# Geospace storm-time plumes in the ionosphere observed by the GNSS system

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NSF

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# Introduction

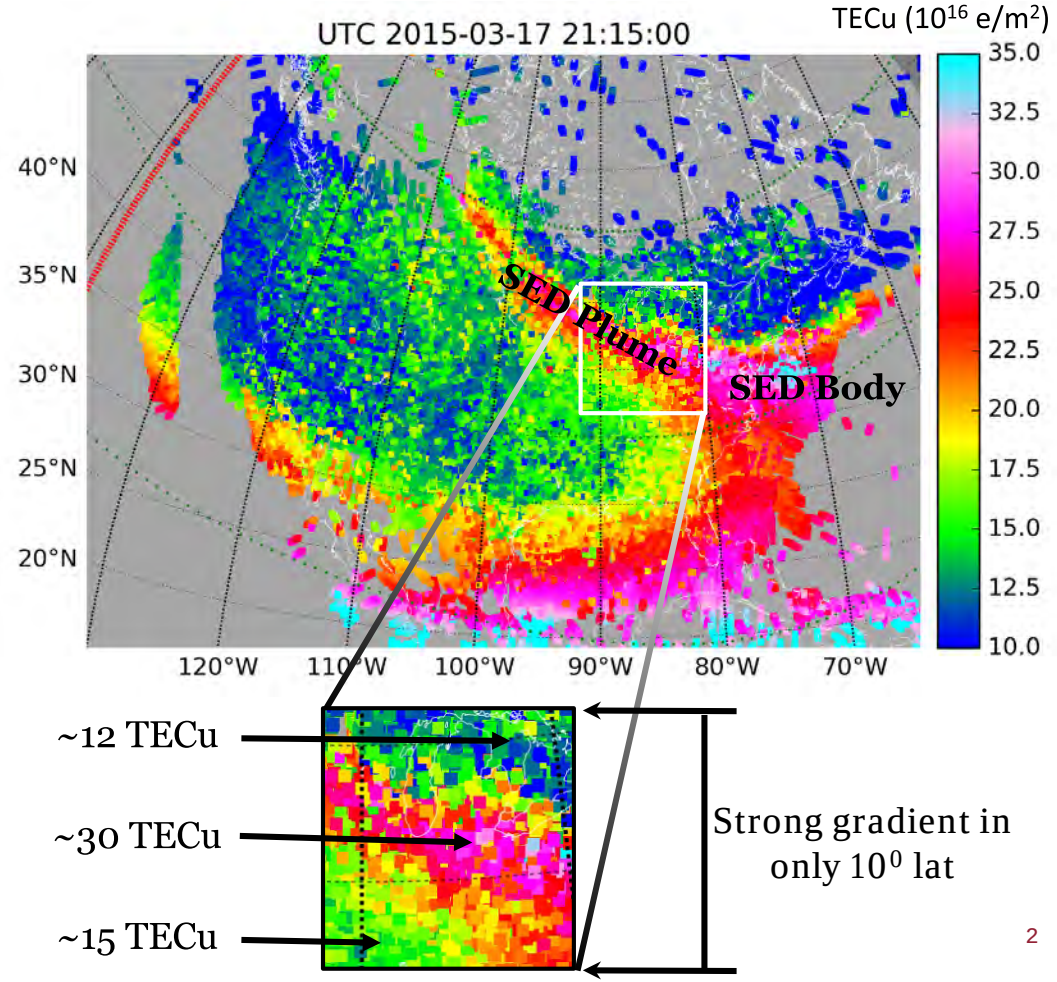
**Goal:** To statistically characterize storm-enhanced density (SED) plume morphology

## Storm-Enhanced Density (SED)

- **Total Electron Content (TEC)** form plume structure that stretches sunward and poleward
- Plasma density gradient structure in the ionosphere during geomagnetic storms
- Dynamic structure, changes in aspects such as location and intensity based on many conditions

## Substantial space weather impact

- Movement of plasma and intense TEC gradients can disrupt telecommunications

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# Instruments and Datasets

## Madrigal GNSS TEC

**G**lobal **N**avigation **S**atellite **S**ystem

- Madrigal is the upper atmosphere database from CEDAR and Haystack
- Vertical TEC data is calculated from GNSS data from 6000+ ground based receivers
- Binned 1° lat × 1° lon × 5 minutes
- 1 TECu = 1e16 electrons/$m^2$

## TIDAS electron density

**T**EC-based **I**onospheric **D**ata **A**ssimilation **S**ystem

- Input: Assimilated from GNSS TEC, MHISR, and a few other sources
- Output:
  - Full profile of ionosphere above continental United States
  - **NmF2: F2 peak density**
  - hmF2: height of F2 peak density

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# Methodology

SED identification from ~50 intense geomagnetic storms

Where minimum Sym-H index < -100 nT (Sym-H index of geomagnetic activity)

| | | |
|---|---|---|
| 2001-03-20 | 2004-04-03 | 2013-03-17 |
| 2001-04-18 | 2004-07-22 | 2013-06-01 |
| 2001-04-22 | 2004-08-30 | 2013-06-28 |
| 2001-08-17 | 2005-01-07 | 2015-01-07 |
| 2001-10-28 | 2005-01-21 | 2015-03-17 |
| 2001-11-01 | 2005-05-08 | 2015-06-08 |
| 2002-03-24 | 2005-06-12 | 2015-06-22 |
| 2002-05-11 | 2005-06-22 | 2015-12-31 |
| 2002-08-02 | 2005-08-24 | 2016-03-06 |
| 2003-05-29 | 2005-08-31 | 2016-10-13 |
| 2003-06-02 | 2006-04-14 | 2017-05-28 |
| 2003-07-11 | 2011-08-05 | 2017-09-08 |
| 2003-08-17 | 2011-09-26 | 2018-08-26 |
| 2003-10-29 | 2011-10-24 | 2021-11-04 |
| 2003-10-30 | 2011-10-25 | 2022-03-13 |
| 2003-11-20 | 2012-04-23 | 2023-02-27 |
| 2004-01-22 | 2012-07-15 | 2023-03-23 |
| 2004-02-11 | 2012-09-30 | 2023-04-23 |
| 2004-03-09 | 2012-11-13 | |

56 intense storms

| | |
|---|---|
| 2001-08-17 | 2005-06-12 |
| 2001-10-28 | 2005-08-31 |
| 2002-05-11 | 2011-08-05 |
| 2002-08-02 | 2011-09-26 |
| 2003-05-29 | 2013-03-17 |
| 2003-10-29 | 2013-06-28 |
| 2003-10-30 | 2015-03-17 |
| 2003-11-20 | 2015-06-22 |
| 2004-01-22 | 2016-03-06 |
| 2004-02-11 | 2016-10-13 |
| 2004-03-09 | 2017-09-08 |
| 2004-04-03 | 2022-03-13 |
| 2004-07-22 | 2023-02-27 |
| 2004-08-30 | 2023-03-23 |
| 2005-01-21 | 2023-04-23 |

30 clear SED plumes

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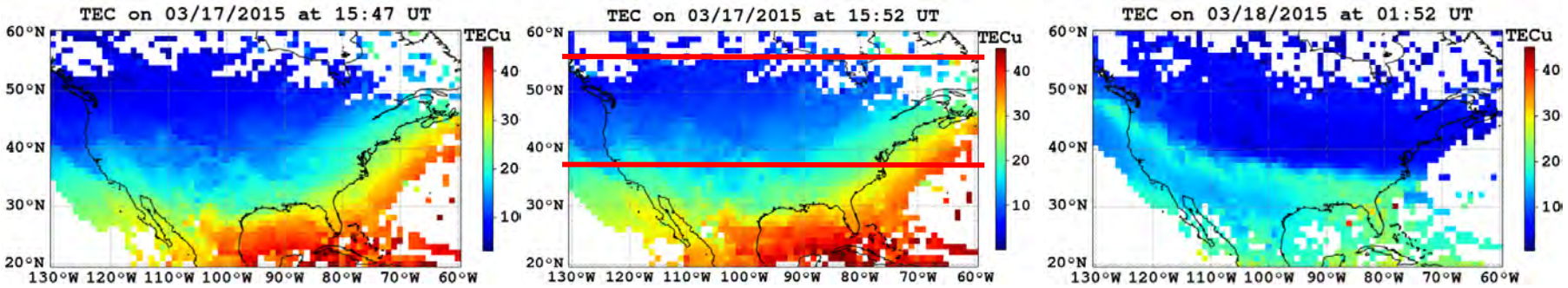
# Methodology

SED identification from ~50 intense geomagnetic storms

(Minimum Geomagnetic Sym-H index < -100 nT)




Start time

Latitudes

End time

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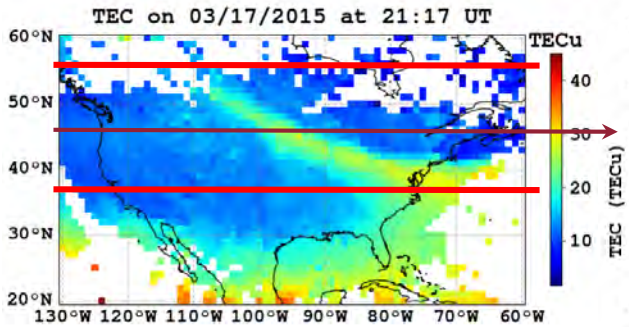
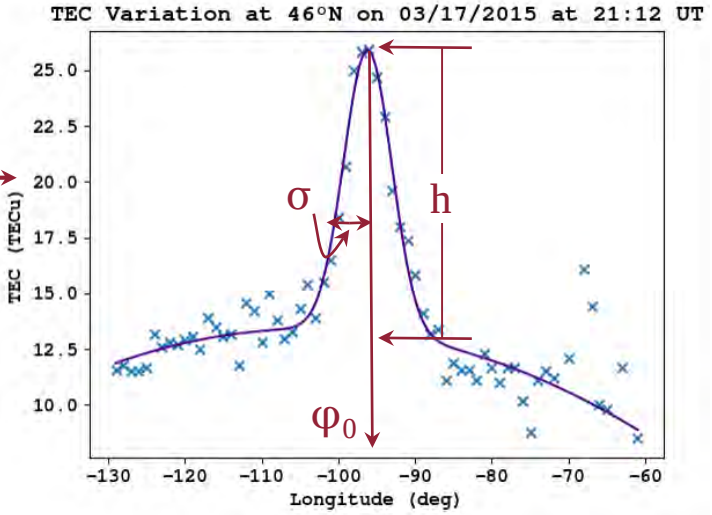
# Methodology

Gaussian fitting at each time bin in the interval, over all the latitudes that SED plume spans, and then averaged to derive SED key features

$$TEC(\varphi) = h \times \exp( -(\varphi - \varphi_0)^2 / 2\sigma^2) + b + c \times \varphi + d \times \varphi^2$$




| φ longitude (deg) | |
|---|---|
| h TEC intensity (TECu) | *12* |
| σ half-width (deg) | *3* |
| $\varphi_0$ central lon (deg) | *-96* |
| b | *-13* |
| c | *-0.5* |
| d | *-0.002* |

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# Results

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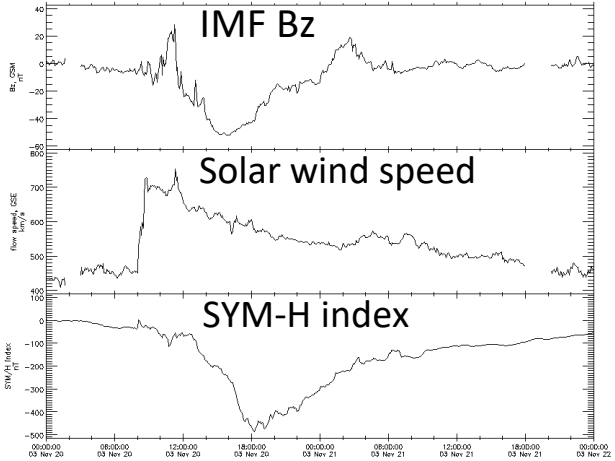
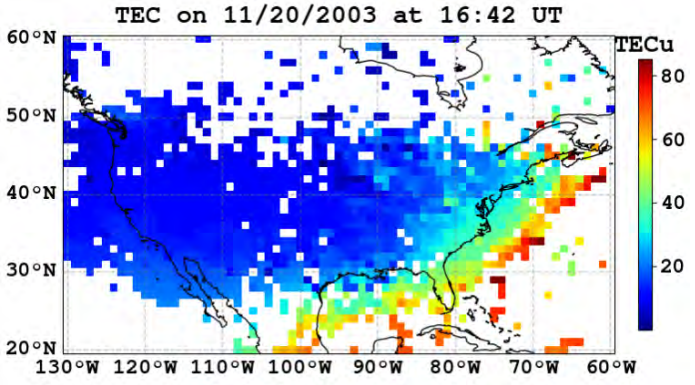
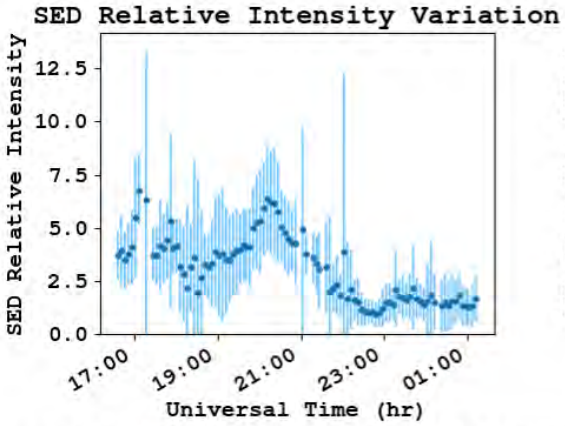
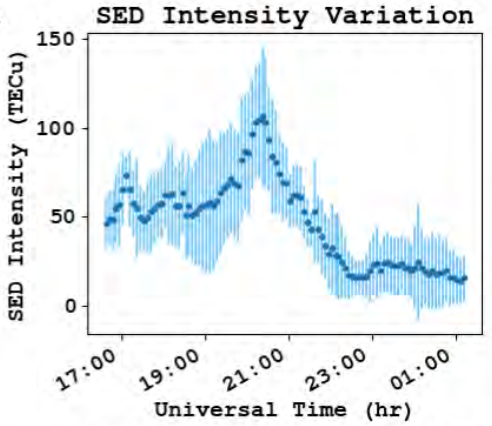
# SED analysis: 20 Nov 2003

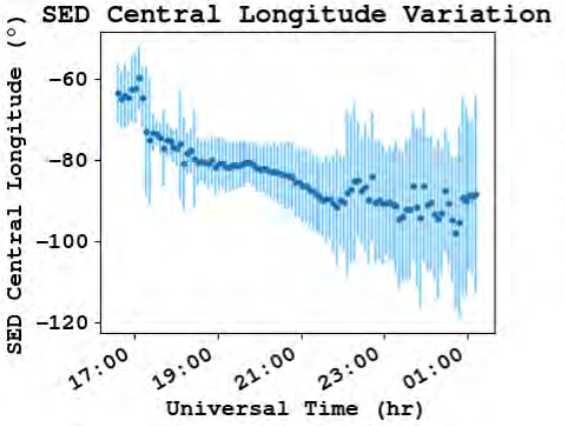
Largest geomagnetic storm in Solar Cycle 23

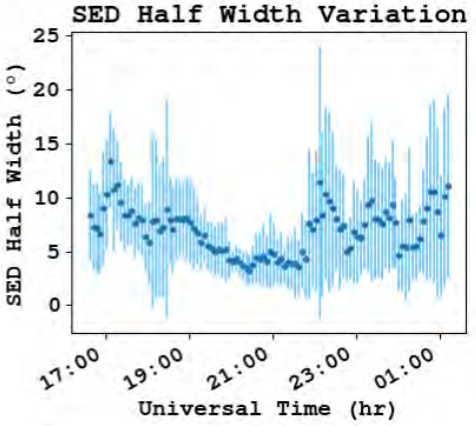


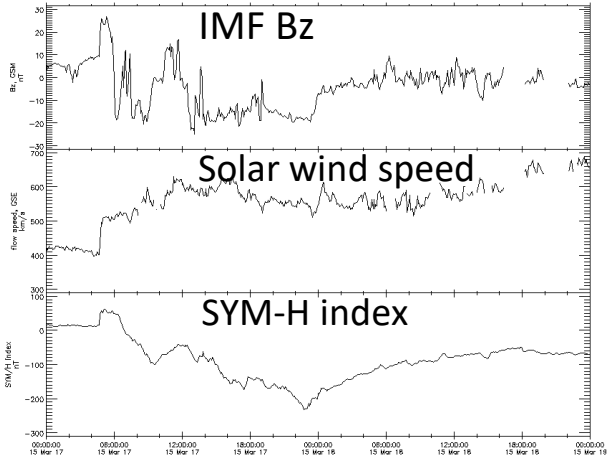



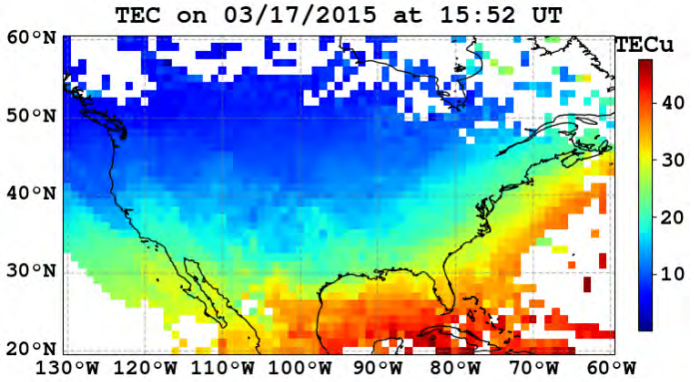



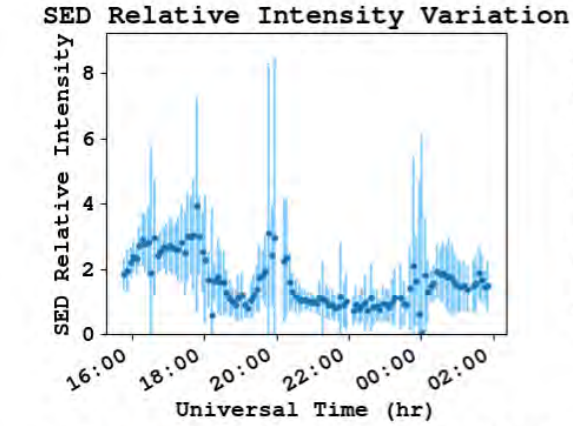



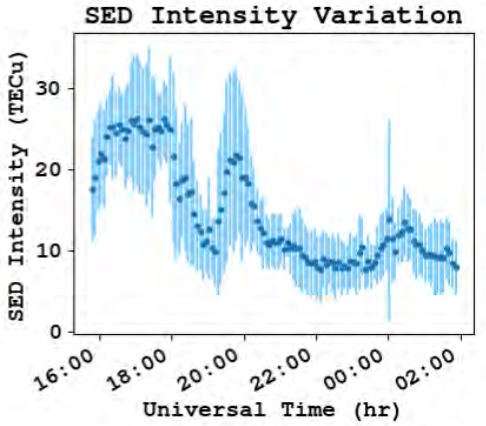
# SED analysis: 17 Mar 2015

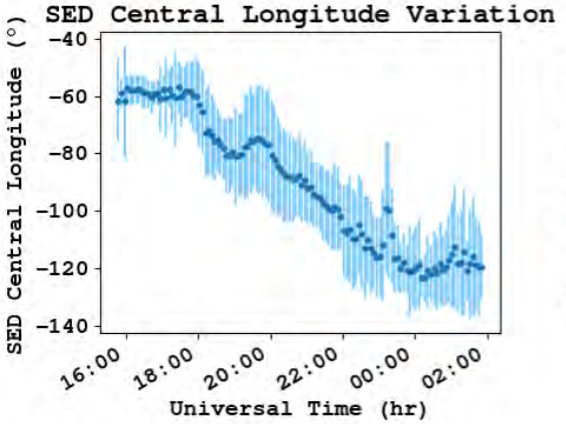
Largest geomagnetic storm in Solar Cycle 24

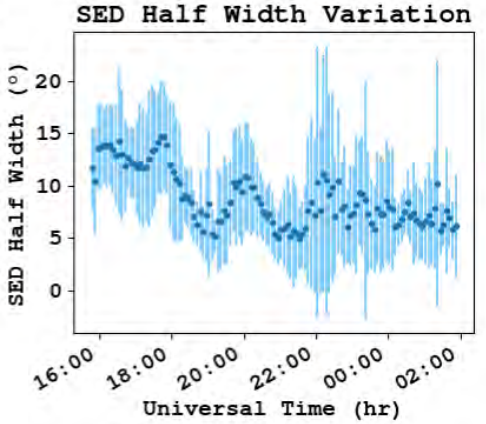


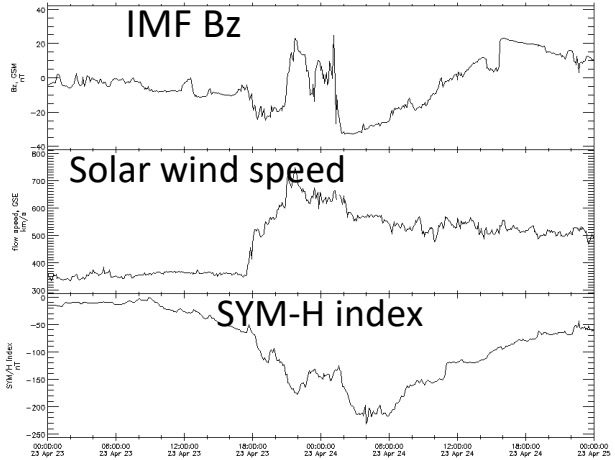



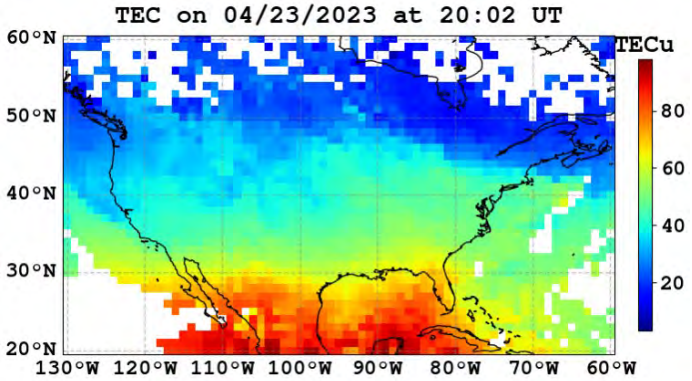



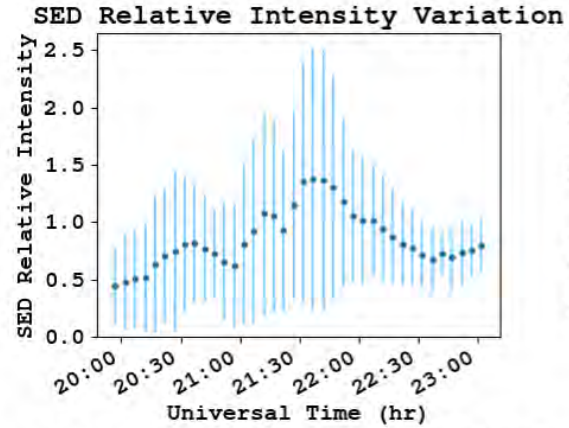



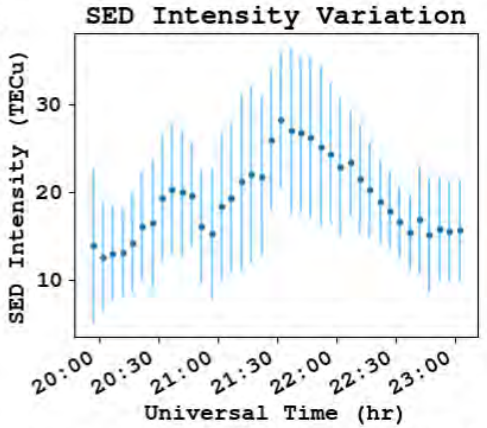
# SED analysis: 23 Apr 2023

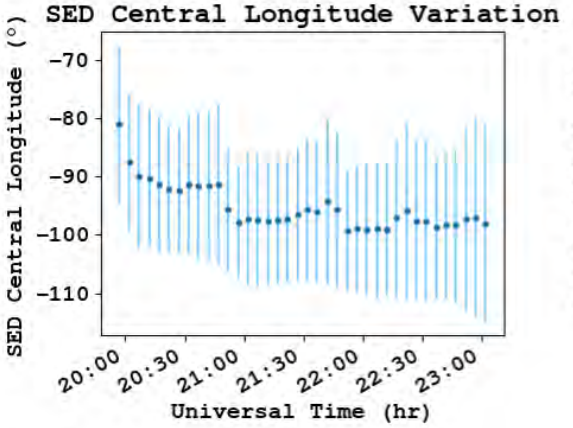
Largest geomagnetic storm in Solar Cycle 25 to date

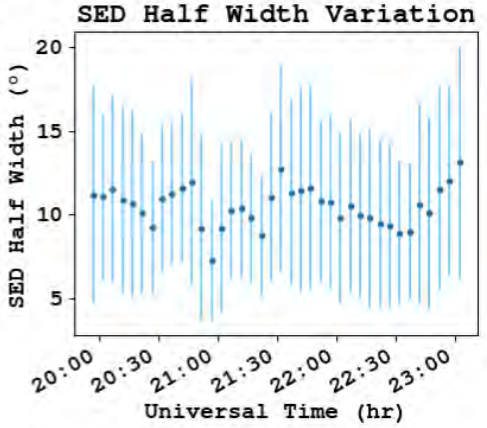


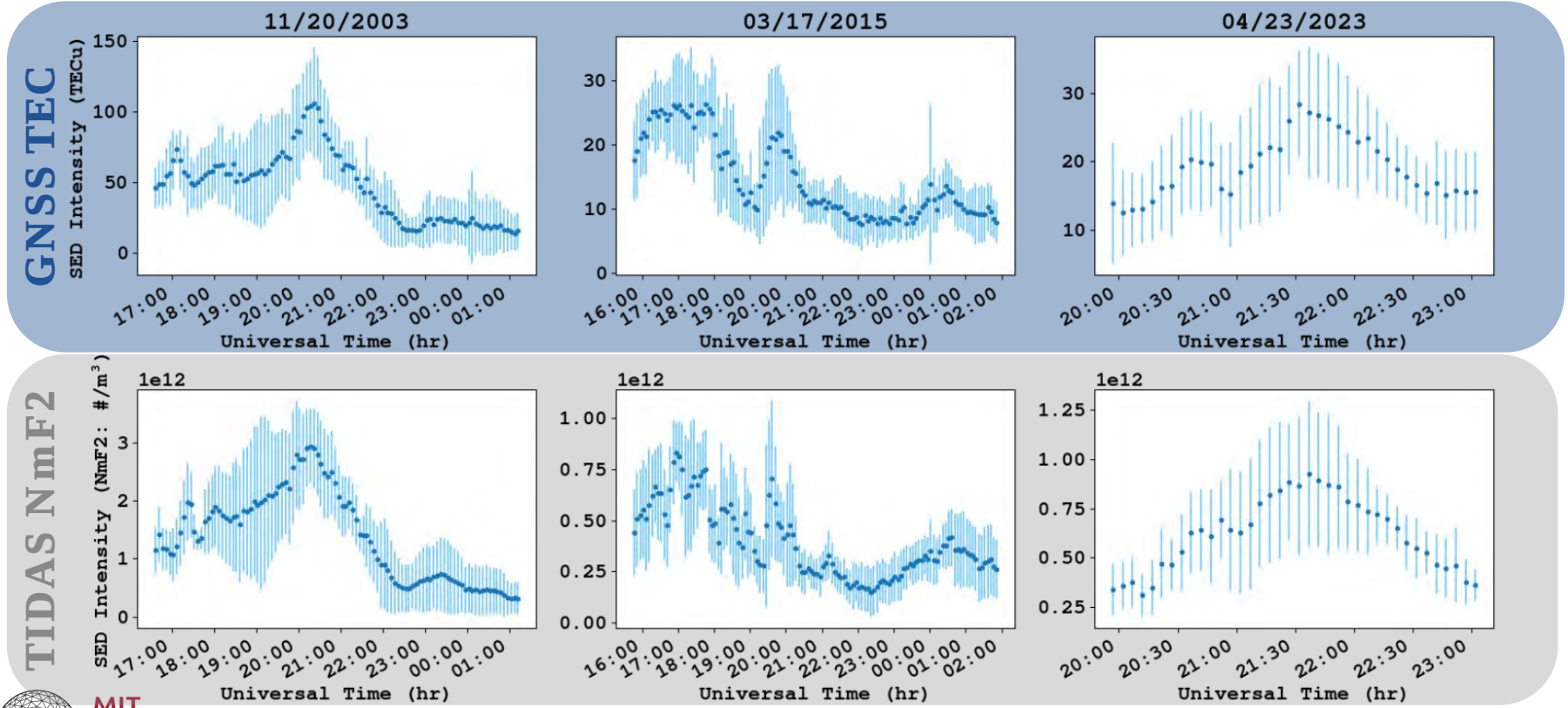



# SED features comparison between GNSS TEC and TIDAS reconstructed NmF2

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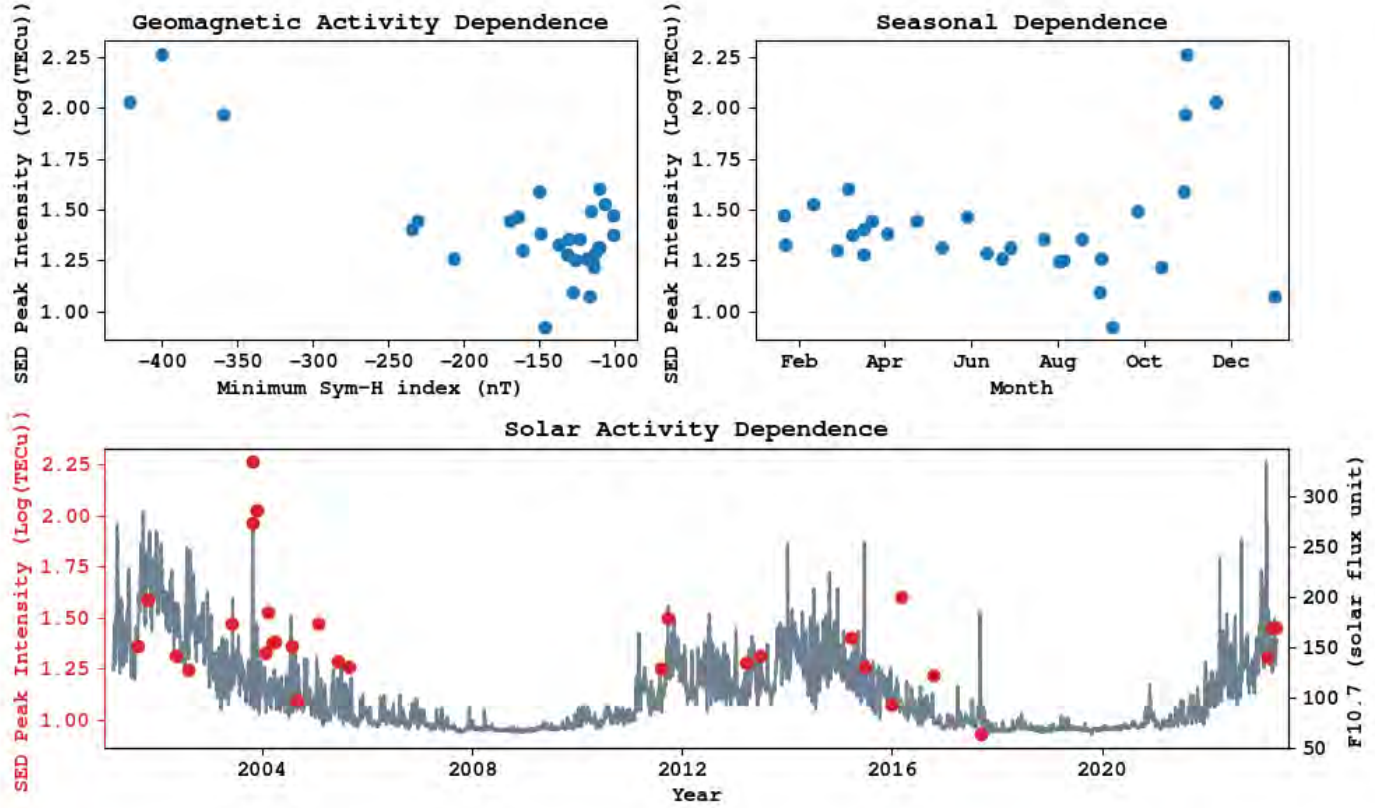
# Statistical analysis of SED features: Peak Intensity

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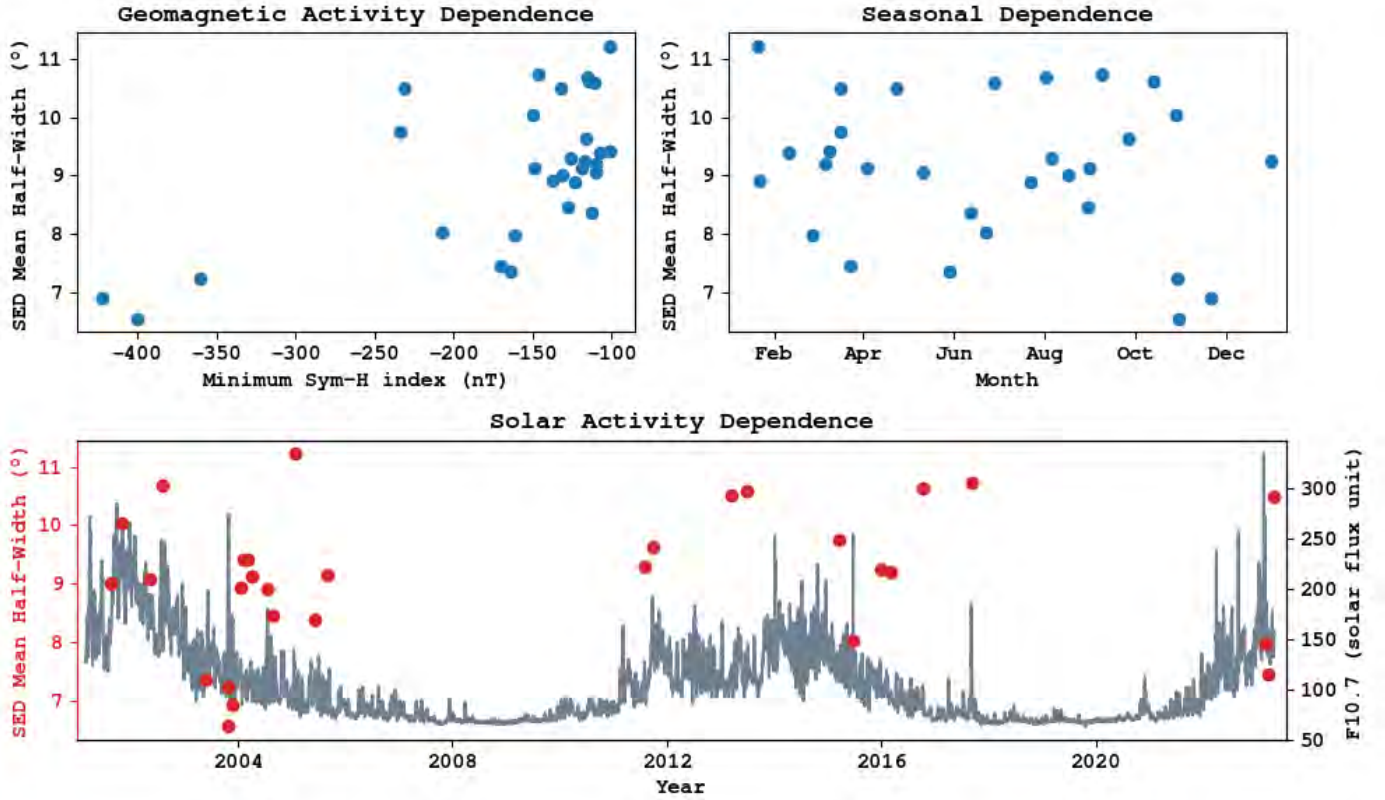
# Statistical analysis of SED features: Peak Half-Width

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# Summary

- Examined 56 geospace storms collectively to identify how many in which SED plume appear
- Systematically calculated SED plume intensity, half-width, and central longitude
- Examined features of statistic results, both features in common between days, and features unique to specific events, such as the superstorm in 2003
- While we still don’t fully understand these, it is important to know these characteristics

# Future Work

- Incorporate more storms and SED as they happen in the future
- Use of TIDAS to analyze SED at different heights, bottomside, topside
- Use calculated characteristics for further analysis, such as modeling SED

- Presenting results at AGU 2023

# Acknowledgments

Thank you to...

- Dr. Ercha Aa and Dr. Shun-Rong Zhang
- Everyone at MIT Haystack
- My fellow REU cohort
- NSF

... for an amazing research experience!

Questions?

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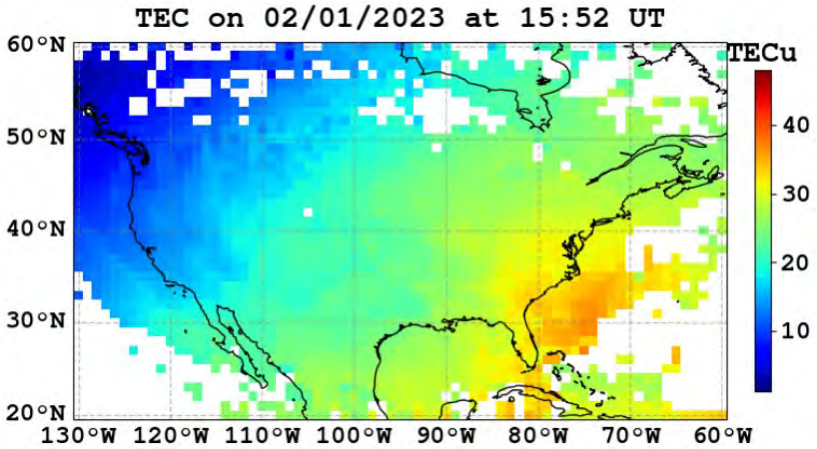
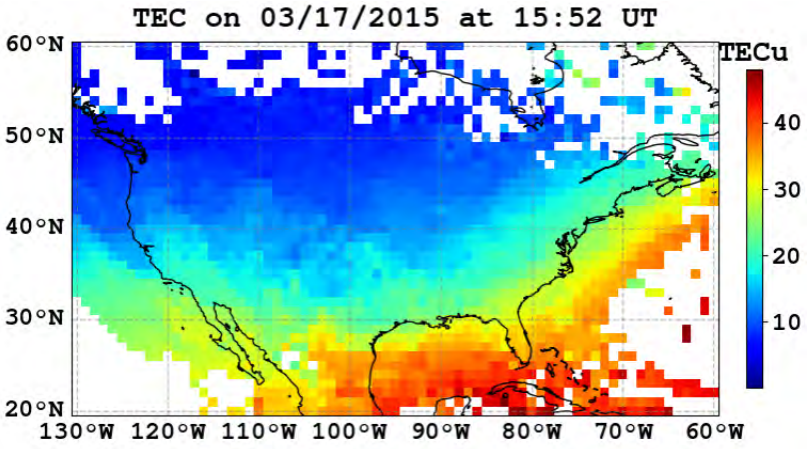
# Quiet Day vs Storm Day

Quiet Time
Minimum Sym-H = -20 nT




Storm-Enhanced Density
Minimum Sym-H = -234 nT

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