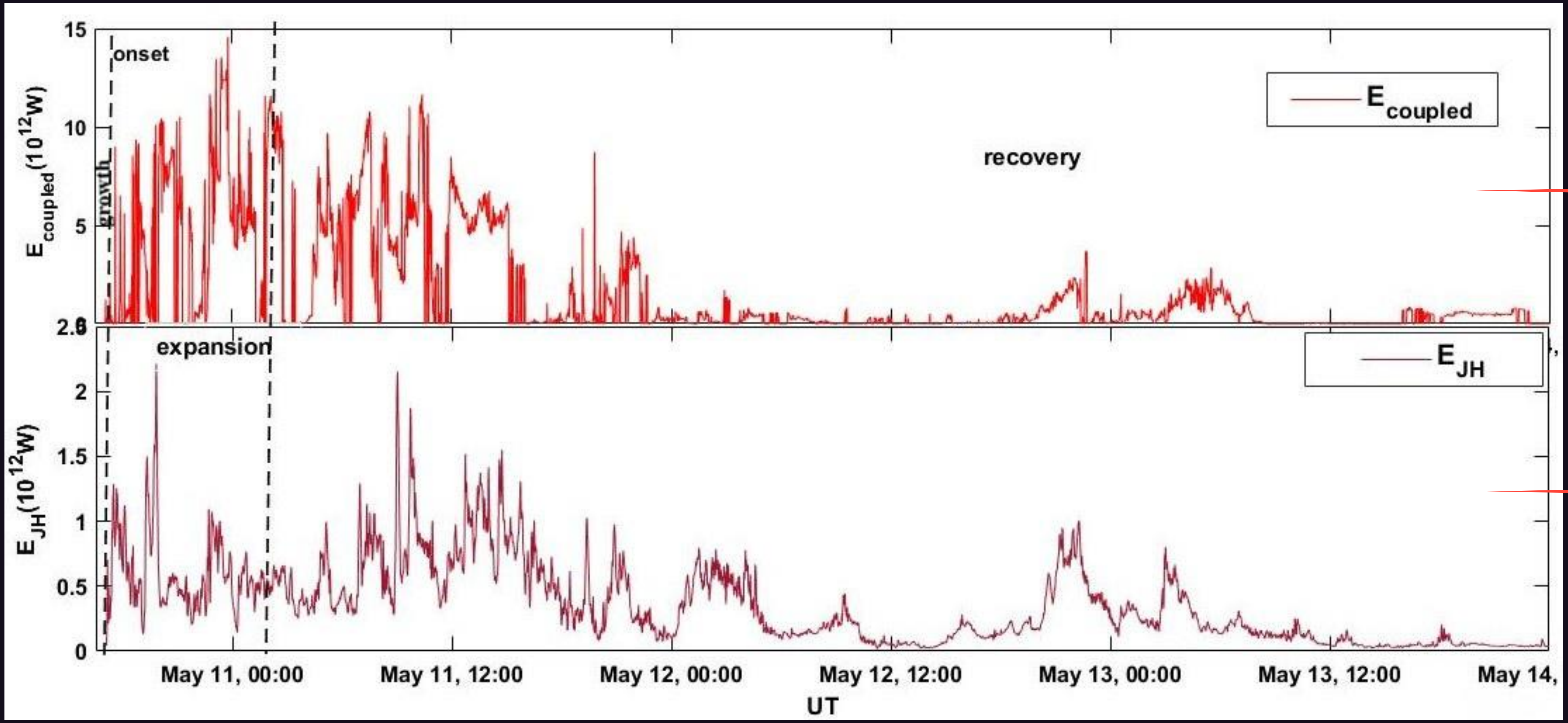
M_A =Alfvénic-Mach number,

$B_T^2 = B_y^2 + B_z^2$; , v_x is the x component of SW velocity,

θ is the IMF clock angle,

R_E is the radius of the earth.

- We estimate the ionospheric JH using AE auroral index (*put forward by Ahn et al. (1983) and modified by Tenfjord and Østgaard (2013)*, $E_{JH}(GW)_{AE} = 0.54AE + 1.8$, and using OpenGGCM model



Rate of energy coupled during the storm period from incident solar wind

energy dissipated through ionospheric joule heating

- We obtained overall SW incident energy to be approx.17x1018J while energy coupled was 4.43 x1017 J
- Share of JH energy from energy coupled from SW during different storm phases:

Growth: 0.51% (0.0227 x1017J)

Expansion: 3.94% (0.175 x1017J)

Recovery : 18.4% (0.817 x1017J) → longer recovery phase hence JH rate is higher during this phase

total JH accounts for 22.87% (1.02 x1017J)of the SW coupled energy

Fig5 :

JH from OpenGGCM (Open Geospace General Circulation Model) run

- physics-based simulation framework for modeling the coupled magnetosphere-ionosphere-thermosphere system in Earth's geospace environment
- solves for plasma flows, magnetic fields, and currents across 3D grids, capturing phenomena like substorms and geomagnetic storms
- Input solar wind parameters : density, velocity, temperature, and interplanetary magnetic field (IMF) components from satellites like ACE or DSCOVR and provides joule dissipation rate

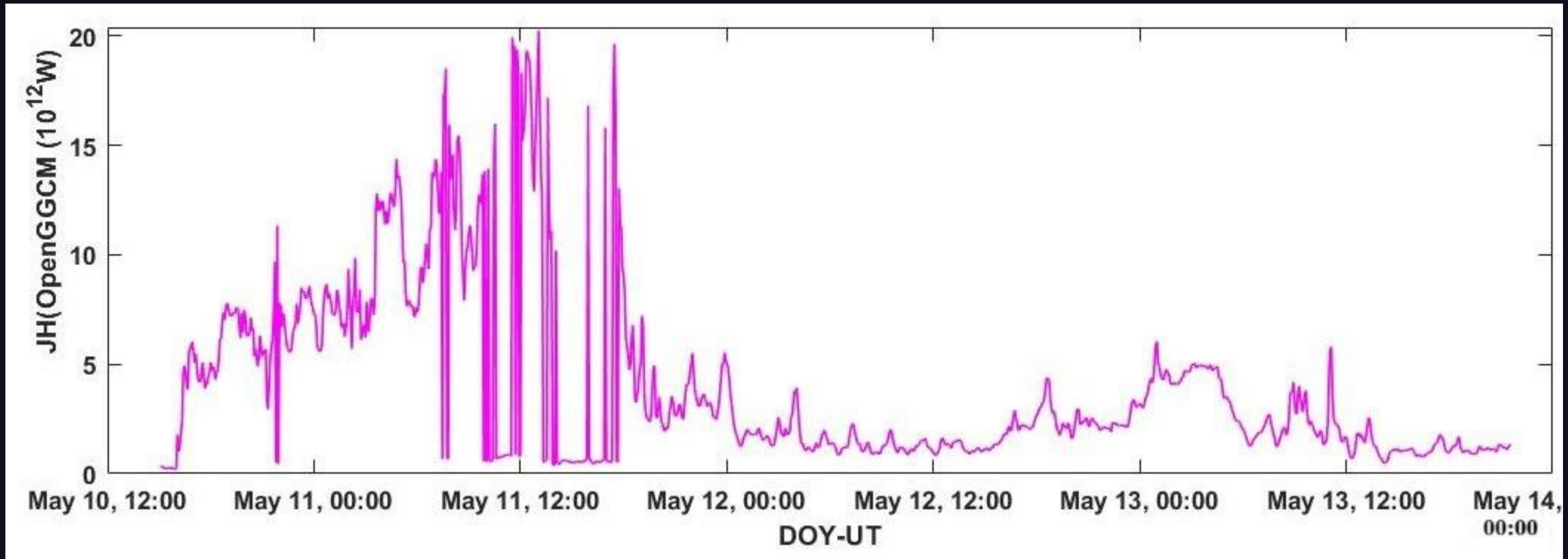


Fig6: JH rate obtained from model run

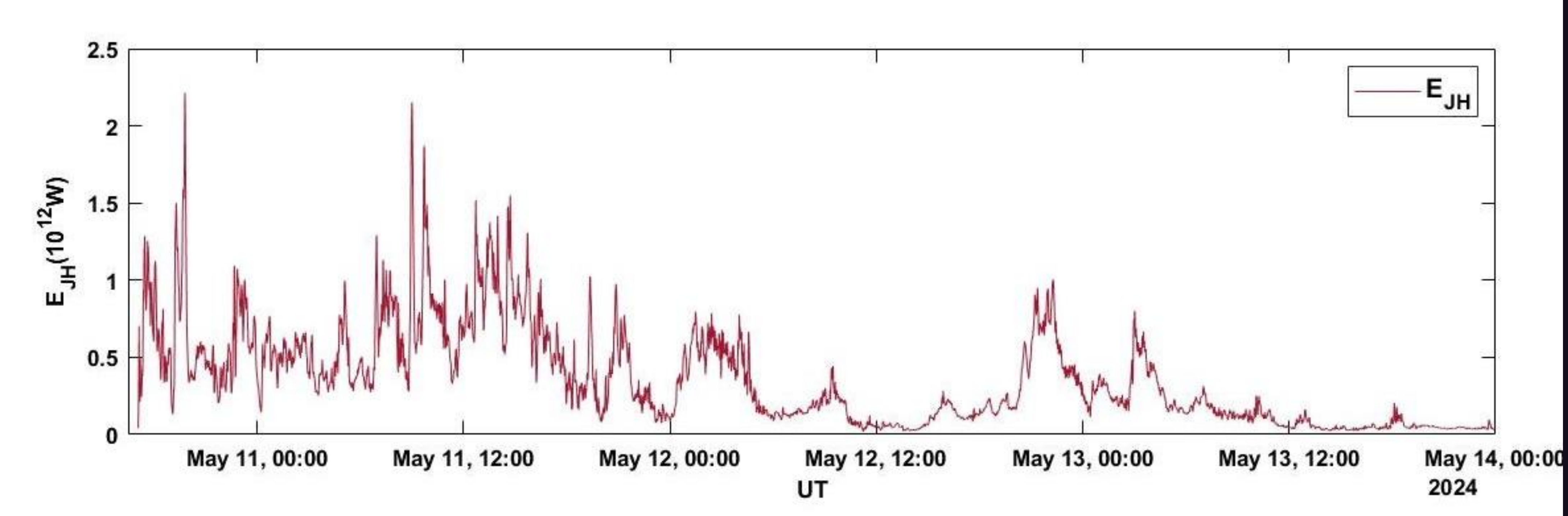


Fig7: JH rate obtained from empirical relation using AE index

Time integrated model output JH energy

is 2.79 times

higher than the empirical result

Observation 3: Thermospheric Nitric Oxide(NO) Cooling Response During May 2024 Storm

- NO emission at 5.3 µm is the dominant thermospheric cooling mechanism
- Effective in the altitude range 100–300 km
- Cooling occurs via inelastic collision with atomic oxygen

$$NO(\nu=1) + O \rightarrow NO(\nu=0) + O$$

- Generated by: Particle precipitation, Increased energy input
- NO Produced under sunlit conditions ,Formed through interaction:

$$N(4S,2D) + O2 \rightarrow NO + O$$

- NO infrared emission is a primary pathway for energy dissipation in the thermosphere
- NO Production enhanced during geomagnetic storms

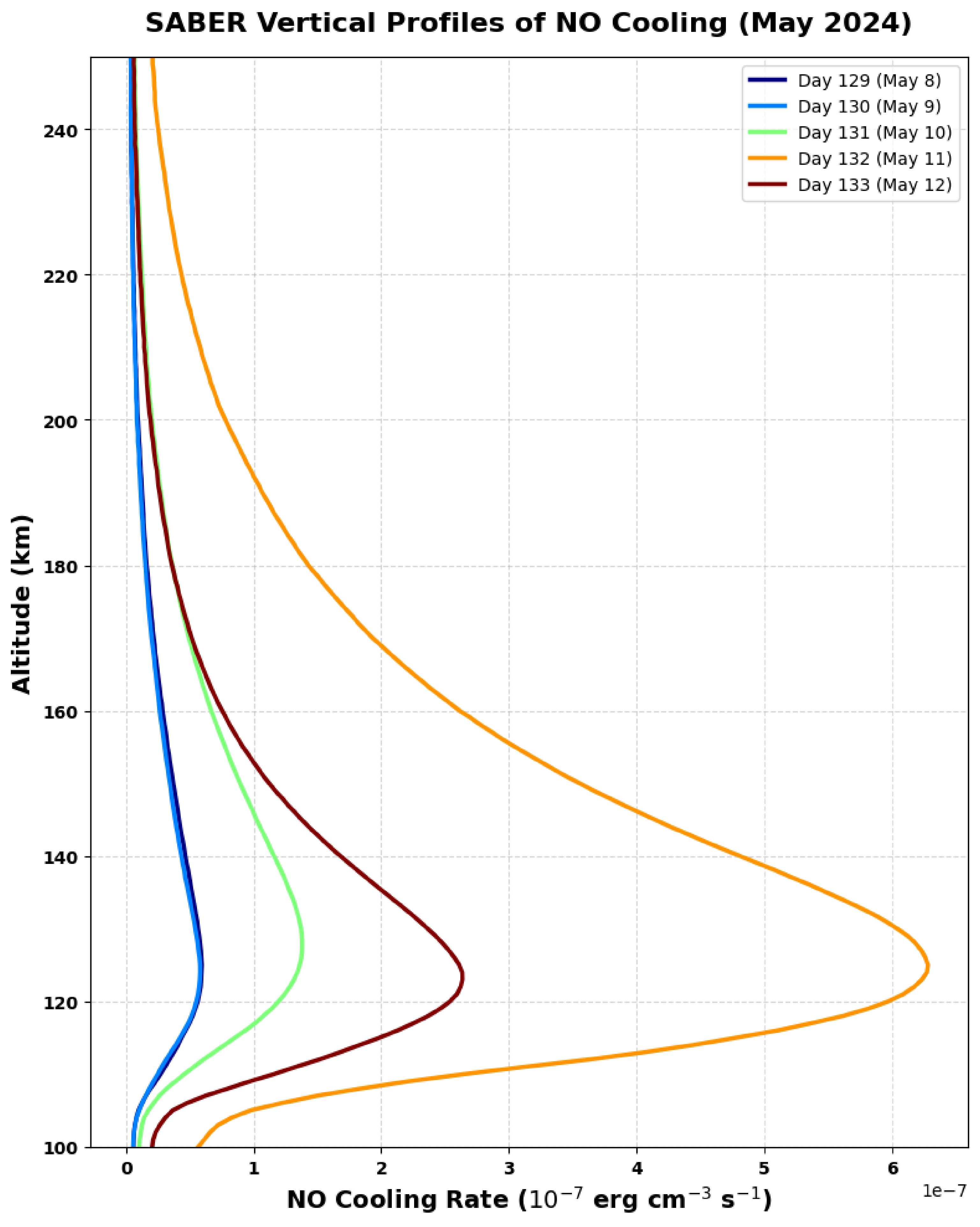
Combined observations + modelling approach
(SABER observations (TIMED satellite)
and TIE-GCM model simulations)

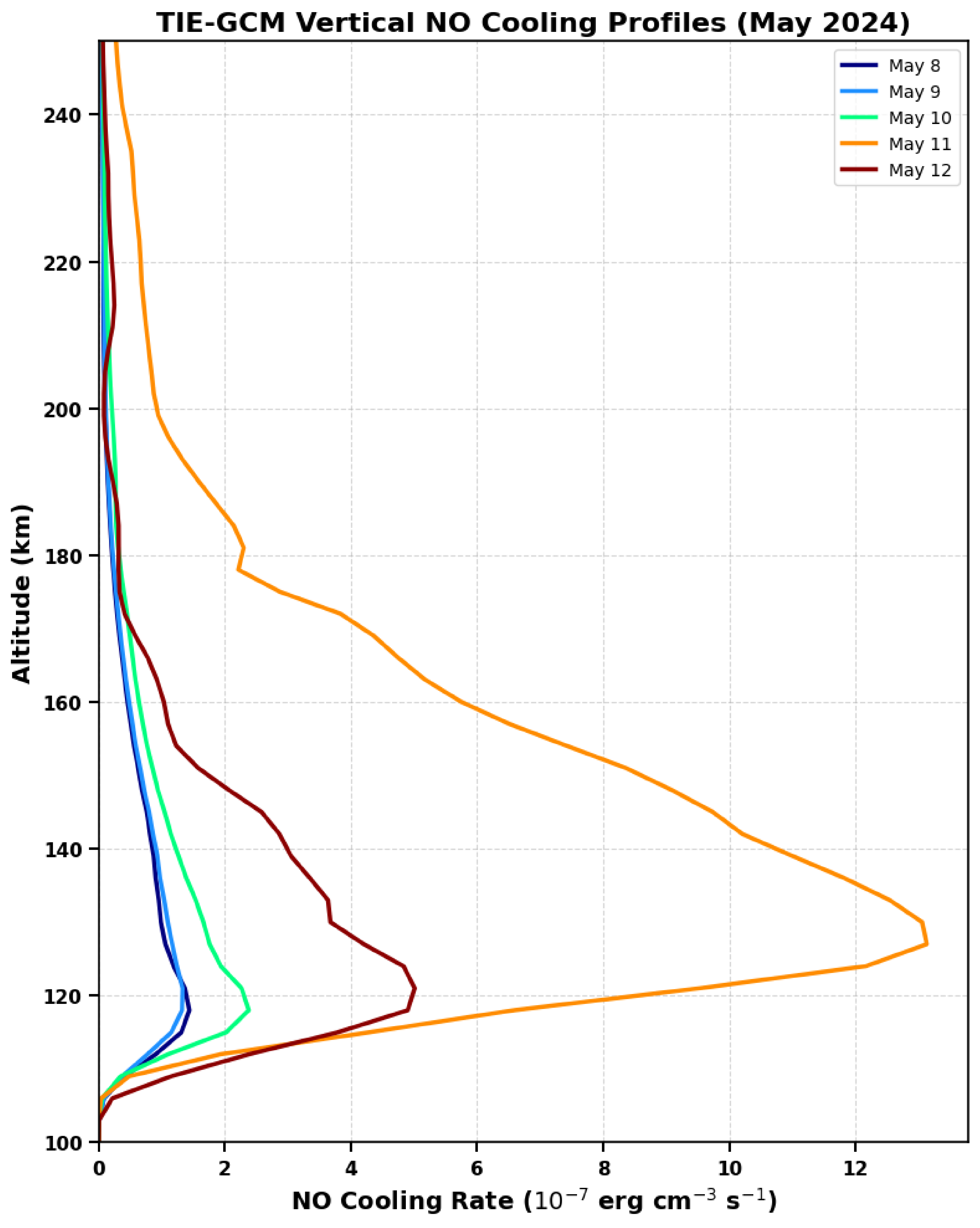
SABER:

- Sounding of the Atmosphere by Broadband Emission Radiometry
- instrument onboard the Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite
- specifications :
    - Measures infrared radiance (2–16 μm)
    - Provides NO volume emission rate (W m^{-3})
    - Integrated over 100–250 km → NO cooling flux (W m^{-2})
    - Global coverage with ~0.4 km vertical resolution

TIEGCM

- Thermosphere ionosphere electrodynamic general circulation model
- Physics-based 3D coupled ionosphere–thermosphere model
- Resolution: 2.5° × 2.5° grid
- 20-min temporal resolution
- 97–500 km altitude





Peak cooling at:~120–140 km

Fig8: NO cooling profiles

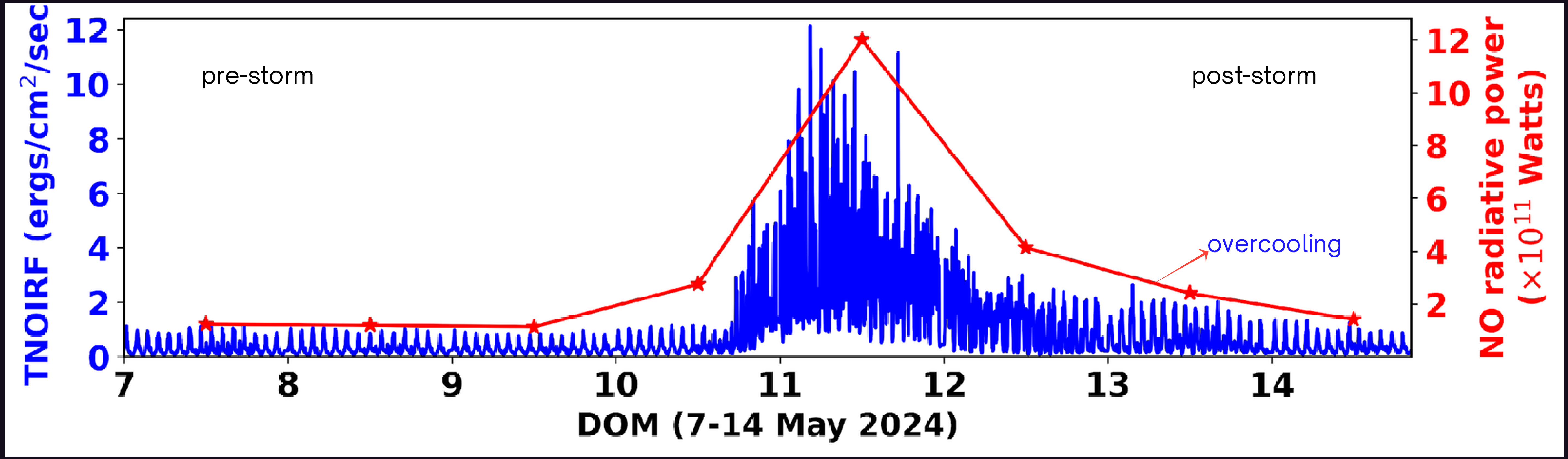
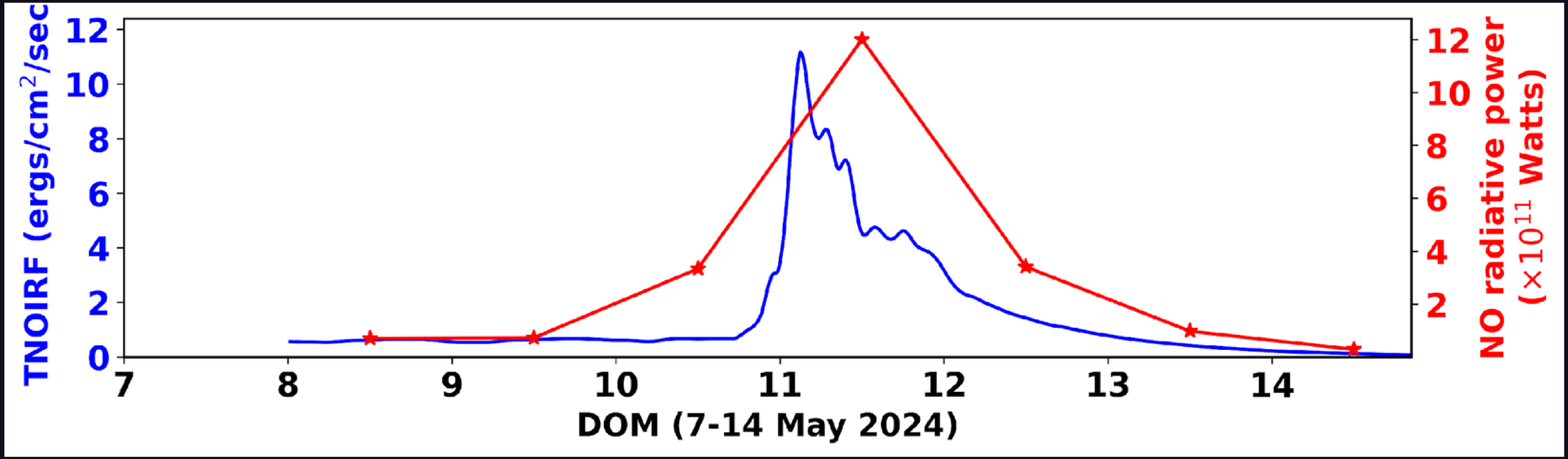


Fig9: TIMED/SABER observed NO infrared radiative flux(NO IRF (blue)) and associated daily radiative power (red)



observed a Sudden enhancement near 11th may Peak ~ 11.84 erg cm^{-2} s^{-1}

in both SABER and Model

Fig10: TIE-GCM model simulation NO IRF(blue) and associated radiative power (red)

- Thermospheric NO radiative cooling reached an exceptionally high level (~11.84 erg cm^{-2} s^{-1}) during the superstorm (used saber observations and tiegcm model simulations)
- An 8–10 times enhancement over quiet conditions confirms intense storm-time energy dissipation
- NO infrared emission acts as a dominant thermospheric cooling mechanism
- Rapid NO cooling facilitates efficient recovery of thermospheric density
- And effectively offsets the enhancements induced by Joule heating
- SABER observations show a faster increase and recovery in NO cooling flux compared to the TIE-GCM model as observed

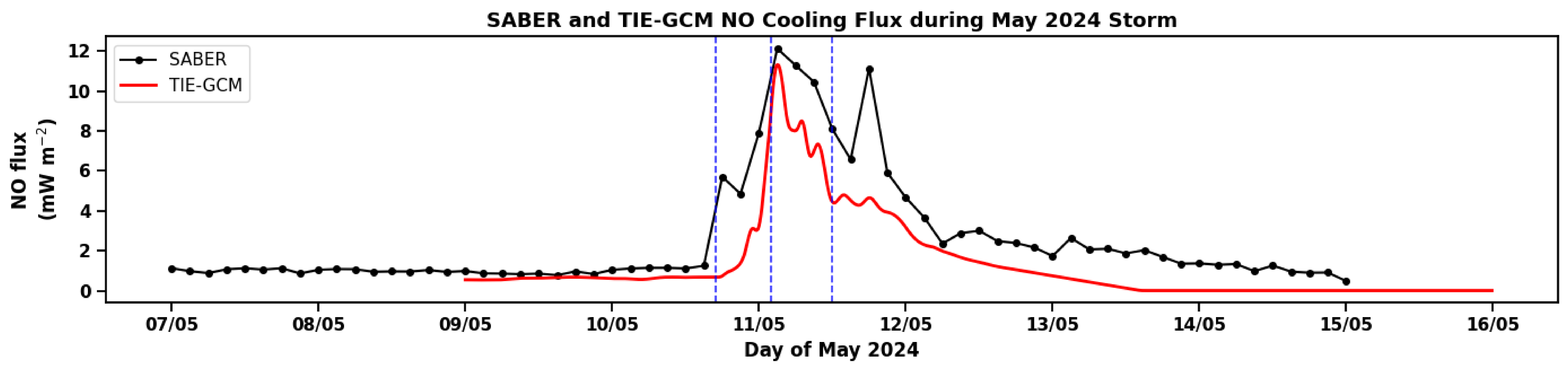


Fig11: combined

Conclusion

- Attempting to address the space weather drivers
- Estimation of share of JH energy from energy coupled from SW during different storm phases
- Storm has a longer recovery phase hence the JH rate is higher during this phase
- Time integrated model output JH energy is 2.79 times higher than the empirical result
- An all-time high NO cooling flux of ~12 mW m-2 during the superstorm
- Observation of overcooling mechanism

Summary and Future Scope of the Study

- Extend the sample EFLARE+ECME estimation to multiple CME-Flare association
- Study to be extended for CME, ICME interactions
- to address SEP events in the chain
- To consider studying the 13 substorms that have been identified during the storm
  - Substorm energetics has been studied in our previous work, refer:
    - *“Energetics of intense substorms of solar cycle 23” DR Nair, PR Prince - Acta Geophysica, 2026*
- *A*ttempt to study Energy budget estimation by considering other dissipation mechanisms as well
- An attempt to estimate the energy carried by space weather drivers and how it get dissipated into earth and near-earth space

Reference

scan HERE !!!!!

SPACE PHYSICS RESEARCH @ University College TVM, Kerala, India

Research Supervisor :
Prof. Prince P R
Professor and Head,
(IUCAA Associate & Coordinator, ICARD)
Department of Physics

Primary Research Areas

SOLAR PHENOMENON

Ms. Sreebala P S, Mr. Deepak Kathait
(in collaboration with Prof.Durgesh Tripathi, IUCAA)

- Studying Solar Flares
- Understanding Large Scale eruptions
- Space weather drivers
- Multi wavelength observations
- SUIT/Aditya-L1 studies

SOLAR-TERRESTRIAL PHYSICS & SPACE WEATHER

Ms. Devi R Nair, Ms. Aswini Thampi S L

- Ionospheric Studies
- Magnetospheric Studies
- Magnetosphere heating mechanisms
- Storms, Substorm, Energetics
- Space weather aspects

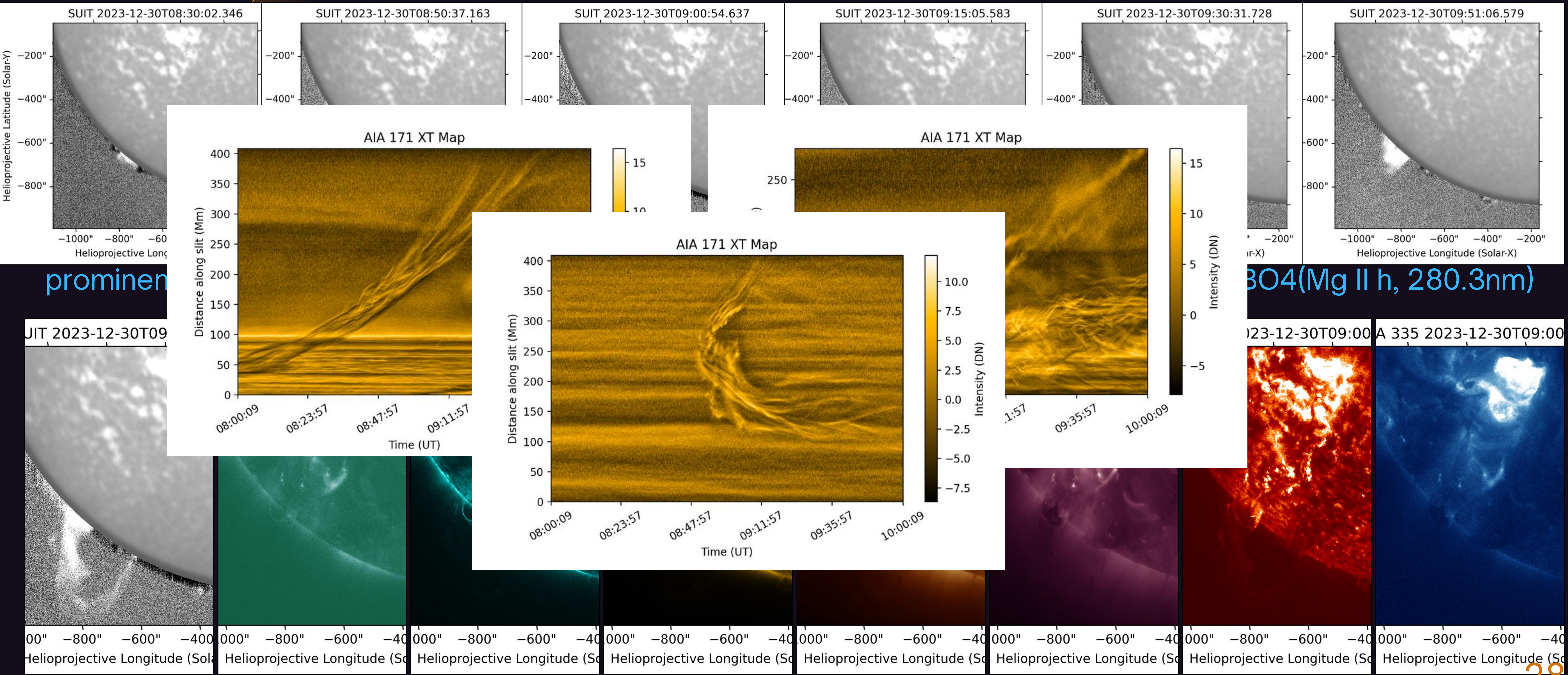
Study of Sunspot Cycle

SPACE PHYSICS RESEARCH Group

1. Dr. Jayalekshmi G L
2. Dr. Sumesh Gopinath
3. Dr. Seema C S
4. Dr. Suji K J
5. Dr. Santhosh Kumar G
6. Dr. Biji M S
7. Ms. Devi R Nair
8. Ms. Aswini Thampi S L
9. Ms. Sreebala P S
10. Mr. Deepak Kathait

Understanding the Promineces through multiwavelength study

Evolution of prominence as observed by Solar ultraviolet Imaging Telescope (SUIT/AdityaL1) in NB04 (Mg II h, 280.3nm)



prominen… …BO4(Mg II h, 280.3nm)

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data & reference, resources

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NASA Eddy Symposium-support and grant

Expressing gratitude : Collaborators, ICARD

THANK YOU

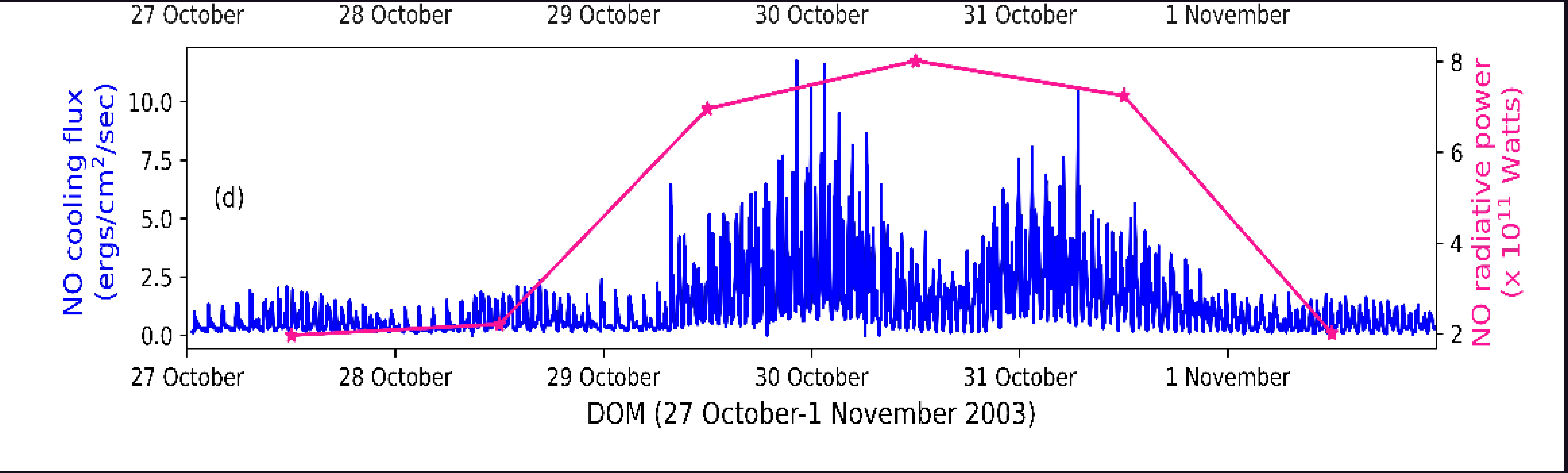
for more information: sreebalaps@universitycollege.ac.in, pssreebala@gmail.com

ADDITIONAL REFERENCE SLIDES

TIEGCM

- Thermosphere ionosphere electrodynamic general circulation model
- maximum limit of model, 97–500 km altitude, we did for 100-250km only
- 20-min temporal resolution
- Driven by:
  - Solar forcing (F10.7) ......which solar data is taken as input?
  - Geomagnetic forcing (Weimer model) ......we have taken input parameters using weimer model(e potential, field aligned current etc taken from here, and using this we estimate JH)
- Outputs used for this study
  - NO cooling (W m^{-3})
  - Joule heating rate

Halloween storm 2003 reference



- The thermospheric cooling response during the May 2024 superstorm is compared with the response during Halloween storms
- This study brings out key aspects of the rare thermospheric overcooling, typically elusive during a majority of severe geomagnetic storms.