Empirical orthogonal function (EOF) analysis of GPS total electron content storm response

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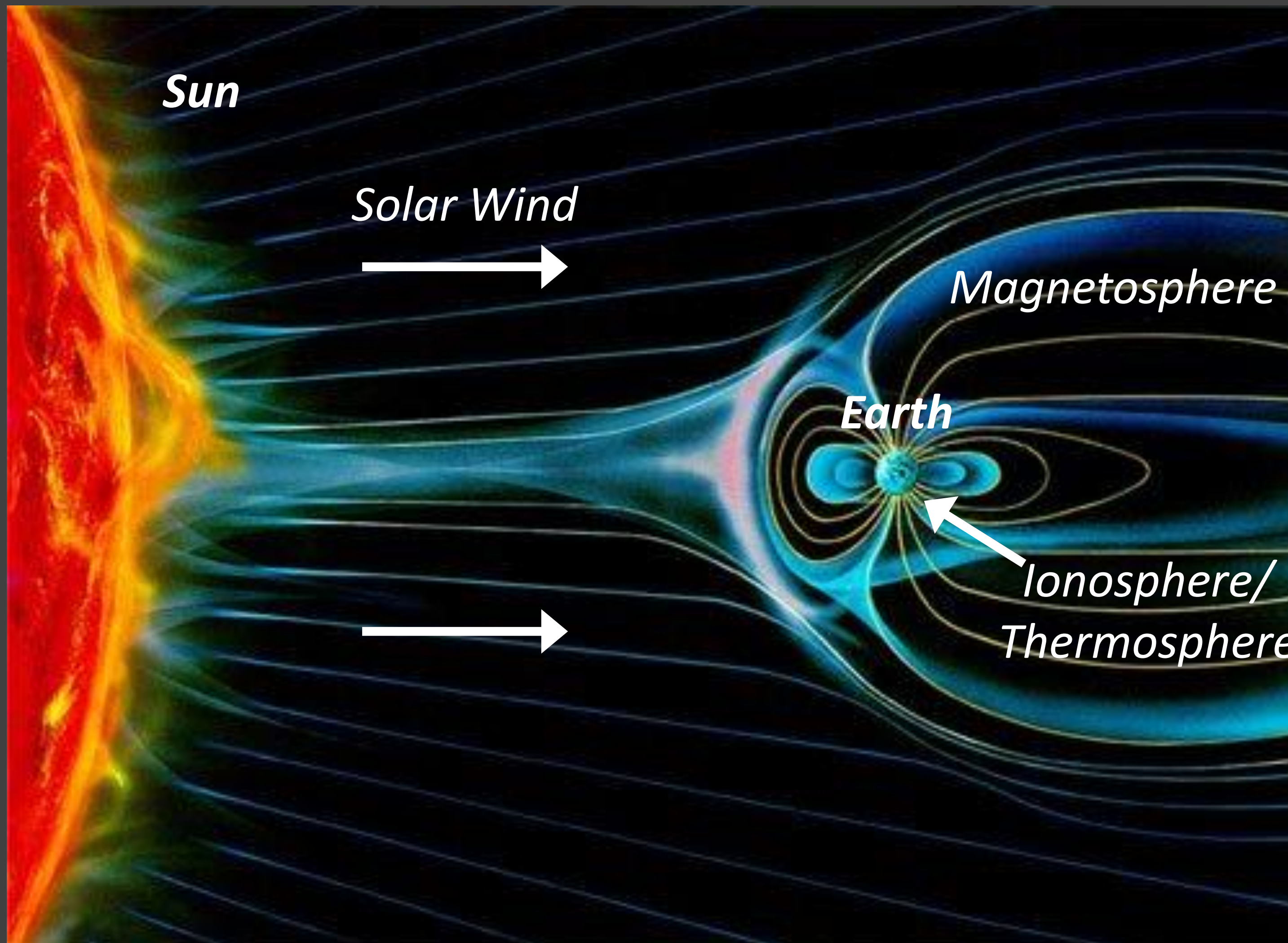


• Dynamic features in the solar wind can trigger geomagnetic disturbances in the coupled magnetosphere-ionosphere-thermosphere (M-I-T) system

Ionospheric Storms

• Ionospheric electron density response to a storm is either a positive (increase) or negative (decrease) effect

• Often an initial positive response due to dayside plasma uplift

• Uplift can occur via either

1) Eastward penetration electric field

2) Travelling atmospheric disturbance

• Negative storm effects are attributed to thermospheric composition and circulation changes due to high-latitude magnetospheric energy input

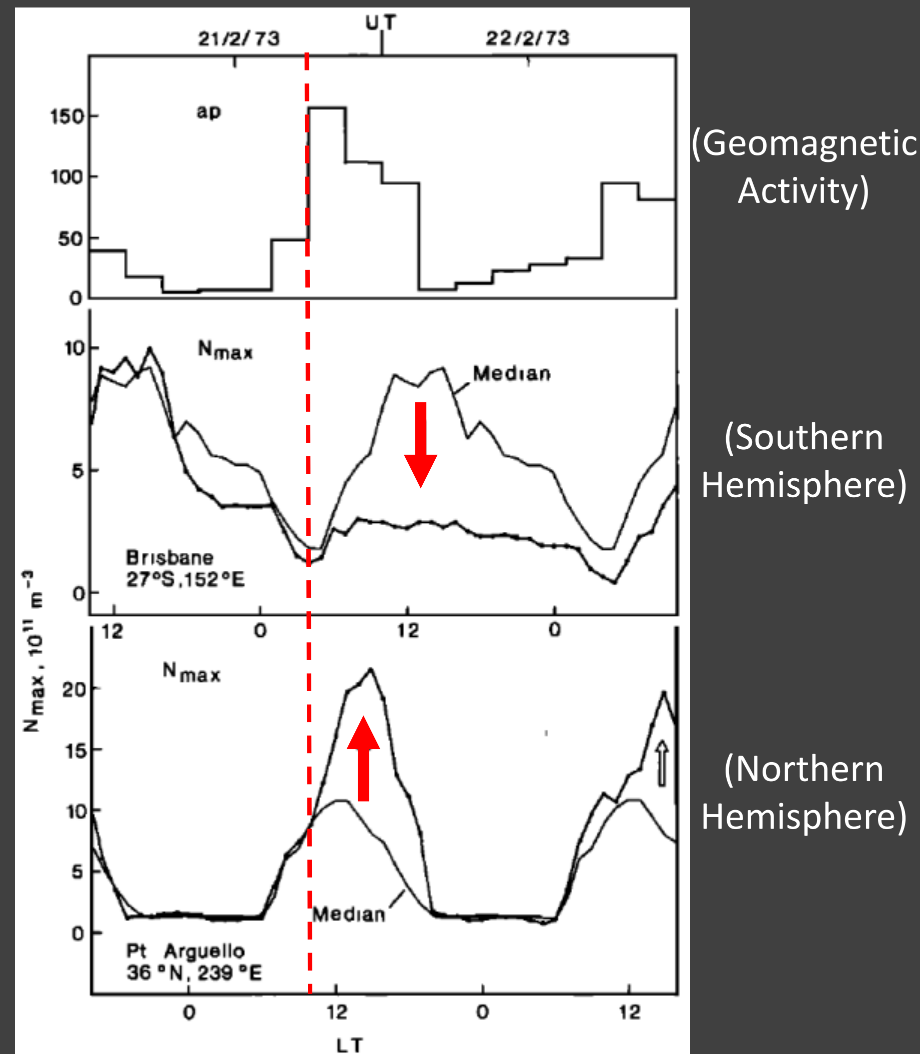
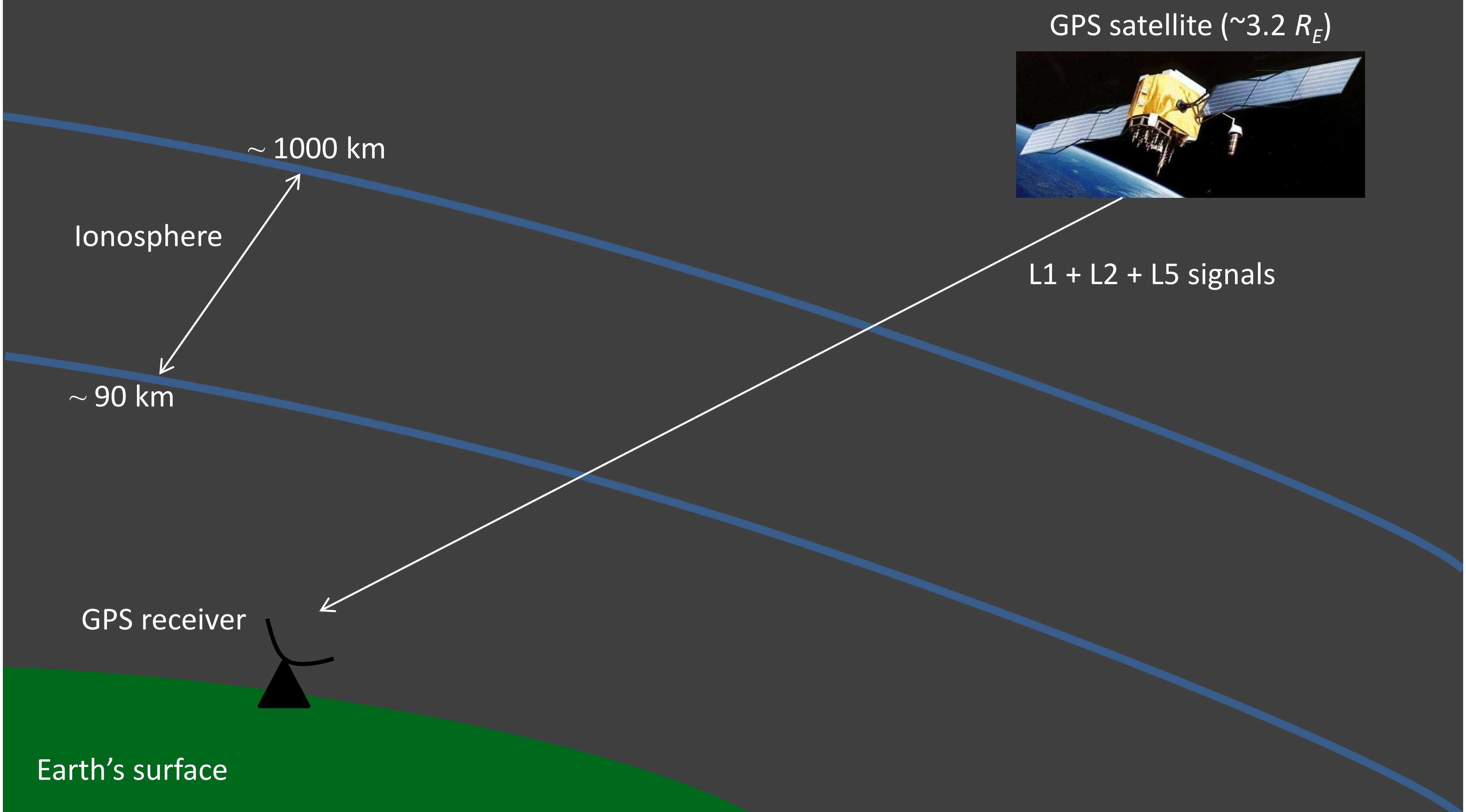
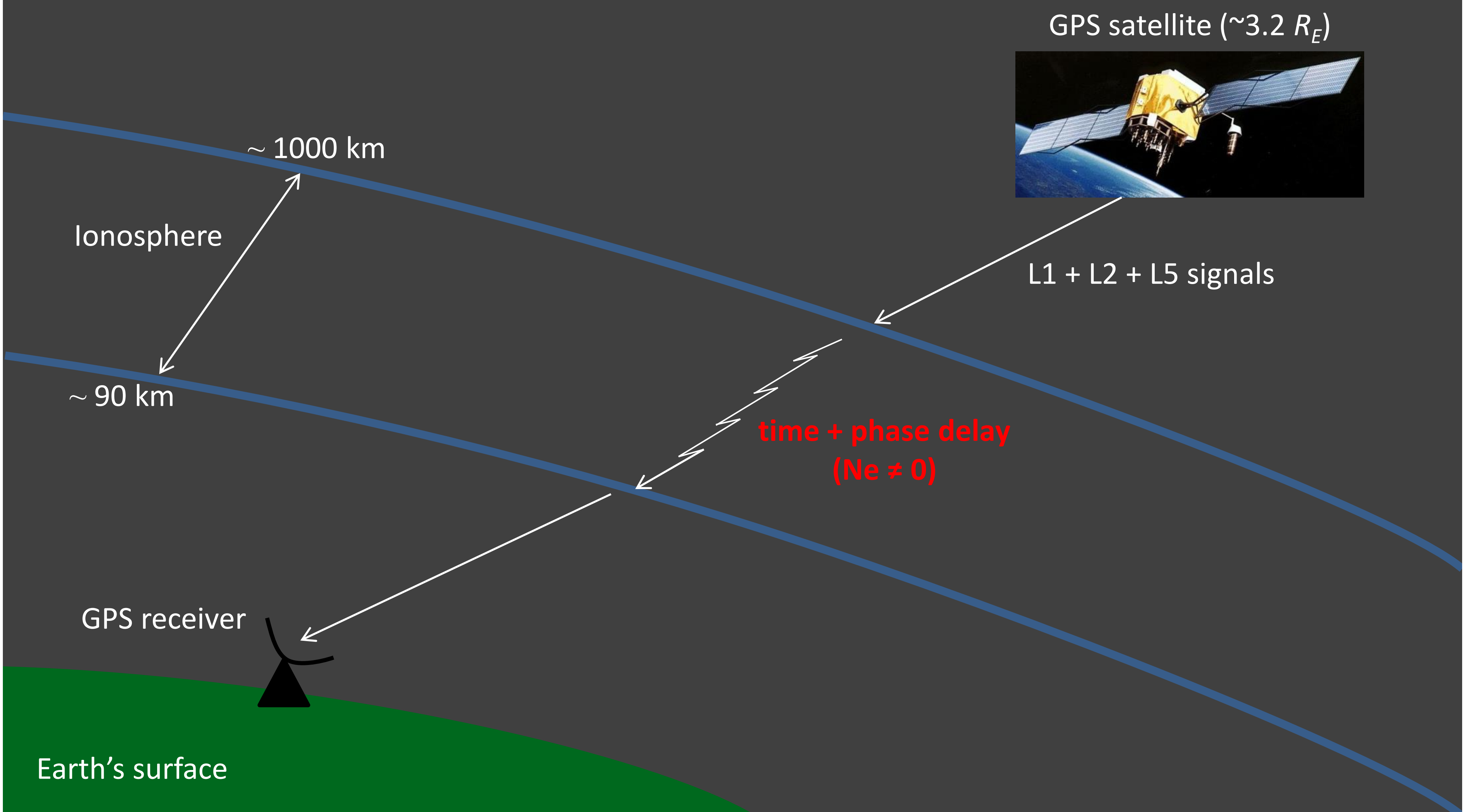


Figure: [*Prölss*, 1980]

GPS Total Electron Content

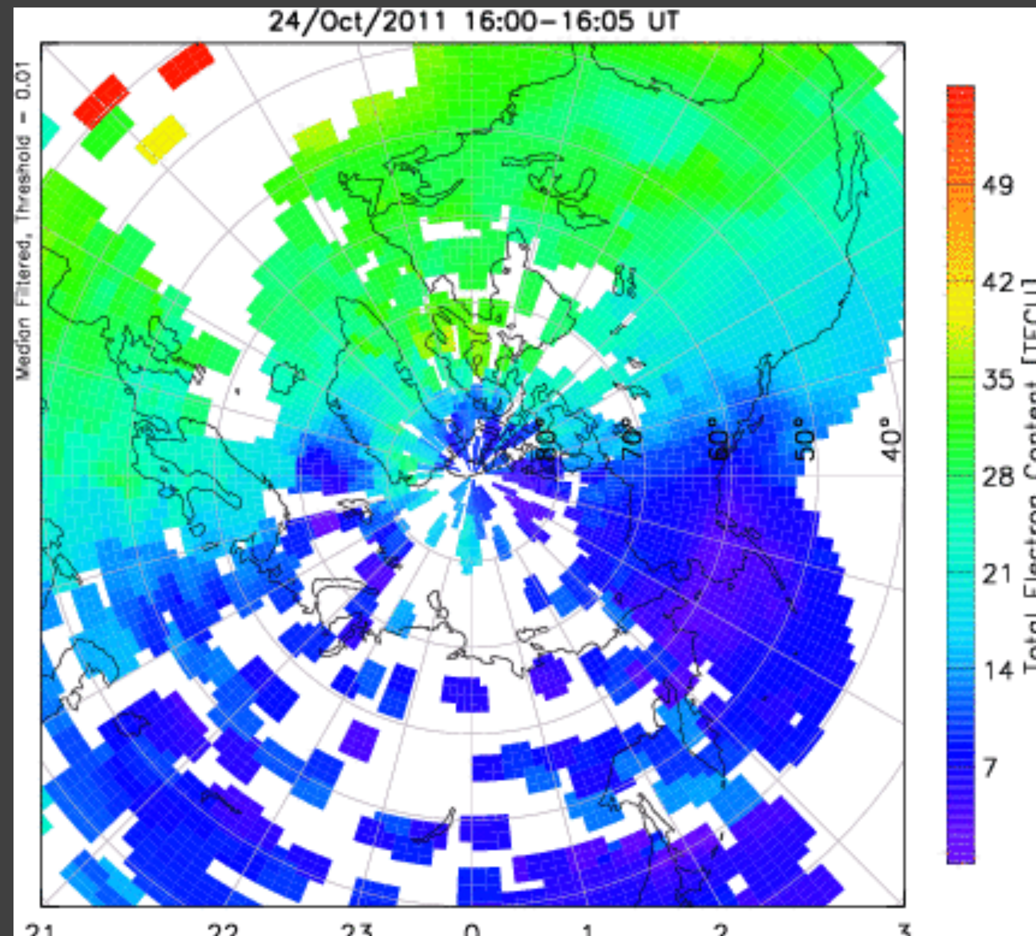


GPS Total Electron Content

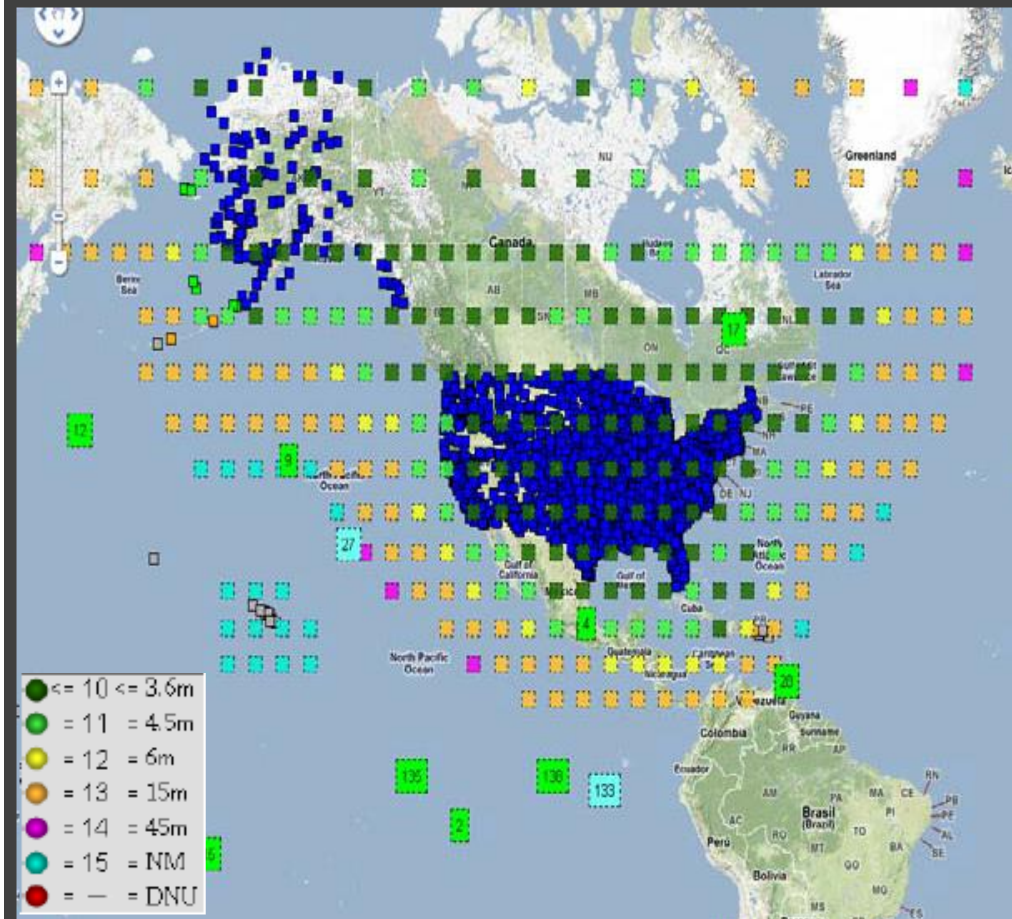


GPS TEC Storm Response

- TEC can image global ionospheric storm response, but there are still large gaps in data coverage
- How does TEC evolve over North America during geomagnetic storms, and why?
- In which seasons do the largest positive/negative storm effects actually occur?
- Are there longitudinal variations in TEC storm response even within the localized North American sector?



Example Storm Impact



September 25th, 2011
19:51:57 UT

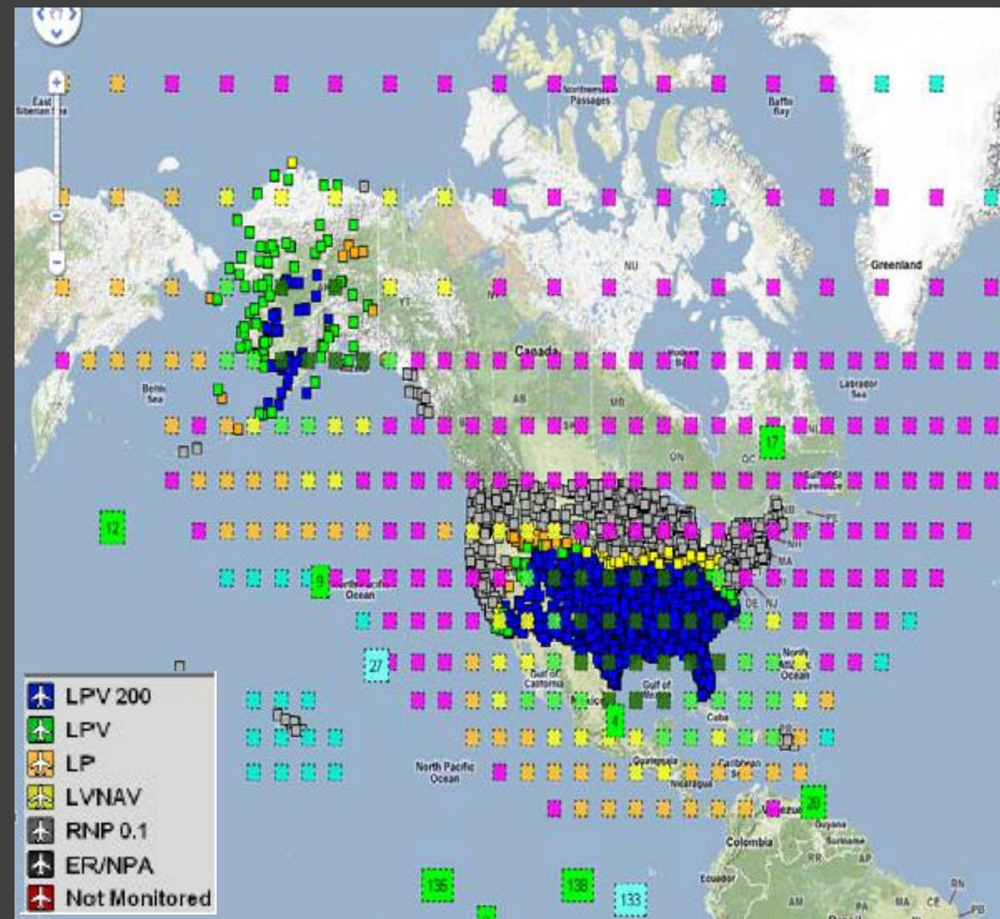


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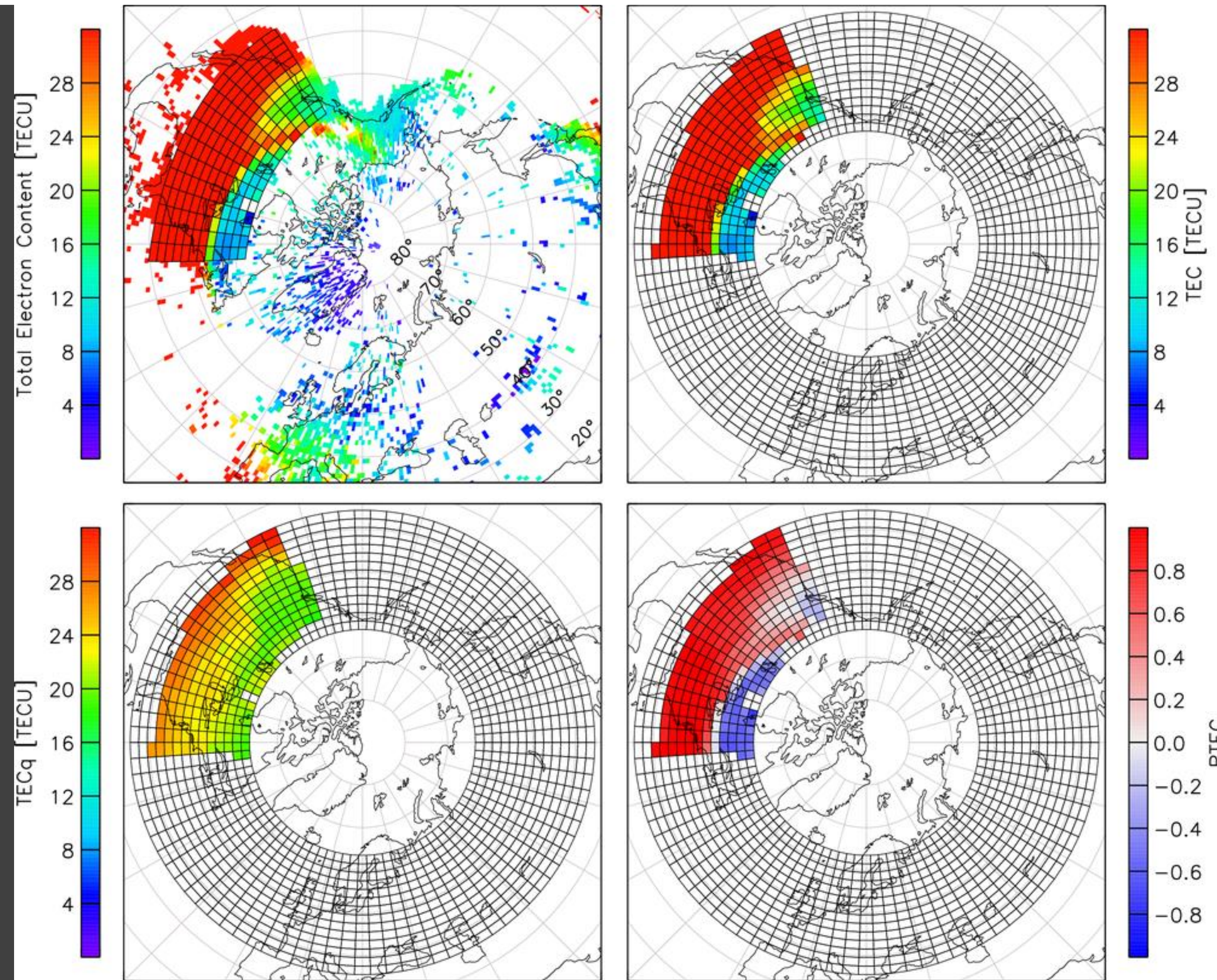
Figure: Wide Area Augmentation System (WAAS) availability over the U.S. before/after storm; small squares denote individual airport status; large squares denote grid ionosphere vertical error [*Wanner*, 2011].

Original 5 min (small pixels) and 30 min avg GPS TEC data in MLAT/MLON

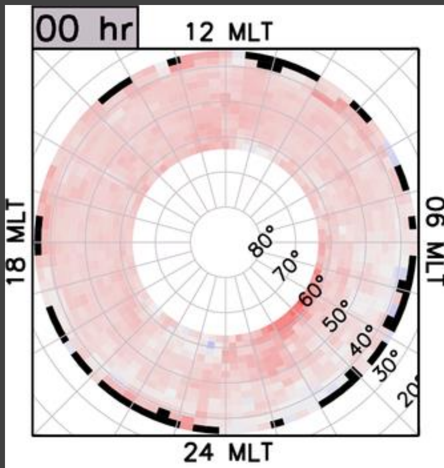
27-day median TEC data (re-binned) [TECq]

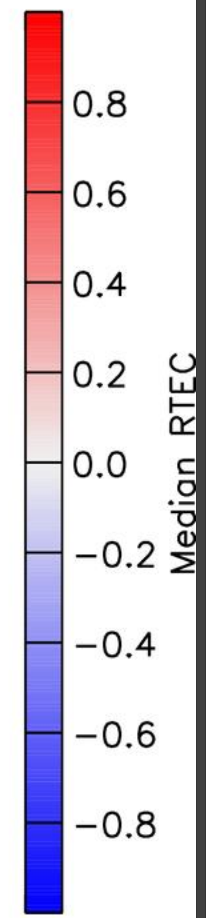


Re-binned 30 min TEC data in MLAT/MLT [TEC]

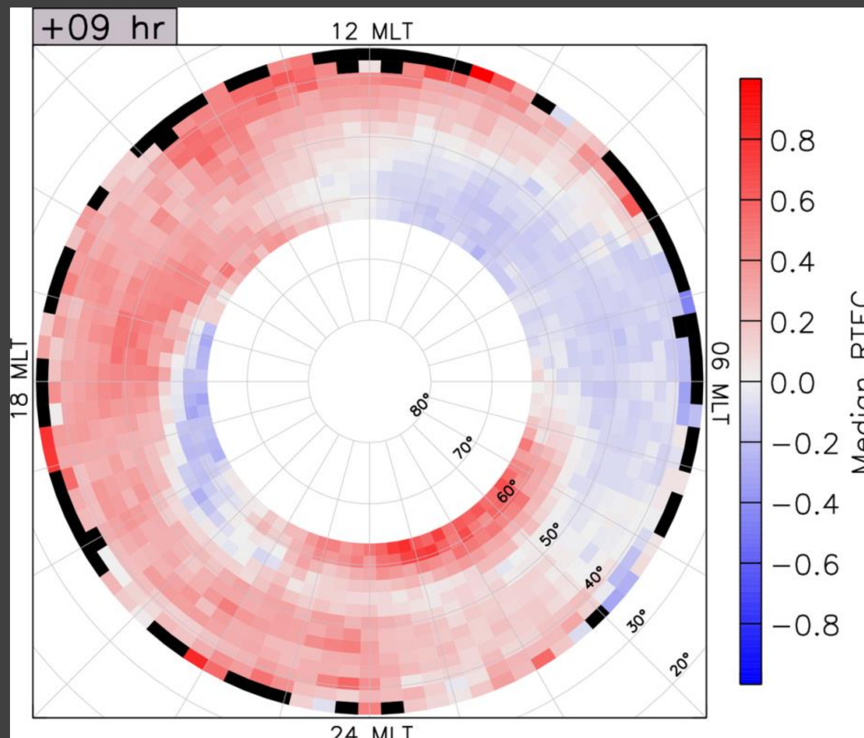
Relative storm-time change in TEC [RTEC]

$$\mathrm{RTEC} = \frac{\mathrm{TEC} - \mathrm{TECq}}{\mathrm{TECq}}$$


00 hr
12 MLT
18 MLT
06 MLT
24 MLT
80°
70°
60°
50°
40°
30°


0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
Median RTEC

Motivation



- *Thomas et al.* [2016] recently derived statistical characterizations of the positive and negative storm response of GPS total electron content (TEC) over North America
- Can these results be applied to space weather modeling for prediction of geomagnetic storm effects on the ionosphere?

GPS TEC Modeling

- Current regional and global empirical TEC models are unable to accurately reproduce these storm-time positive and negative response features [e.g. *Mao et al.*, 2008; *A et al.*, 2012]

- The empirical orthogonal function (EOF) technique, also known as principal component analysis (PCA), has a strong history of being used to model climatology of ionospheric parameters such as ion composition, fof2, and TEC [e.g. *Daniell et al.*, 1995; *Chen et al.*, 2015]

- The EOF approach decomposes a data vector $D(x,t)$ into a series of orthogonal basis functions $E_k(x)$ and corresponding principal components $P_k(t)$

$$D(x,t) = \overline{D}(x) + \sum_{k=1}^{N} \mathbf{E}_k(x) \times \boldsymbol{P}_{\boldsymbol{k}}(t)$$

where here $\overline{D}(x)$ is the mean value at each spatial grid point and N is the total number of EOF basis functions (in this case, equal to the length of x)

EOF Decomposition

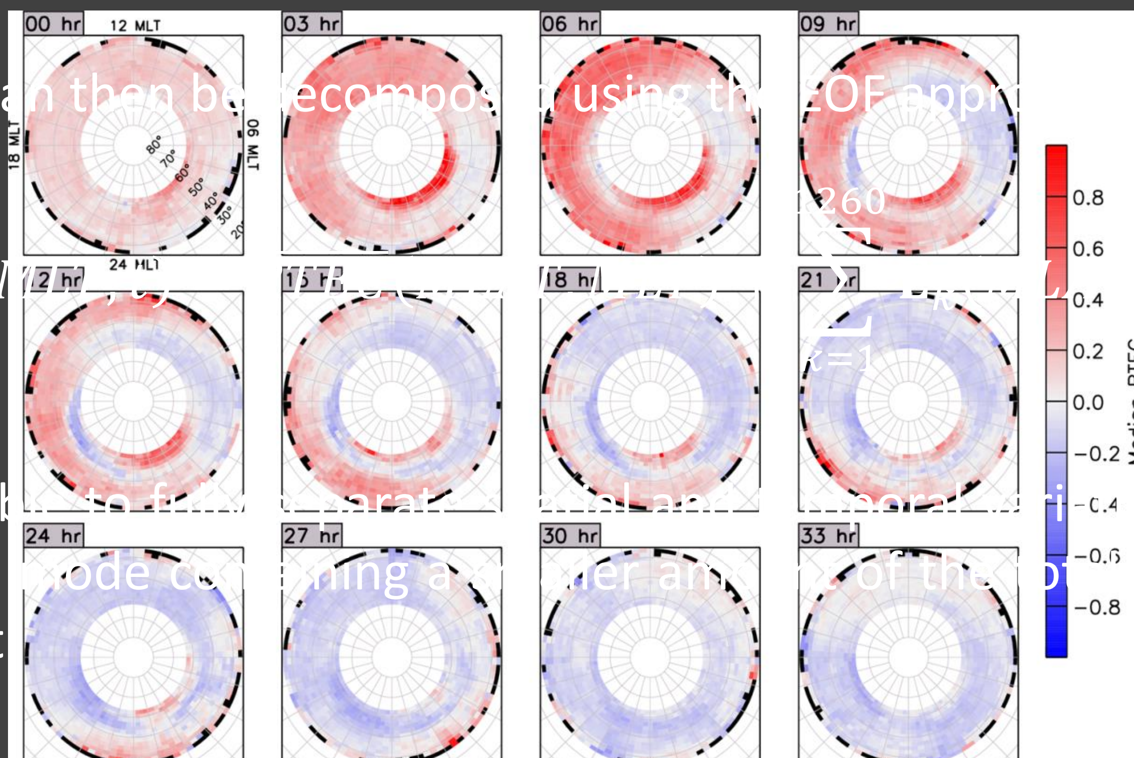
- In our previous study, a database of 30 min storm time relative GPS TEC variations (*RTEC*) over North America was created using observations from 139 storm events during the years 2001-2013:

$$RTEC(MLAT, MLT, t)$$

- These values can then be decomposed using the EOF approach as

$$RTEC(MLAT, MLT, t) = \sum_{k=1}^{260} \boldsymbol{E_k}(MLAT, MLT) \times \boldsymbol{P_k}(t)$$

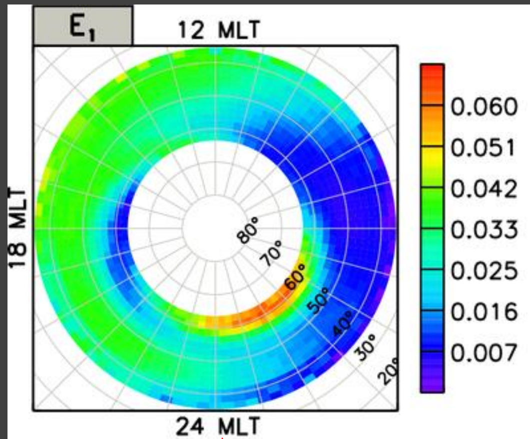
- Thus we are able to find separate spatial and temporal variations in *RTEC* with each successive mode containing a smaller amount of the total variability in the original data set

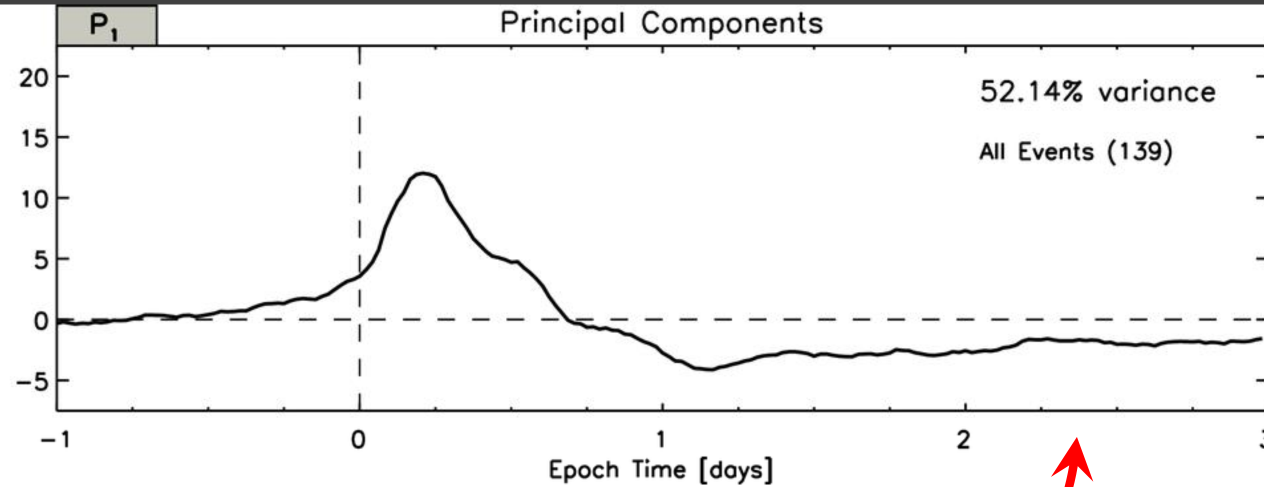


Variance

EOF Series	Variance (%)	Cumulative Variance (%)
$E_1 \times P_1$	52.14	52.14
$E_2 \times P_2$	13.01	65.15
$E_3 \times P_3$	5.44	70.59
$E_4 \times P_4$	2.86	73.45
$E_5 \times P_5$	1.99	75.44
$E_6 \times P_6$	1.34	76.77
$E_7 \times P_7$	1.29	78.06
$E_8 \times P_8$	1.19	79.24

- The first eight EOF series (or modes) capture 79.24% of the total variance in the original RTEC data set
- This means that we can drastically reduce the complexity of our reconstruction by discarding most of the higher-order modes (here $N = 1260$)

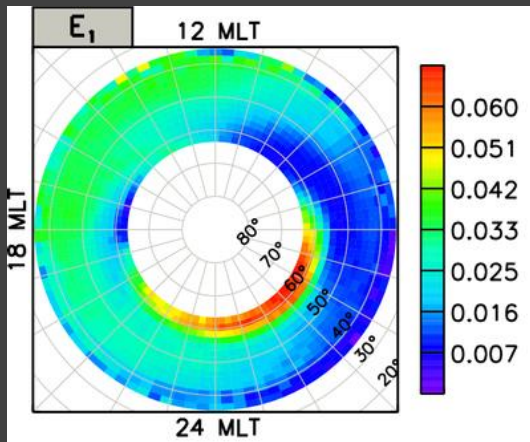


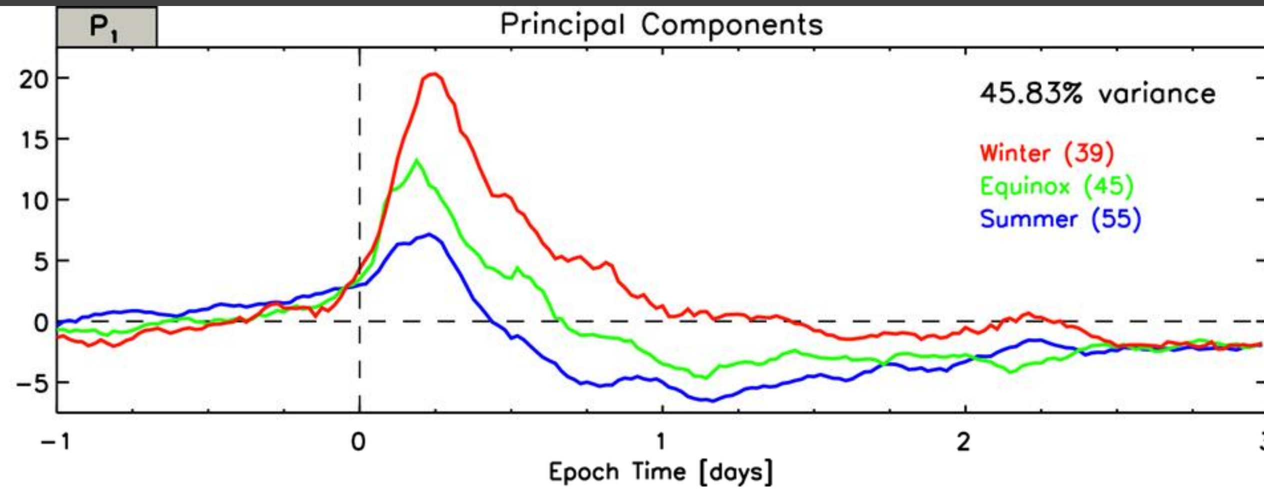


$$RTEC(MLAT, MLT, t) = \overline{RTEC}(MLAT, MLT) + \sum_{k=1}^{1260} \mathbf{E}_k(MLAT, MLT) \times \boldsymbol{P_k}(t)$$

−1 0 1 2 3

Epoch Time [days]

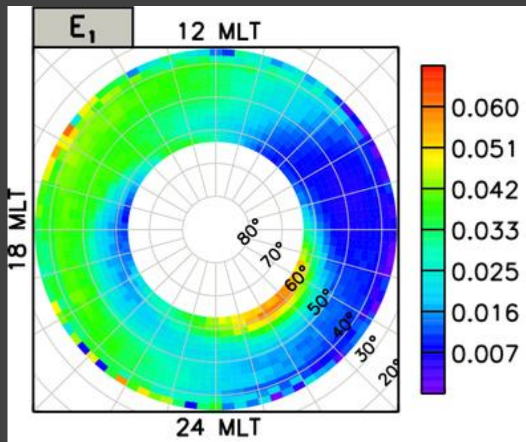


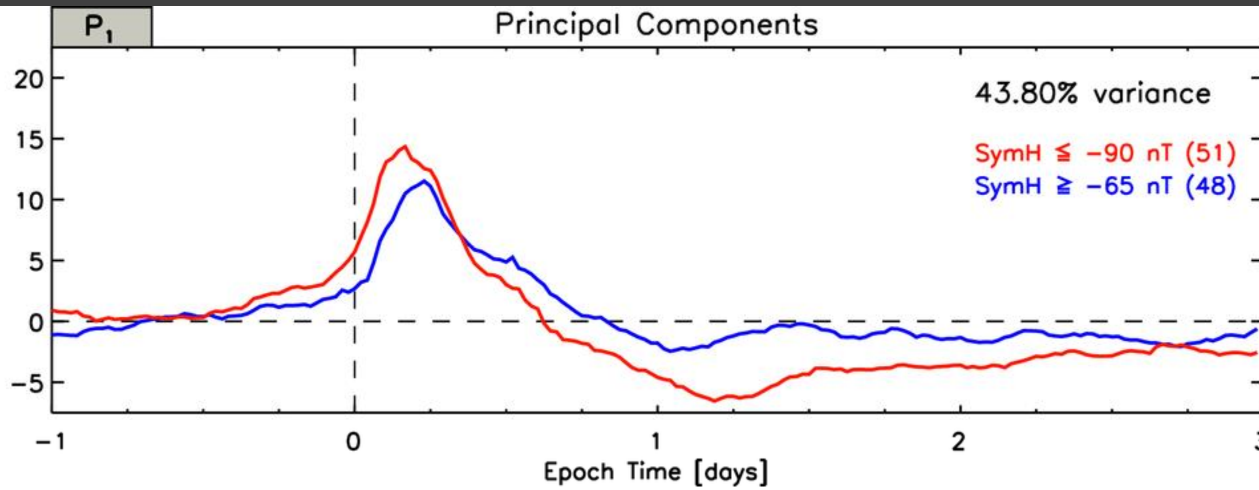


$$RTEC(MLAT, MLT, t, s) = \overline{RTEC}(MLAT, MLT) + \sum_{k=1}^{1260} \mathbf{E}_k(MLAT, MLT) \times \boldsymbol{P_k}(t, s)$$

−1 0 1 2 3

Epoch Time [days]





$$RTEC(MLAT, MLT, t, i) = \overline{RTEC}(MLAT, MLT) + \sum_{k=1}^{1260} \mathbf{E}_k(MLAT, MLT) \times \boldsymbol{P_k}(t, i)$$

−1 0 1 2 3
Epoch Time [days]

Future Work – Predictive Model

- Remember that the RTEC parameter is calculated as a relative storm time deviation from some background mean or climatological value (TECq)

$$\mathrm{RTEC} = \frac{\mathrm{TEC} - \mathrm{TECq}}{\mathrm{TECq}}$$

- Rearranging this equation, we can solve for a predicted storm time TEC value using our EOF reconstruction of RTEC and a climatological TECq value as

$$\mathrm{TEC_{storm}} = \mathrm{TECq}(1 + \mathrm{RTEC_{model}})$$

- Future work includes parameterization of the seasonal (DOY) and geomagnetic activity dependence (Sym-H) in the EOF decomposition and evaluating the ability of such a model to reproduce actual storm time TEC values for events outside our original data set window (2001-2013)

EOF TEC Storm Results

- EOF decomposition of storm-time TEC response allows for identification of dominant modes of spatial and temporal variability

- Spatial patterns highlight morphological features such as SED plume, trough, auroral oval, composition bulge, etc.

- Temporal variations show clear dependence on season and storm intensity, suggesting possibility of parameterization by DOY or Sym-H magnitude for future empirical models

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Thank You!