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Title: Total Electron Content Variation over Thunderstorms

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Total Electron Content Variation over Thunderstorms

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Outline

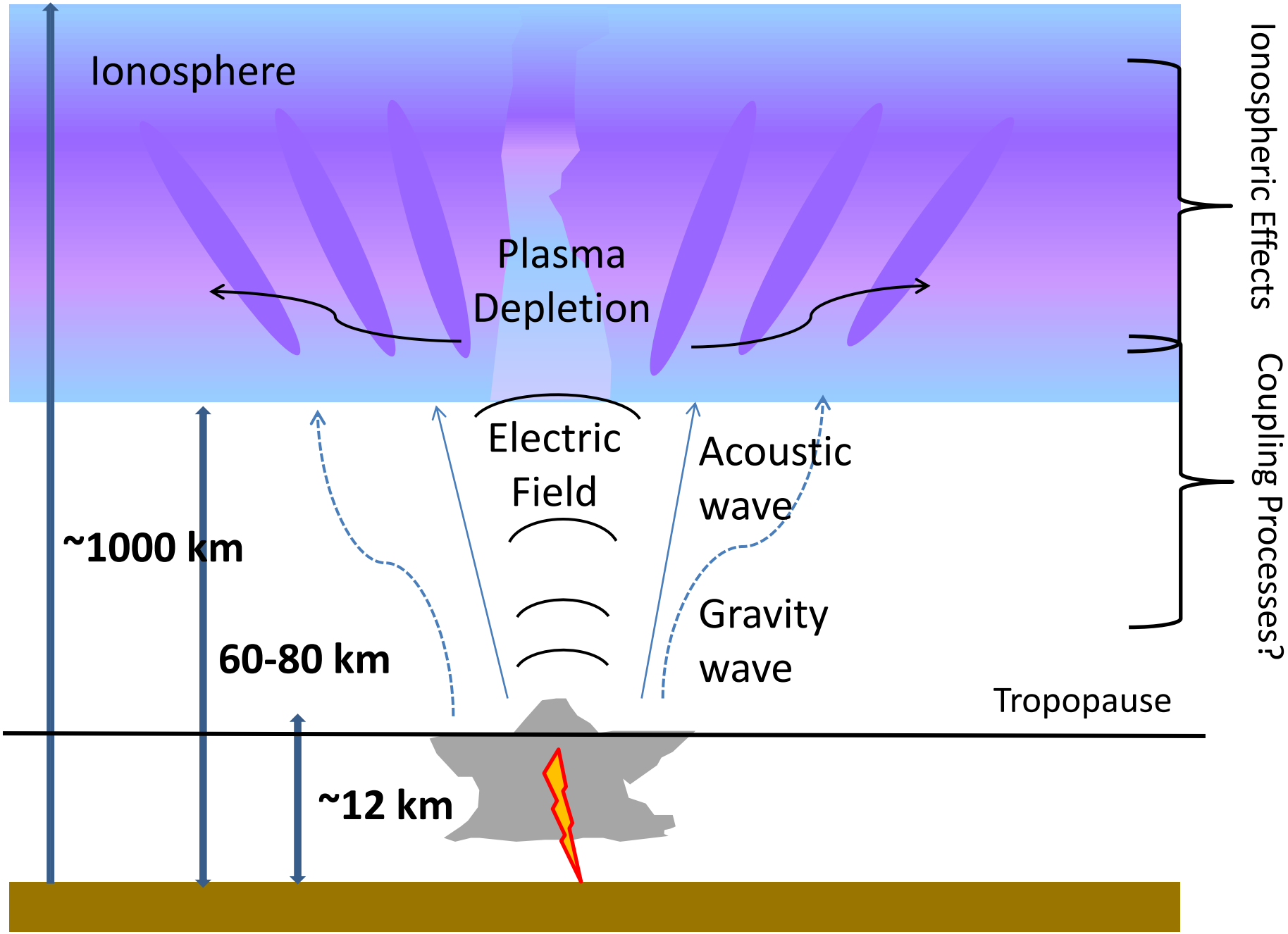
- Background Information
- Introduction
- Thermospheric to Ionospheric Coupling Processes
- TEC Data Processing Procedure
- Observed TEC Variation Results
- Meteorological Analysis of TEC Variation Events
- Conclusions

Background Information

- **Total Electron Content (TEC) is an integrated measurement of the number of electrons between a GPS receiver on the ground and a satellite**
- **1 Total Electron Content Unit (TECU) = 10^{16} electrons/m^2**
- **TEC variations have traditionally been associated with geomagnetic and solar activity**
- **The continuously operating reference station (CORS) network of GPS receivers was used to calculate the TEC variation over various regions in the US**

Introduction

- Large tropical storm systems have been found to impact the electron density in the ionosphere (Bishop et.al 2006)
- Simulations of atmospheric gravity waves have predicted a detectable TEC variation over large convective systems (Vadas and Liu, 2009)
- Lightning has been associated with an intensification of the ionospheric sporadic E layer (Davis and Johnson, 2005)
- Thunderstorm-generated gravity waves have been found to impact the D-layer of the ionosphere (Lay and Shao, 2011)
- TEC variation has been associated with large mesoscale thunderstorms in the Great Plains of the US (Lay et al., 2013)
- 35 storm days have been investigated for TEC variation in the Great Plains and New Mexico so far


Ionosphere
Plasma
Depletion
Electric
Field
Acoustic
wave
Gravity
wave
~1000 km
60-80 km
~12 km
Tropopause
Ionospheric Effects
Coupling Processes?

TEC Perturbations

Gravity Waves

- **~0.5-3.0 mHz (~5-20 minute period) associated with thunderstorms**
- **Potentially generated by large storm systems overshooting and oscillating about the tropopause**
- **Duration over thunderstorms about ~1-2+ hours**

Acoustic Waves

- **~3-5 mHz (~3-5 minute period)**
- **Observed over thunderstorms**
- **Coupling Mechanisms?**
  - Tornadoes
  - Upper-atmospheric discharges (sprites)
- **Duration over thunderstorms ~1-2 hours**

Earthquakes/Tsunami TEC Perturbations

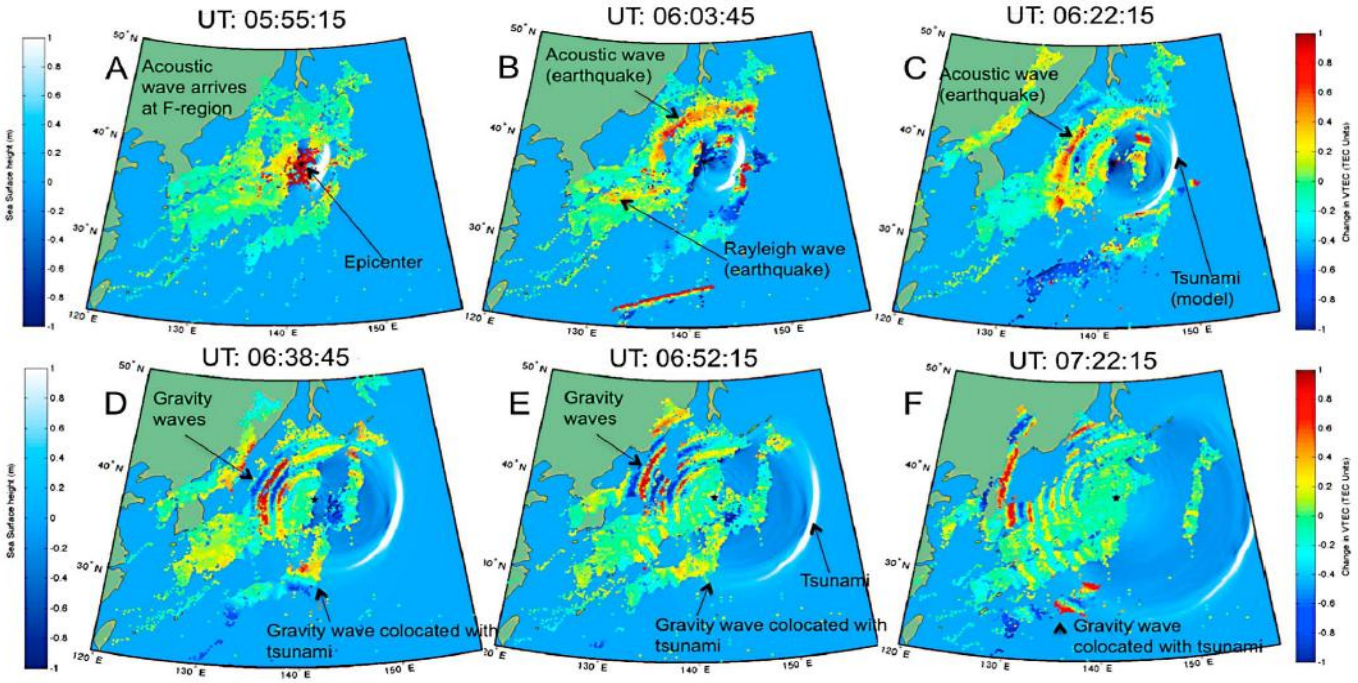


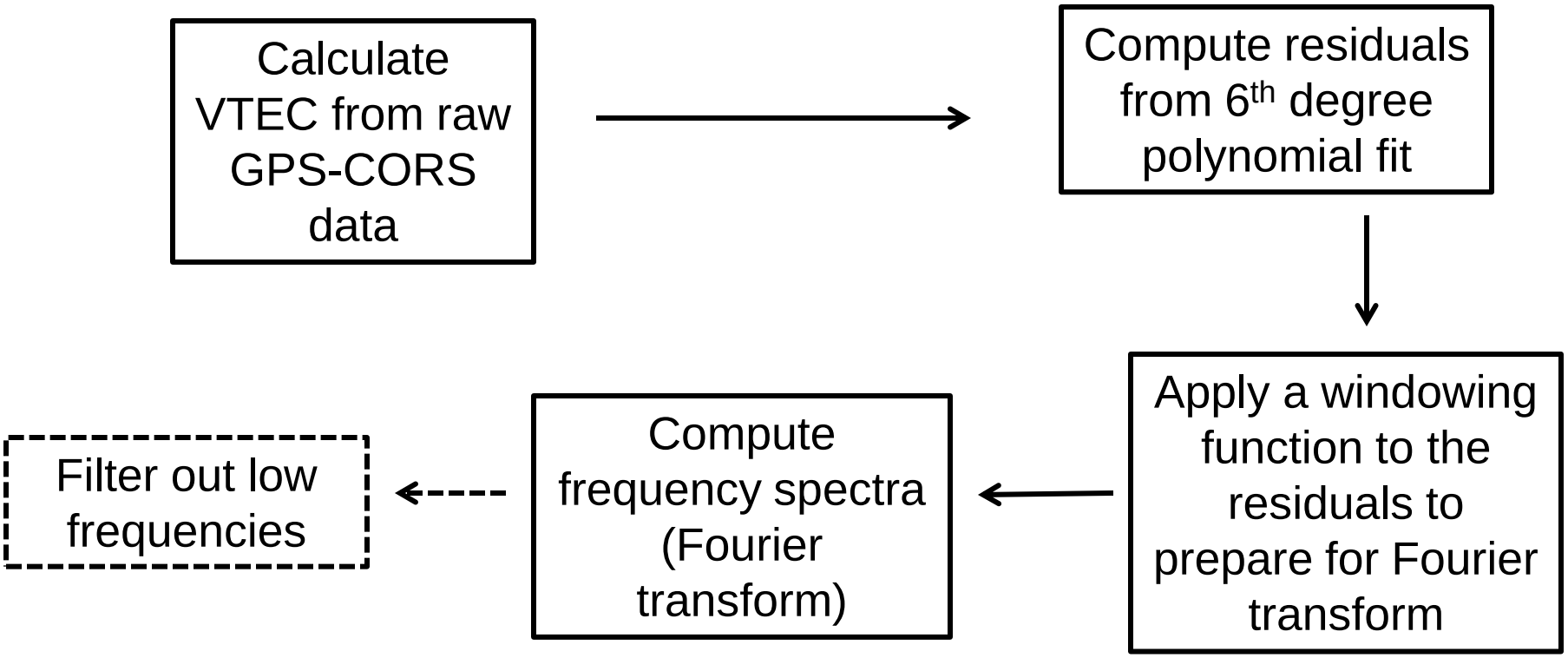
Figure 2. Map plots showing band-pass filtered VTEC (in units of TECU, right color bar) at ionospheric pierce points (IPPs) above Japan at different times on March 11, 2011. Each cluster of IPPs represents locations in the ionosphere where the signal from one GPS satellite, communicating with all GEONET receivers, passes through the *F* region peak at 300 km altitude. IPPs are plotted over sea surface heights from the Song tsunami model (in units of meters, left color bar) for comparison of wavefront positions in the ocean and ionosphere. These are frames from an animation available as dynamic content. (Animation S3)

Galvan, D. A., et al., Ionospheric signatures of the Tohoku-Oki tsunami of March 11, 2011: Model comparisons near the epicenter, *Radio Sci., 47*, 2012

Objectives

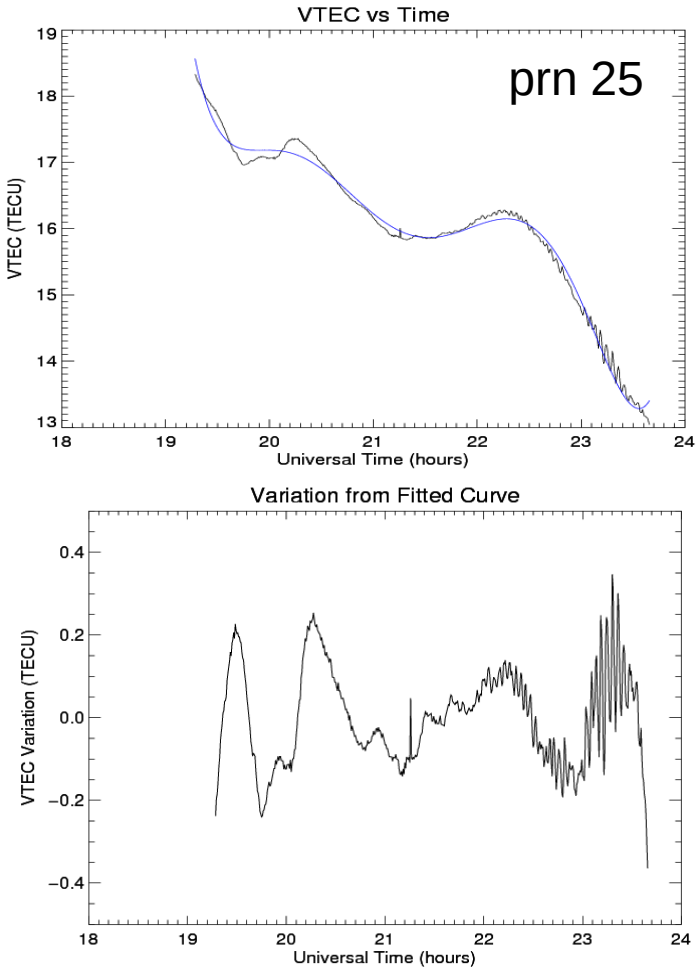
- Identify thunderstorms that exhibit TEC variation in the Great Plains region during the summer of 2005
- Characterize the thunderstorms over which the variation is observed using available meteorological data
- Investigate smaller New Mexican storm systems for similar types of TEC variation

Processing Procedure

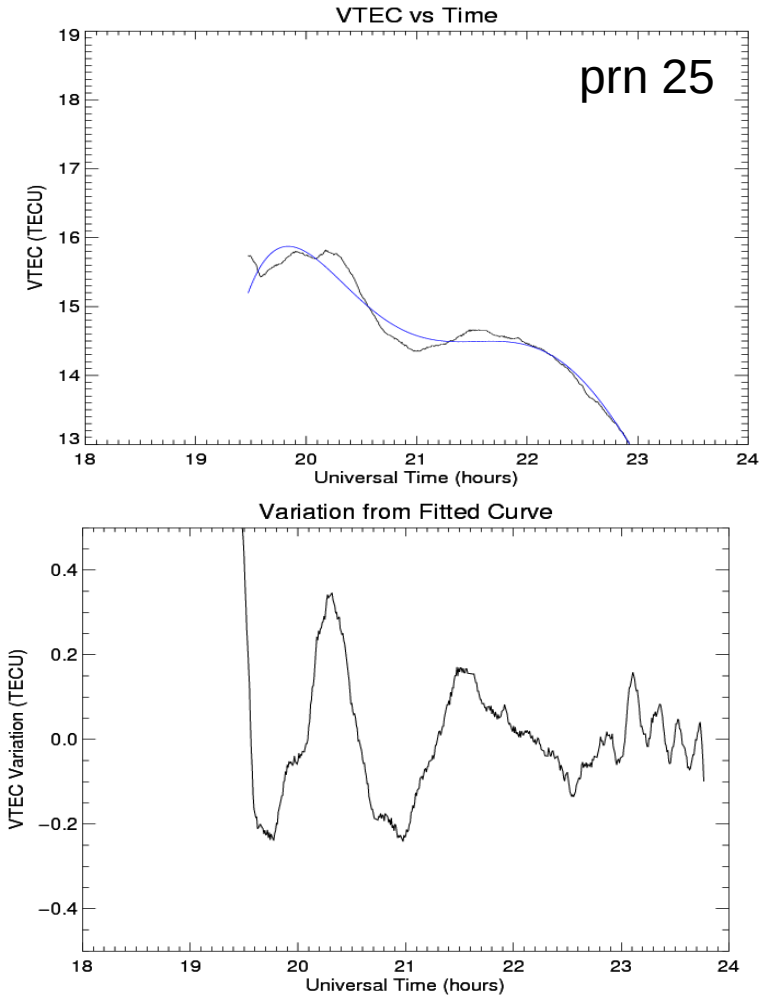


Processing Procedure

Disturbed Station (with acoustic wave variation) (tcun, 6/16/05)



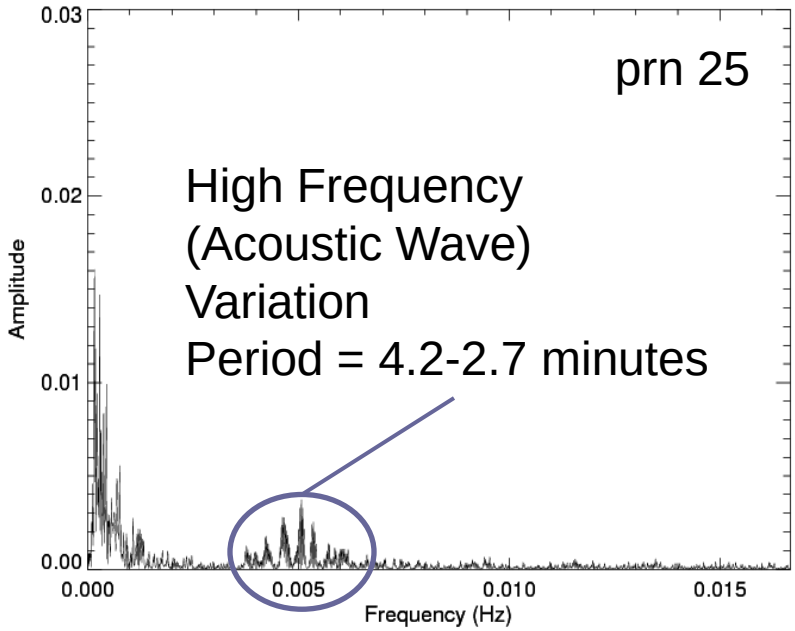
Quiet Station (no acoustic wave variation) (pltc, 6/16/05)



Processing Procedure (Spectral Analysis)

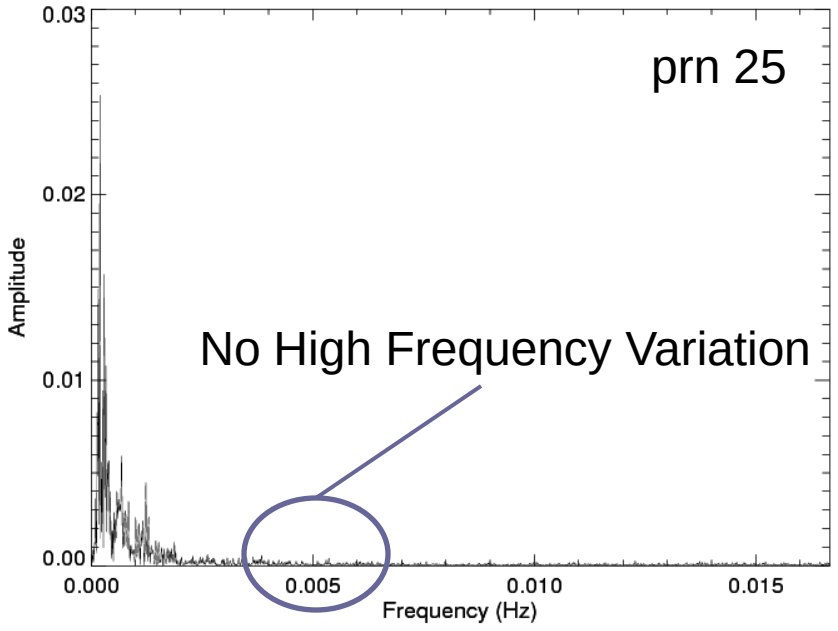
Disturbed Station (tcun, 6/16/05)

Frequency Spectra



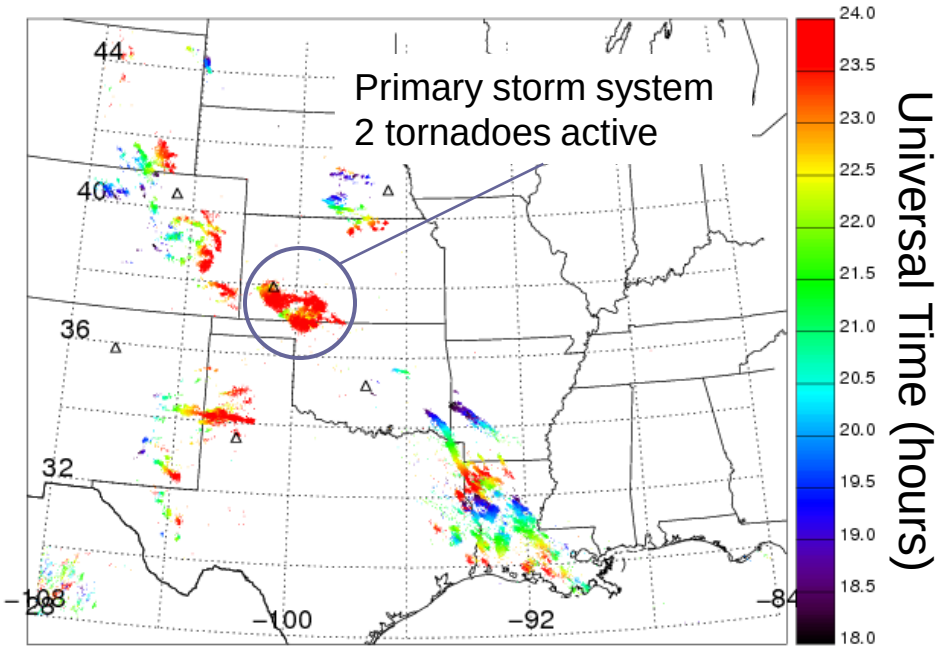
Quiet Station (pltc, 6/16/05)

Frequency Spectra

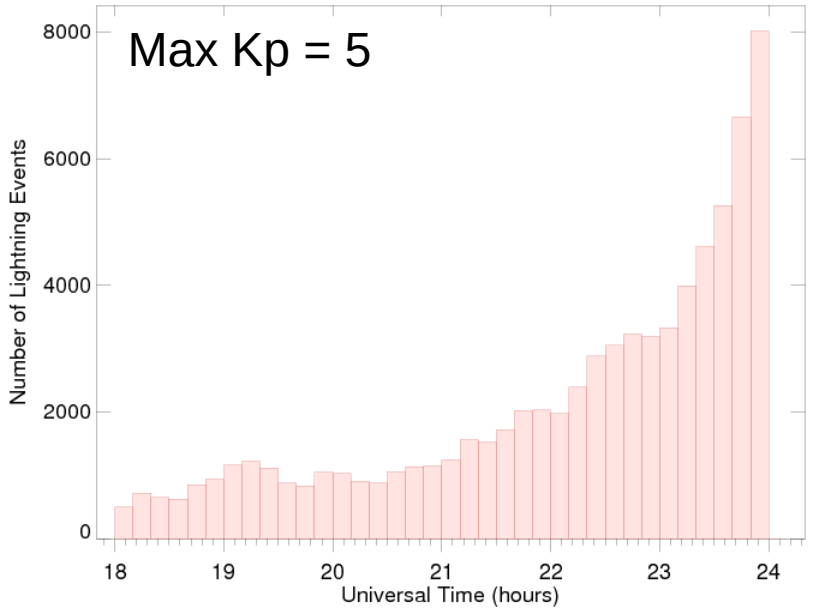


Lightning Data (6/16/2005)

Lightning Location Map



Histogram of Lightning Events



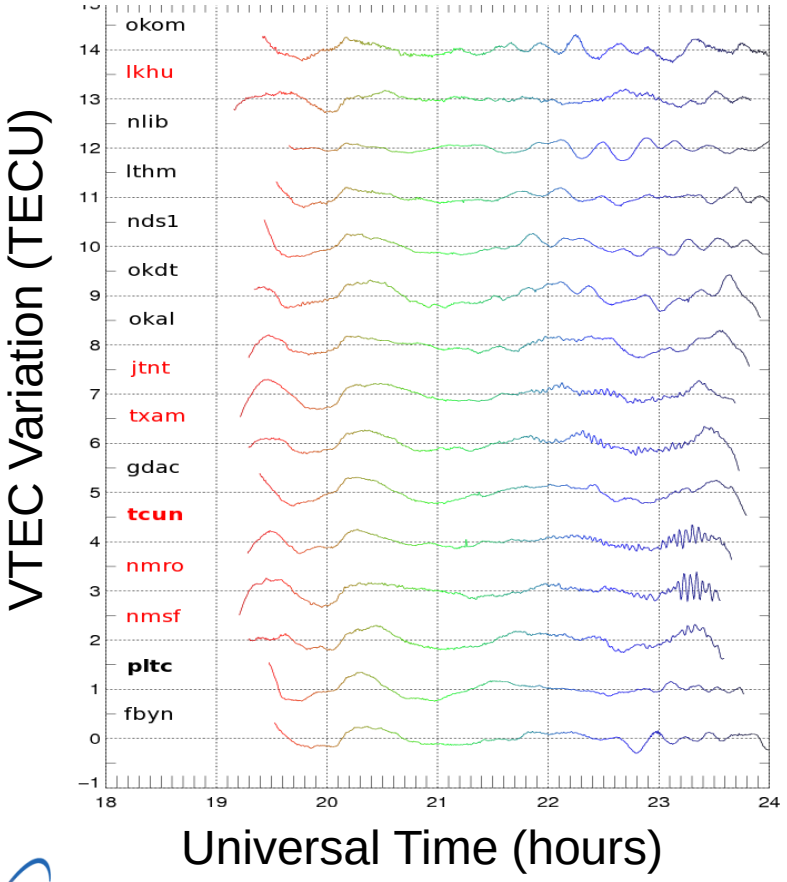
Large storm system developing in southwest Kansas, significant lightning is present, 2 tornadoes have developed by 23-24 UT

Histogram bin size is 10 minutes

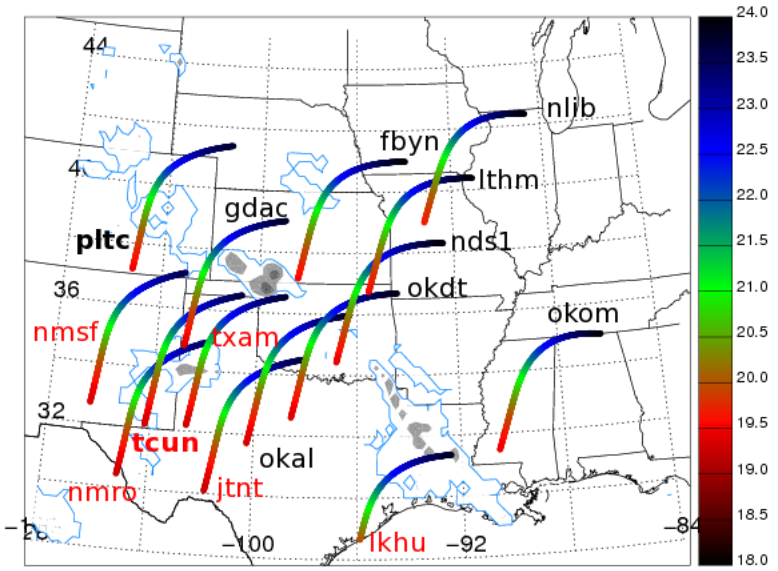
18-24 UT is 13-19 CDT (1-7 PM) Sunset = ~2:00 UT (9:00 CDT) Sunrise = ~11:00 UT (~6:00 CDT)

TEC Results (6/16/2005)

VTEC Variation from fitted curve (prn 25)



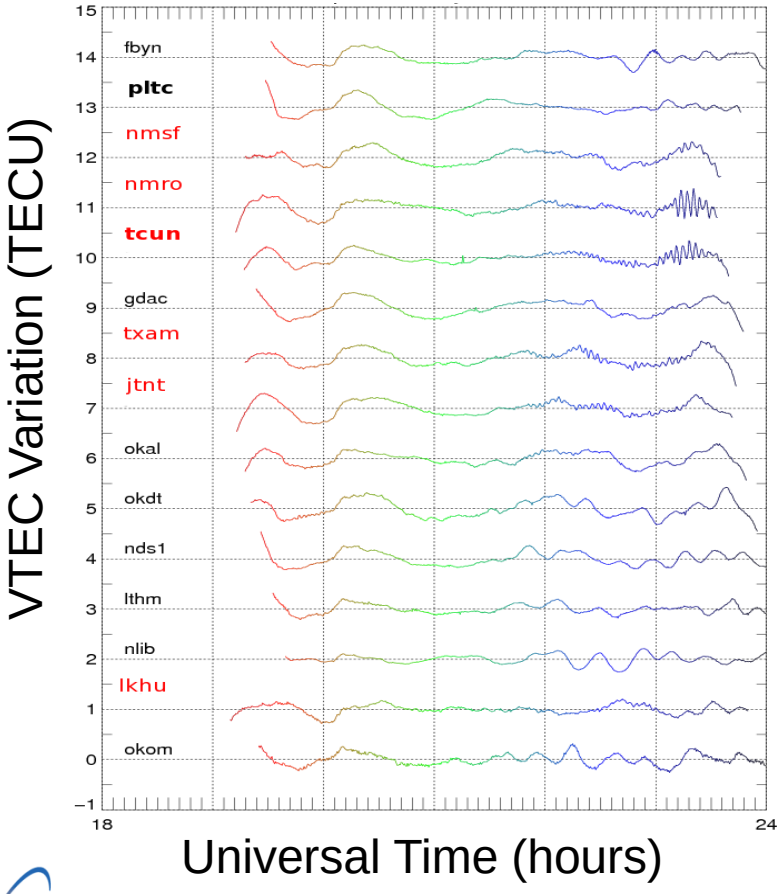
Map of Satellite Arcs (prn 25)



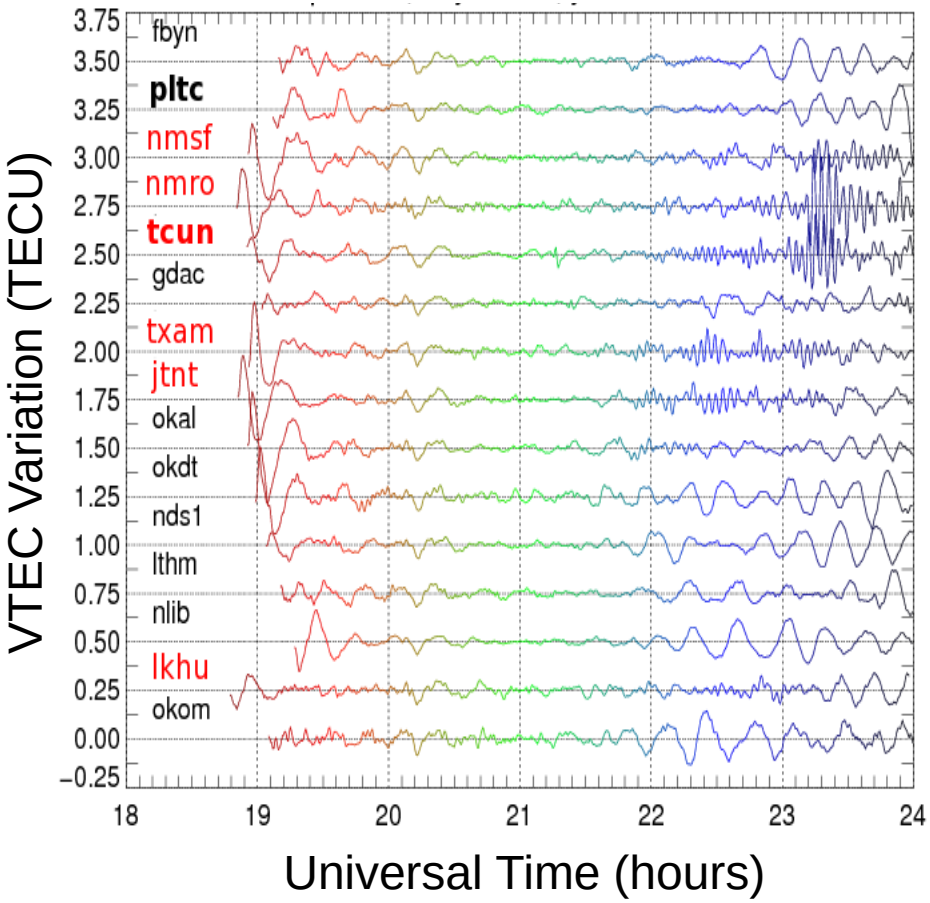
Data sets that are in **bold** were used as examples in the data processing section

TEC Results (6/16/2005)

VTEC Variation from fitted curve (prn 25)

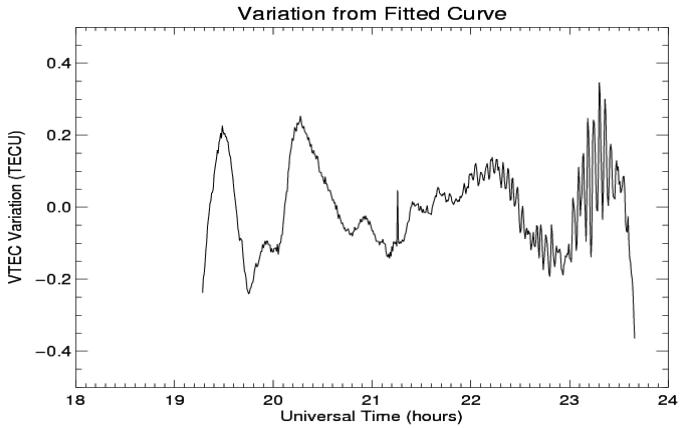


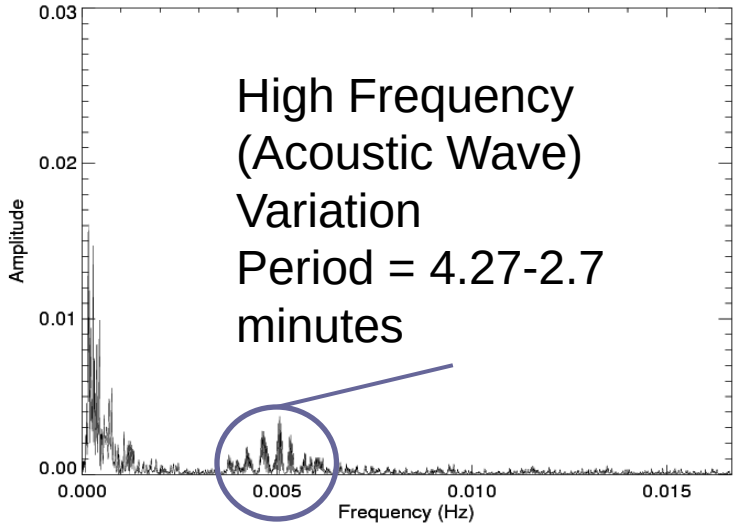
High Pass filtered VTEC Variation (prn 25)



Data Processing

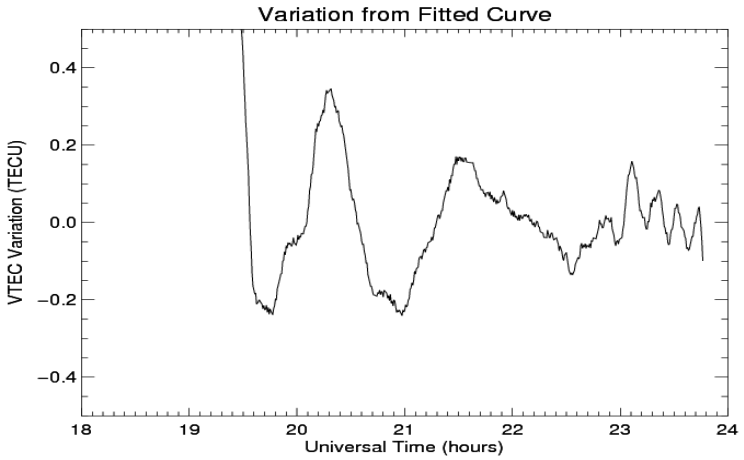
Disturbed Station (tcun, 6/16/05)

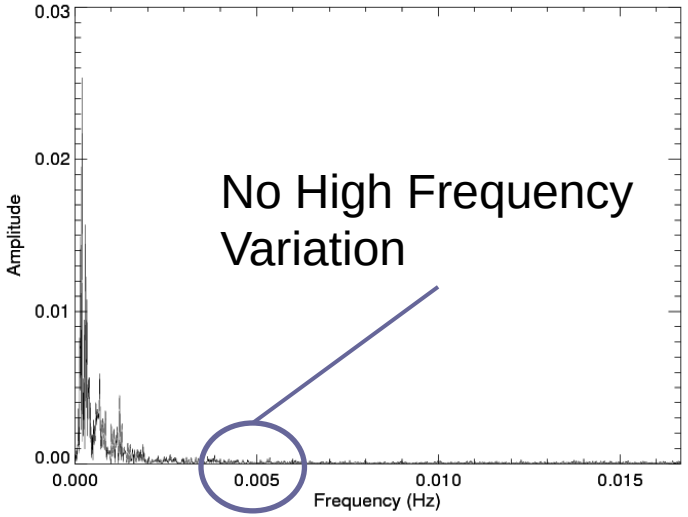




High Frequency (Acoustic Wave) Variation Period = 4.27-2.7 minutes

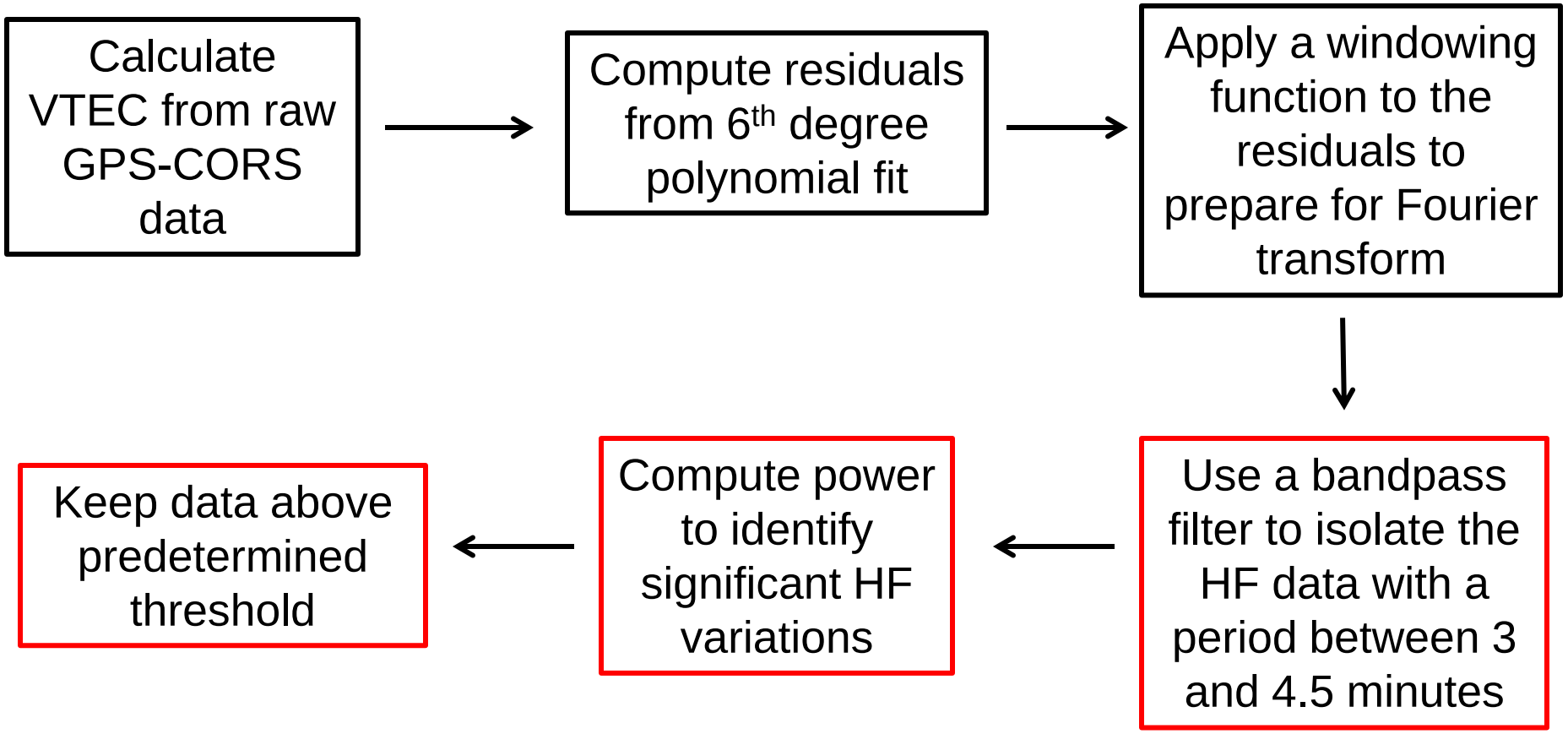
Quiet Station (pltc, 6/16/05)





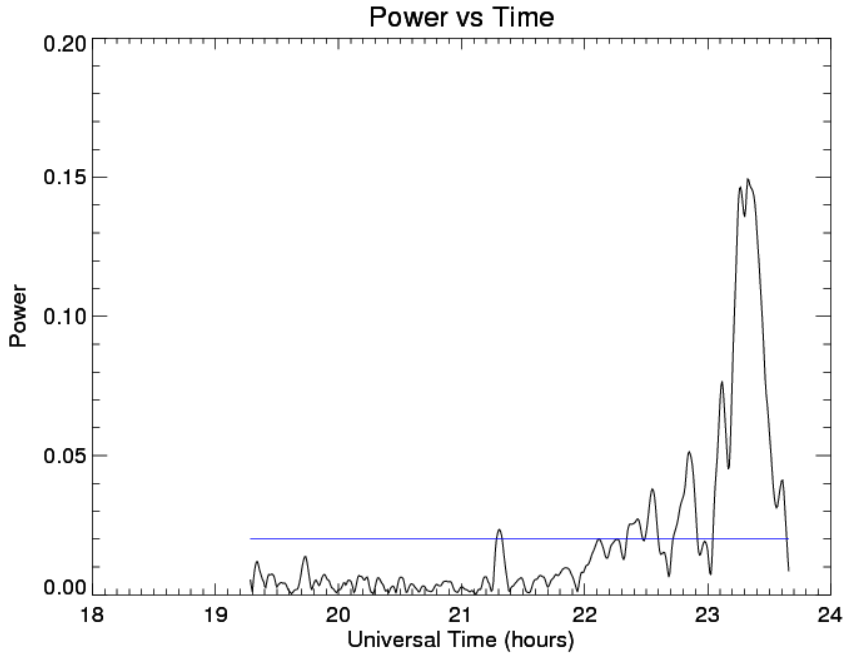
No High Frequency Variation

High Frequency Filtering

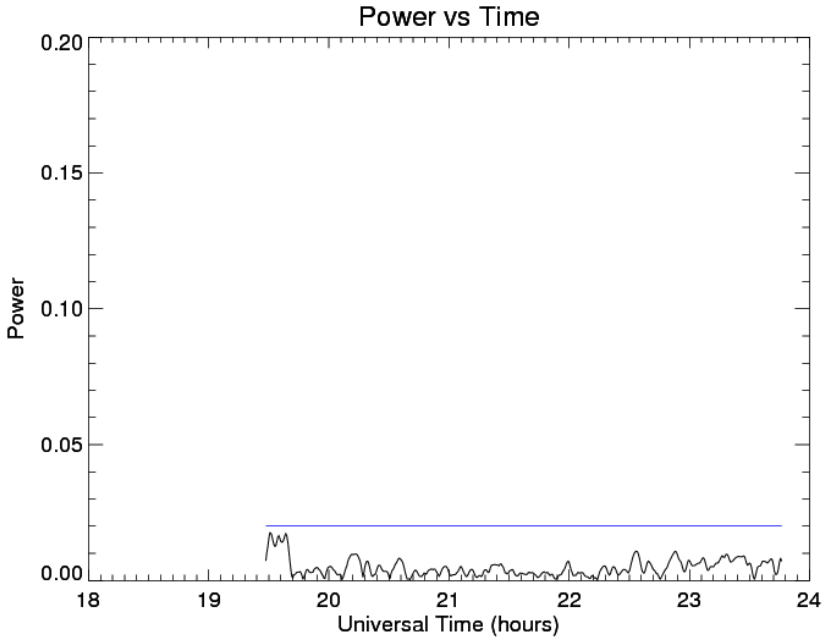


High Frequency (Acoustic Wave) Filtering

Disturbed Station (tcun, 6/16/05)

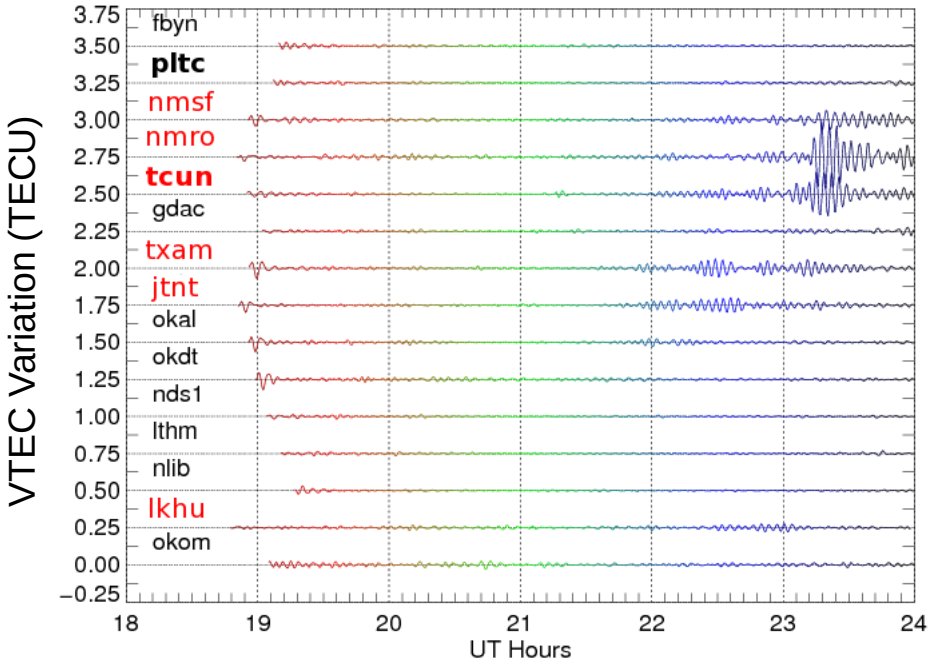


Quiet Station (pltc, 6/16/05)

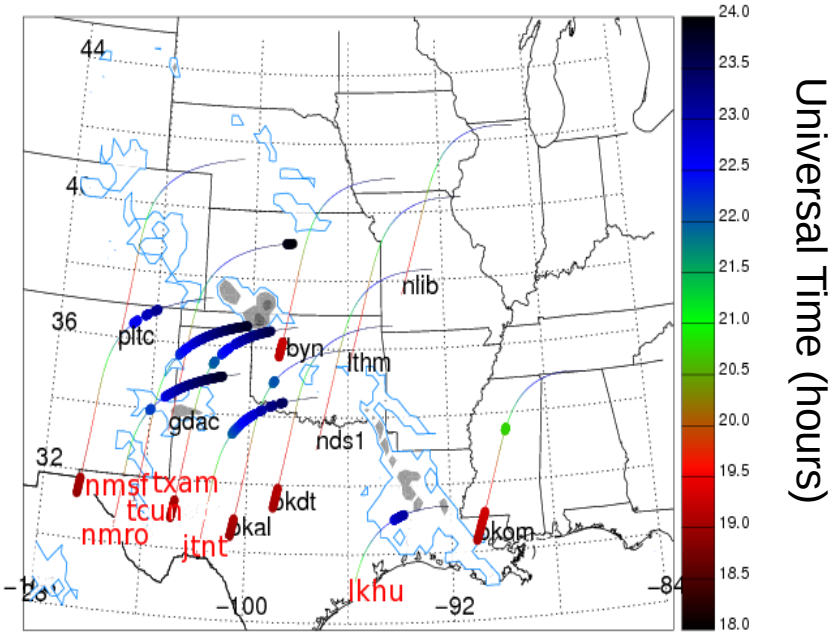


High Frequency (Acoustic Wave) Results (6/16/2005)

High Frequency Variation (prn 25)

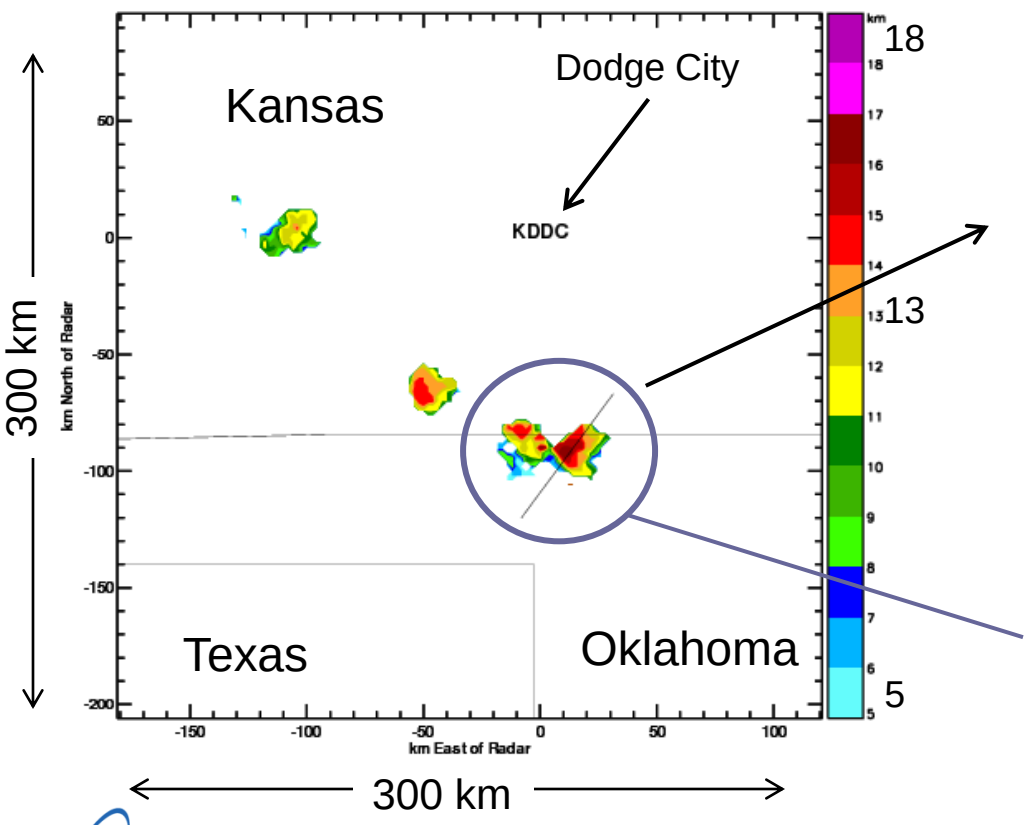


HF Variation Map (prn 25)

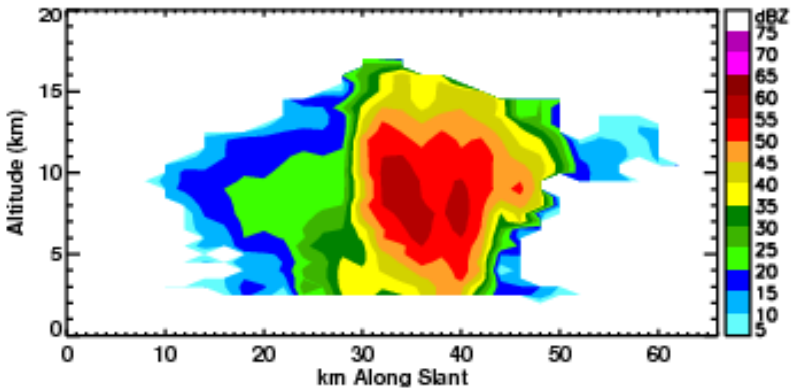


Meteorological Analysis (6/16/05)

Dodge City NEXRAD 21:36-21:41 UT
Max Height > 30.0 dBZ



Reflectivity Along Slant

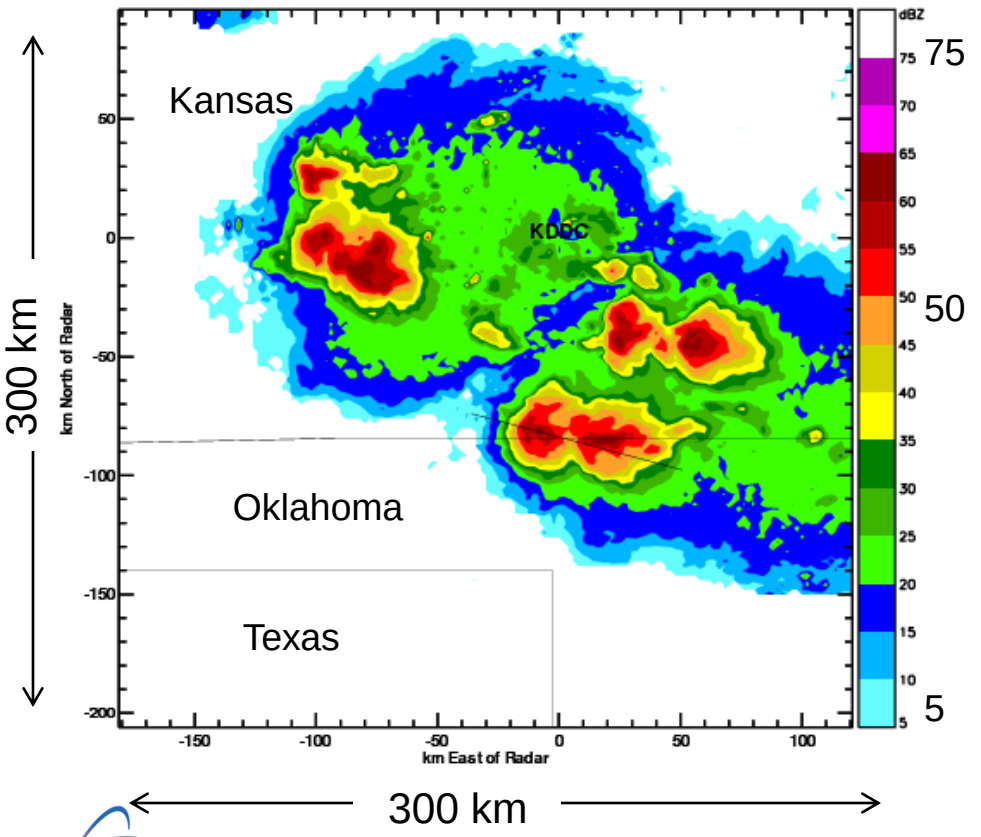


First timestamp (~21:40 UT) with echo tops above 15 km.

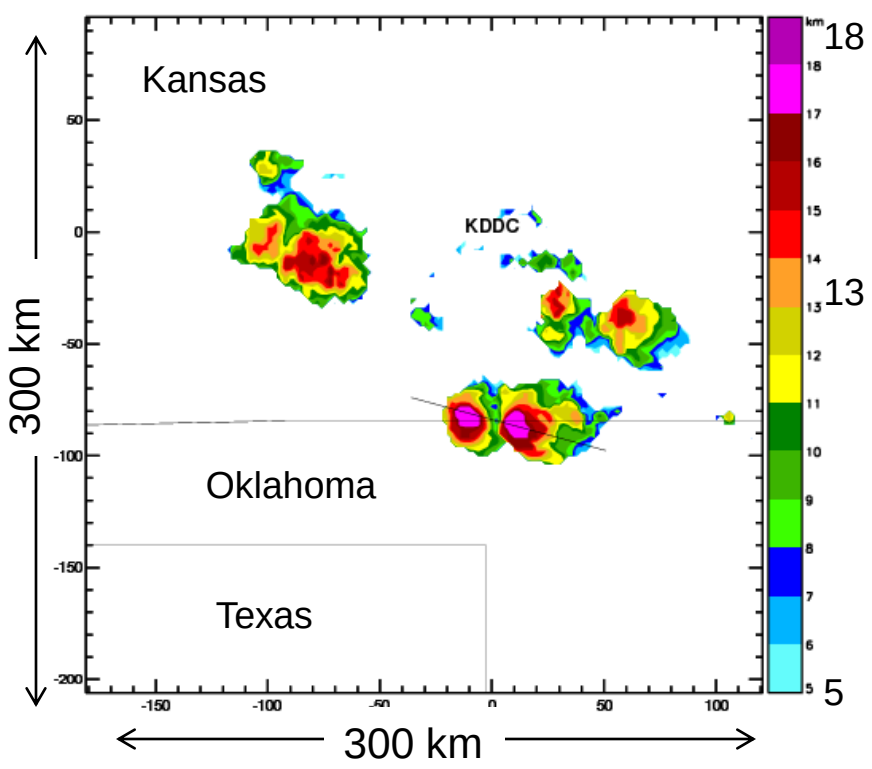
Gravity wave TEC variations appear to start between 21:35-21:45 UT on station jtnt south of the storm system

Meteorological Analysis (6/16/2005)

Dodge City NEXRAD 23:15-23:19 UT
Composite Reflectivity



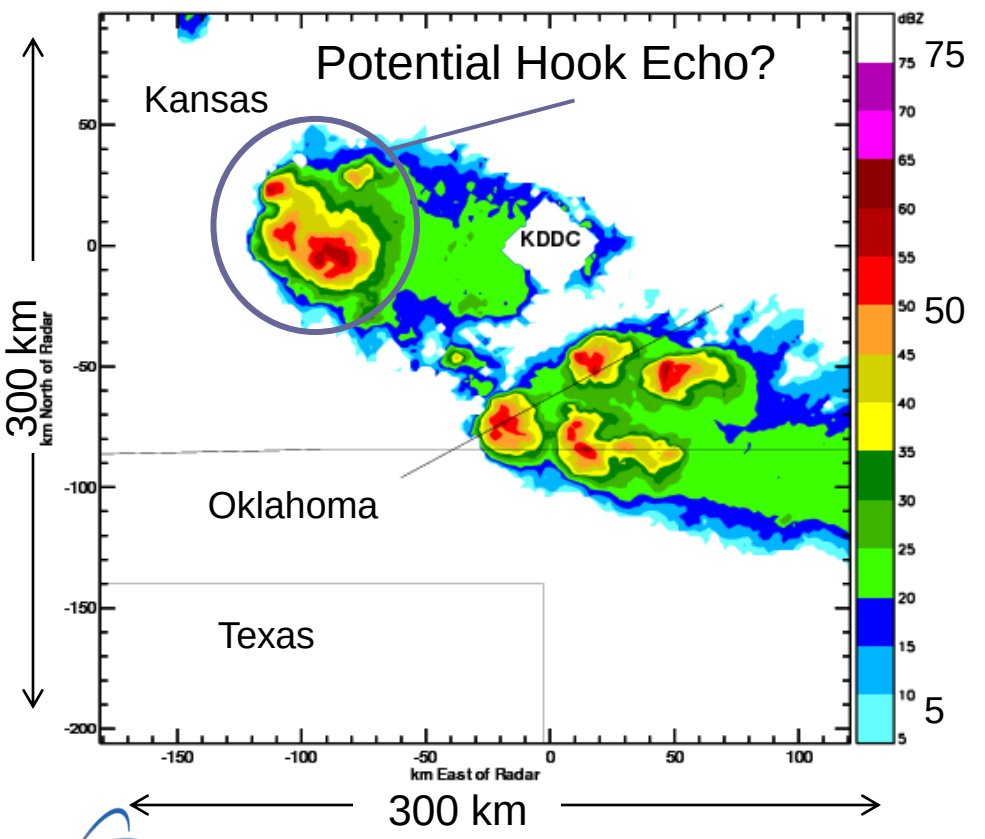
Dodge City NEXRAD 23:15-23:19 UT
Max Height > 30.0 dBZ



Multiple storm cells with a reflectivity of 30 dBZ at or above 15 km

Meteorological Analysis (6/16/2005)

Dodge City NEXRAD 23:15-23:19 UT
Base Reflectivity 8 km

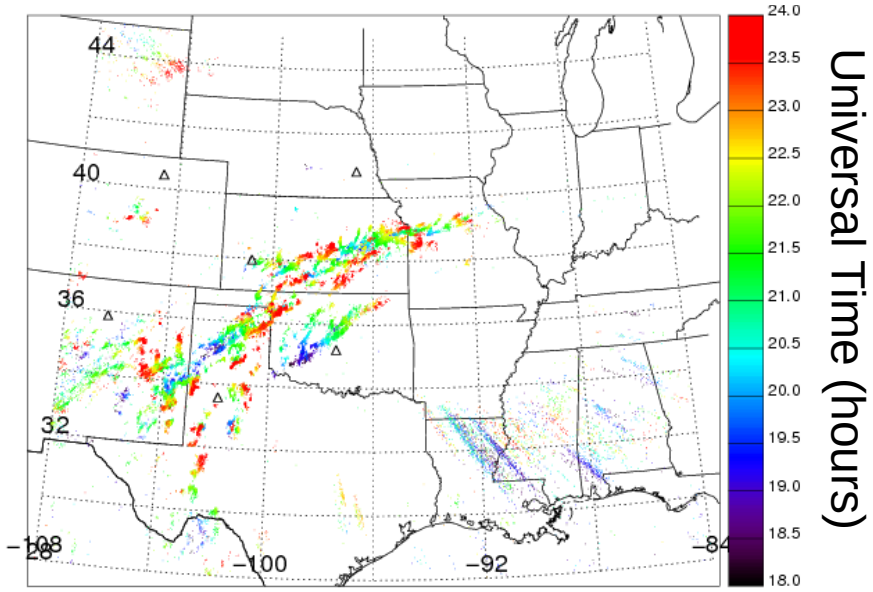


Take Away Points

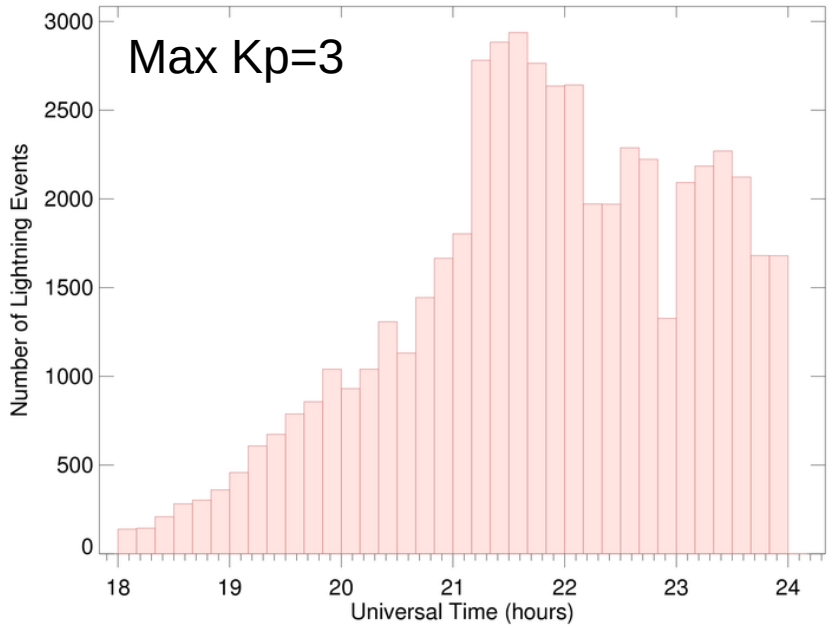
- TEC variation not observed until shortly after 30 dBZ heights reached above 15 km
- Significant magnitude increase in TEC variation at about 23:20 UT
- Additional storm volume above 30 dBZ causing greater variation?
- 2 Tornadoes were reported by NOAA between 23:00 – 23:40
- Could tornado development influence TEC variation?

Lightning Data (8/12/2005)

Lightning Location Map



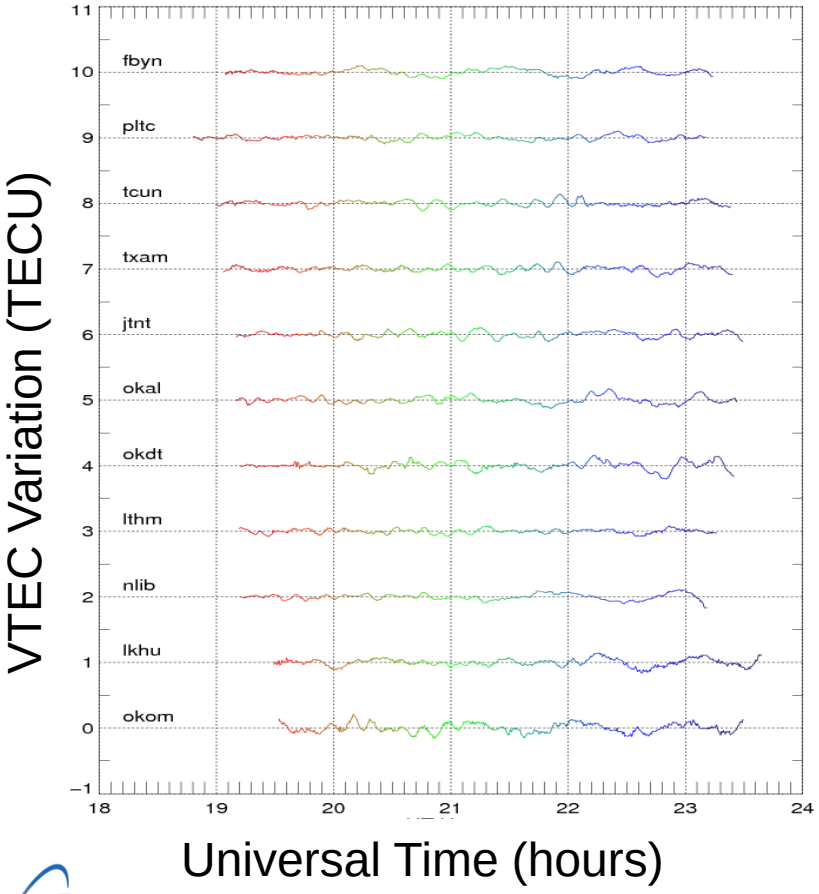
Histogram of Lightning Events



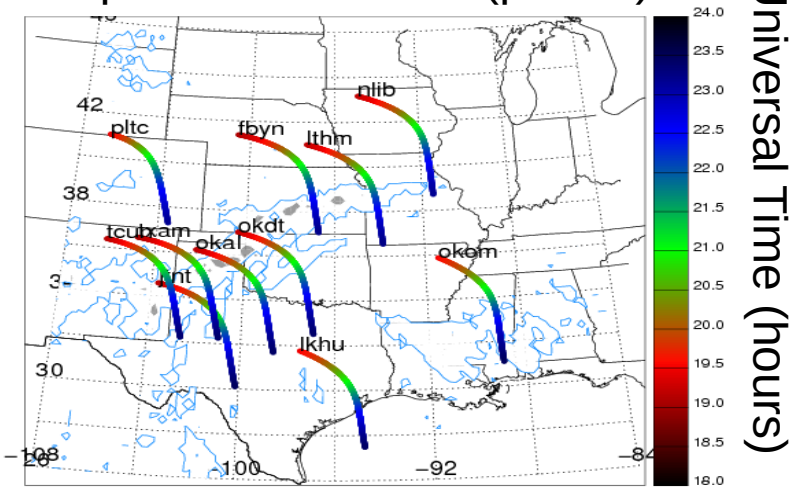
- Group of smaller localized storms spread over a wide region
- Still reasonably electrically active looking at the lightning event histogram
- No mesoscale convective systems present

TEC Results (8/12/2005)

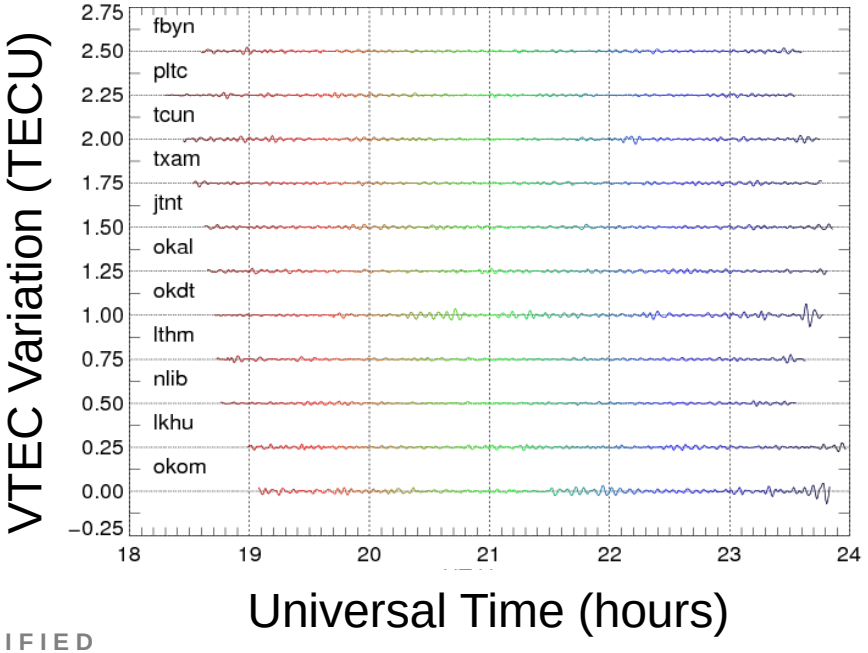
VTEC Variation from fitted curve (prn 23)



Map of Satellite Arcs (prn 23)

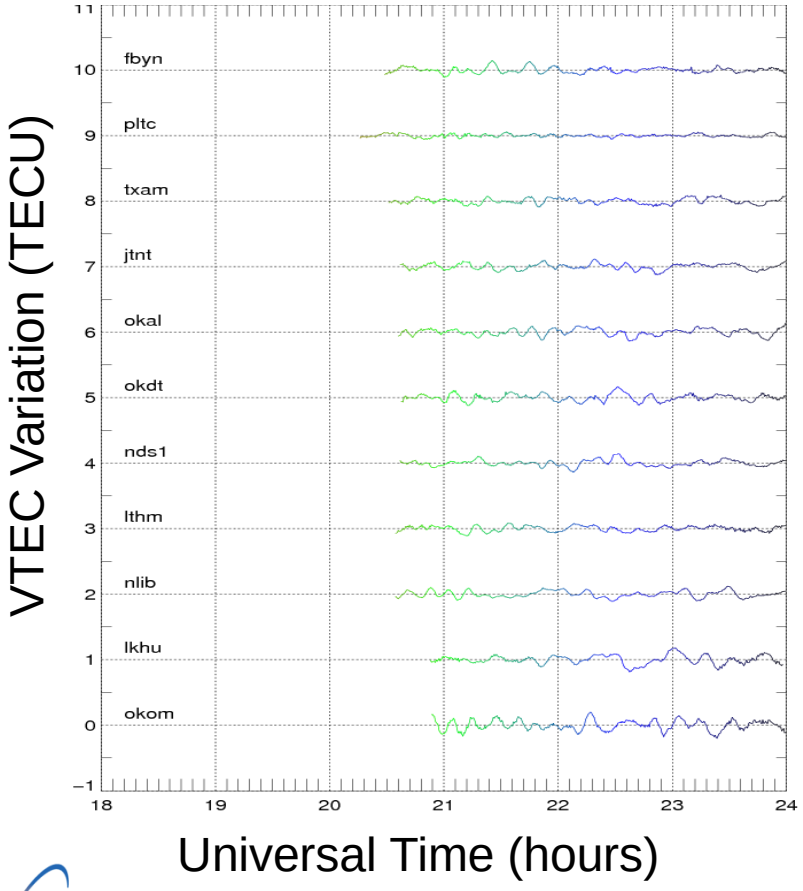


High Frequency Variation (prn 23)

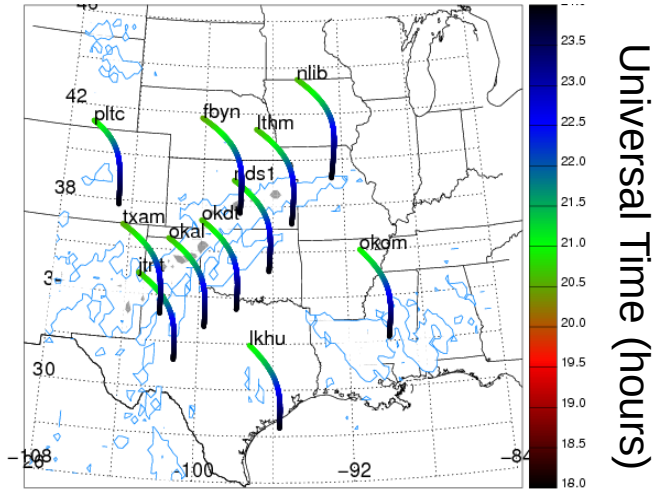


TEC Results (8/12/2005)

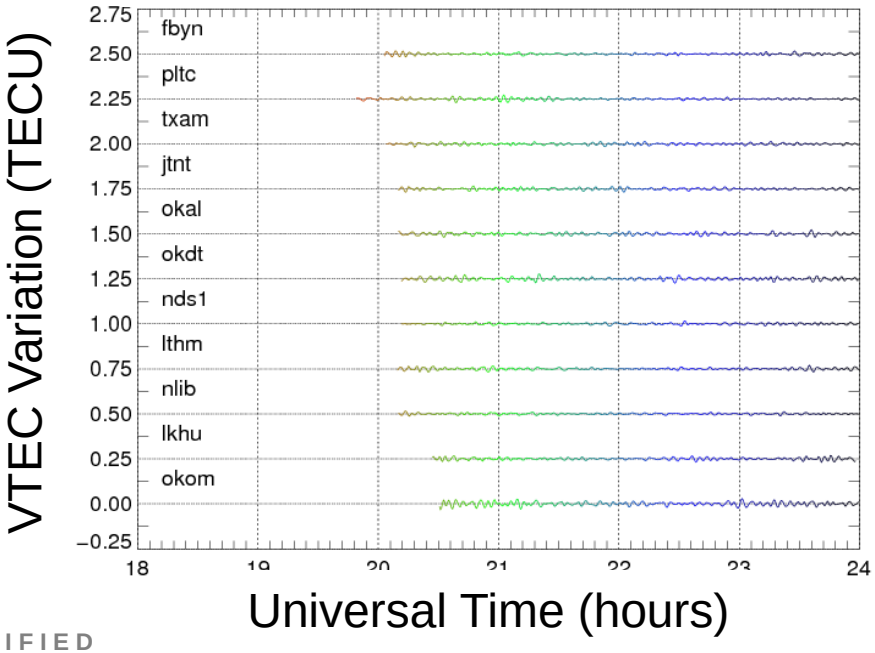
VTEC Variation from fitted curve (prn 13)



Map of Satellite Arcs (prn 13)

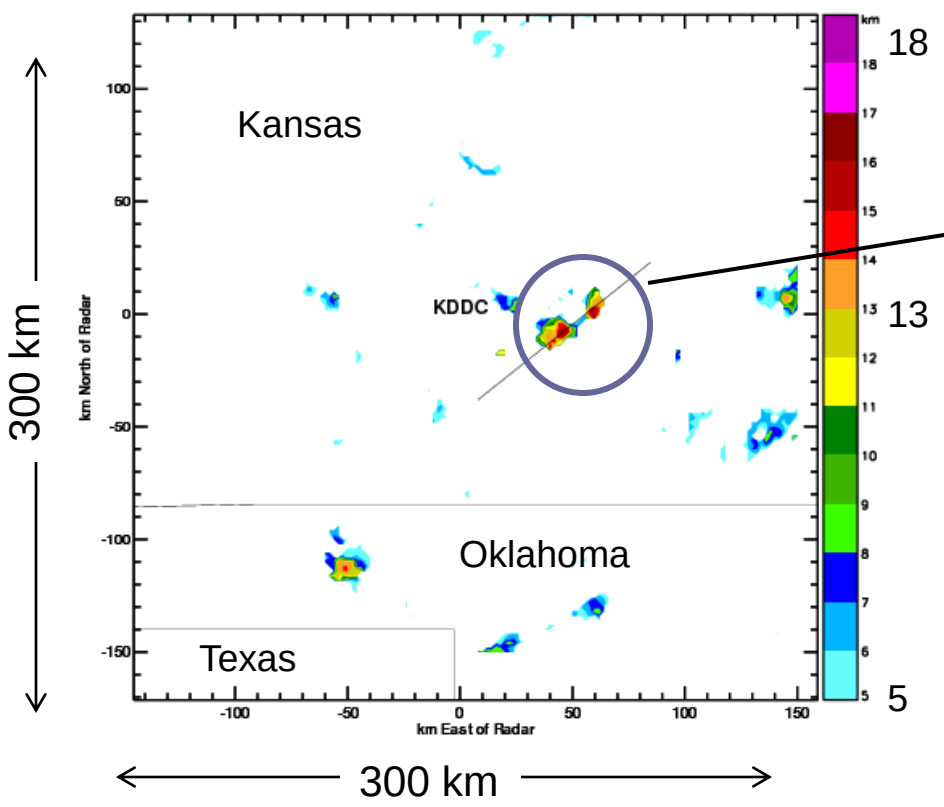


High Frequency Variation (prn 13)

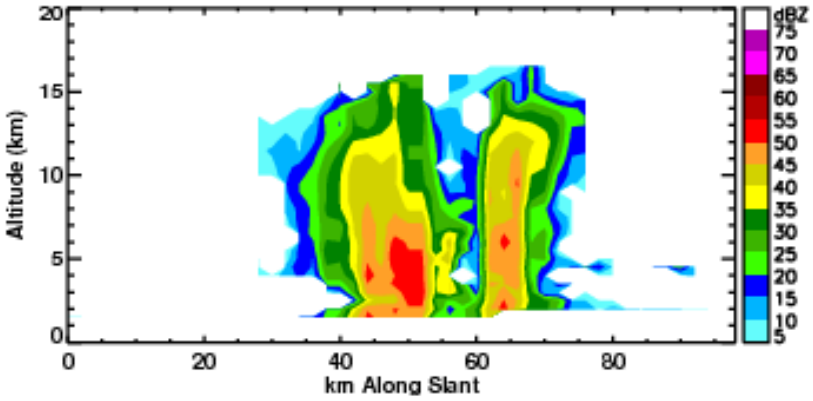


Meteorological Analysis (8/12/2005)

Dodge City NEXRAD 20:59-21:03 UT
Max Height > 30.0 dBZ



Reflectivity Along Slant

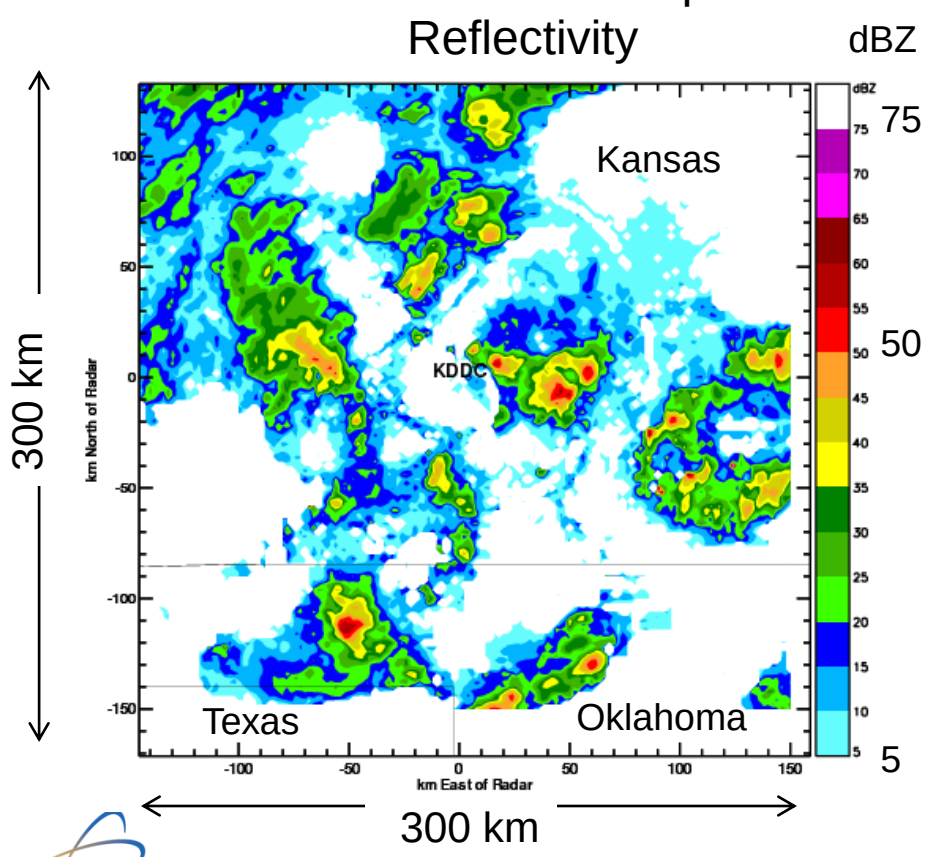


First timestamp with a 30 dBZ height of above 15 km (~21 UT)

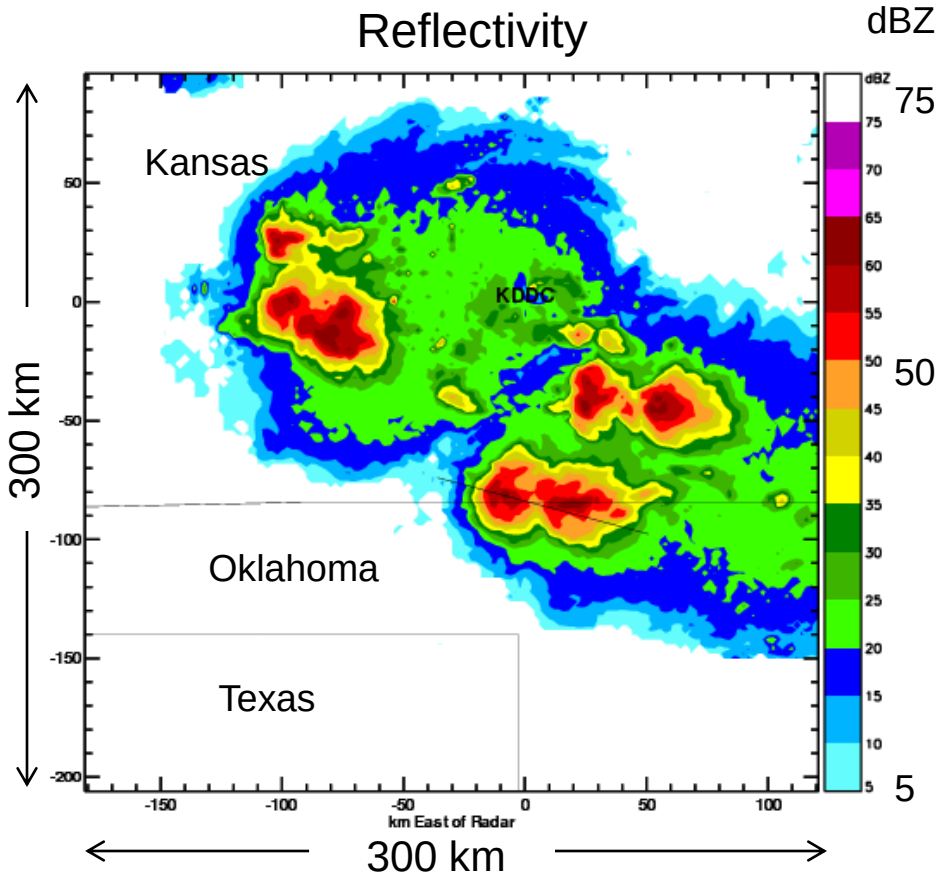
No clear start to gravity wave variation observed from the TEC results

Meteorological Analysis (8/12/2005)

Dodge City, KS NEXRAD (8/12/05)
20:59-21:03 UT Composite
Reflectivity



Dodge City, KS NEXRAD (6/16/05)
23:15-23:19 UT Composite
Reflectivity

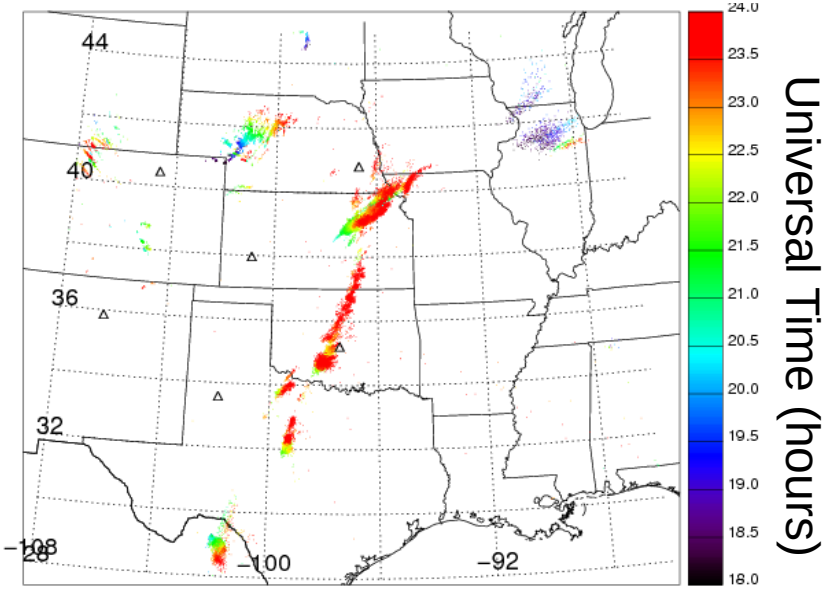


Take Away Points (8/12/2005)

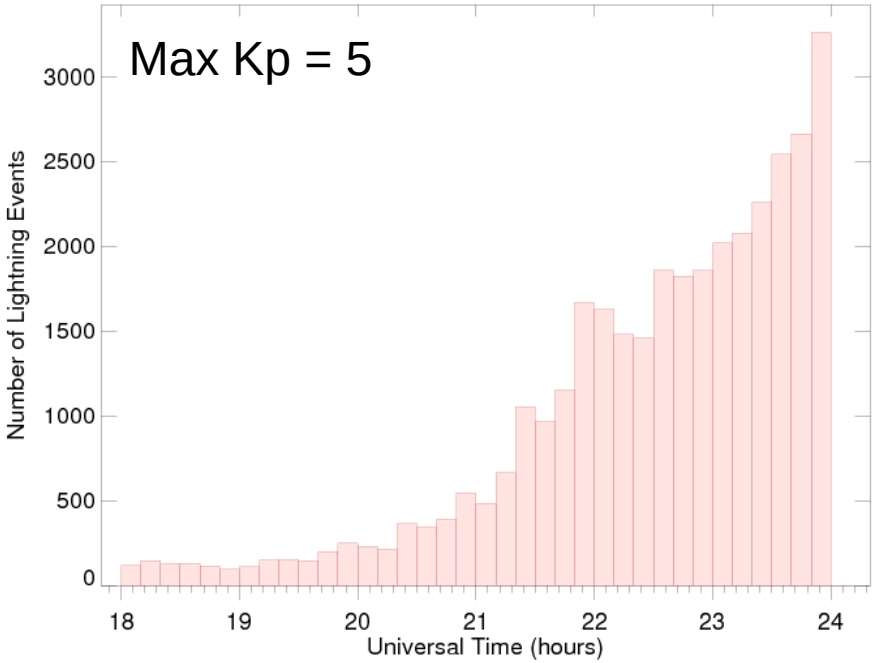
- Localized storm system with multiple small storm cells, no mesoscale convective system, no tornadoes were reported
- No high frequency TEC variation from acoustic waves observed over the storm system
- Limited gravity wave variation over the storm even though a few small thunderstorm cells briefly had 30 dBZ heights over 15 km from 18-24 UT
- Gravity waves were observed later for 1 hour on August 13, 2005 from 0-1 UT
- Mesoscale systems required for acoustic wave generation?

Lightning Data (6/04/2005)

Lightning Location Map



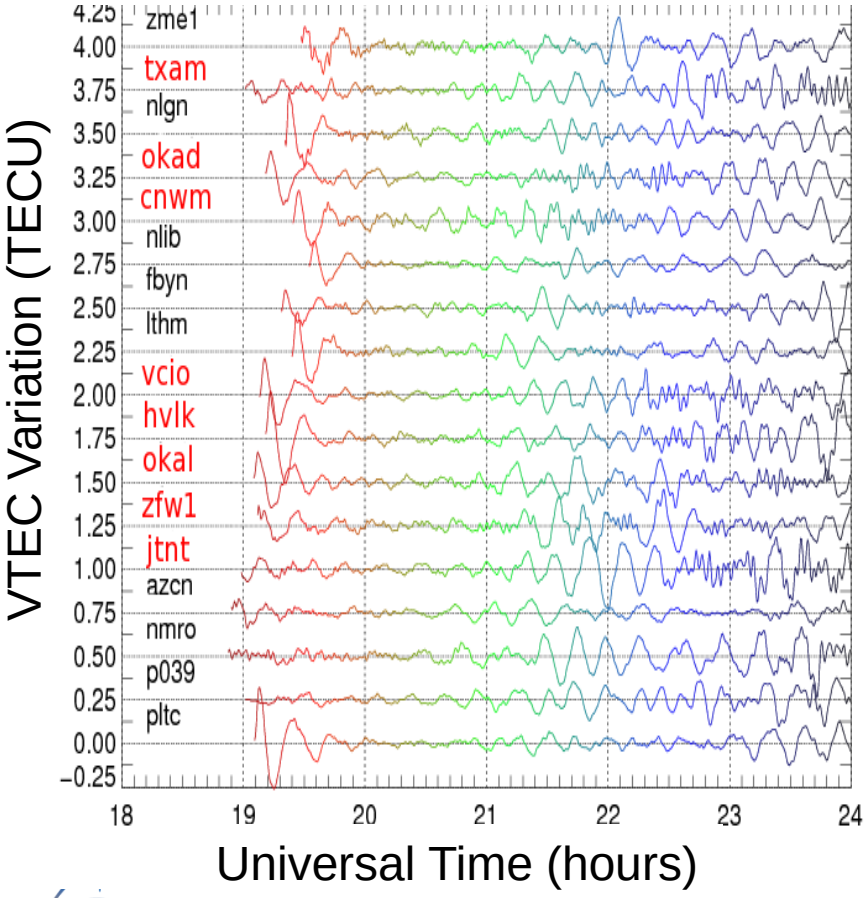
Histogram of Lightning Events



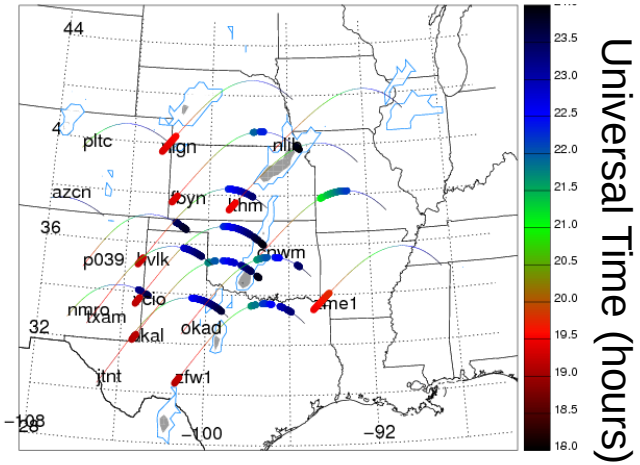
Widespread developing storm front with increasing lightning activity

TEC Results (6/04/2005)

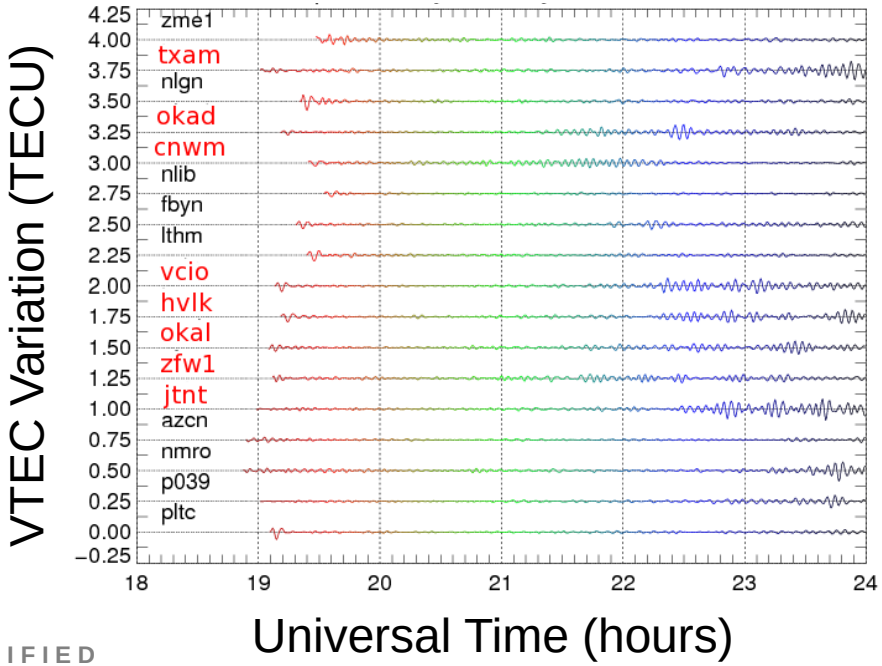
High Pass Filtered VTEC variation(prn 1)



Map of Satellite Arcs (prn 1)

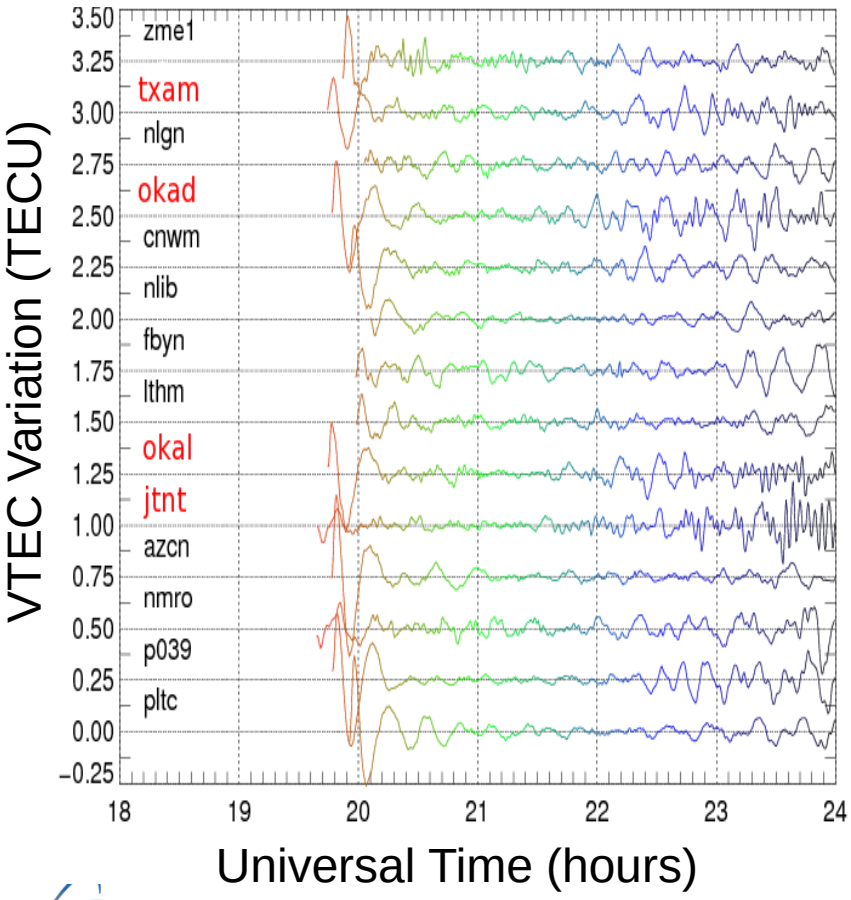


High Frequency Variation (prn 1)

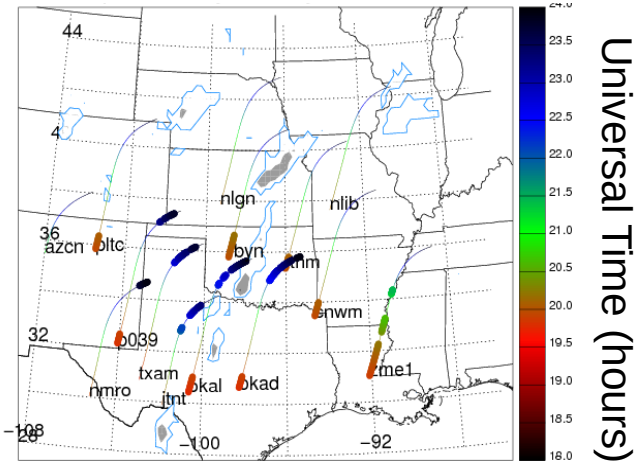


TEC Results (6/04/2005)

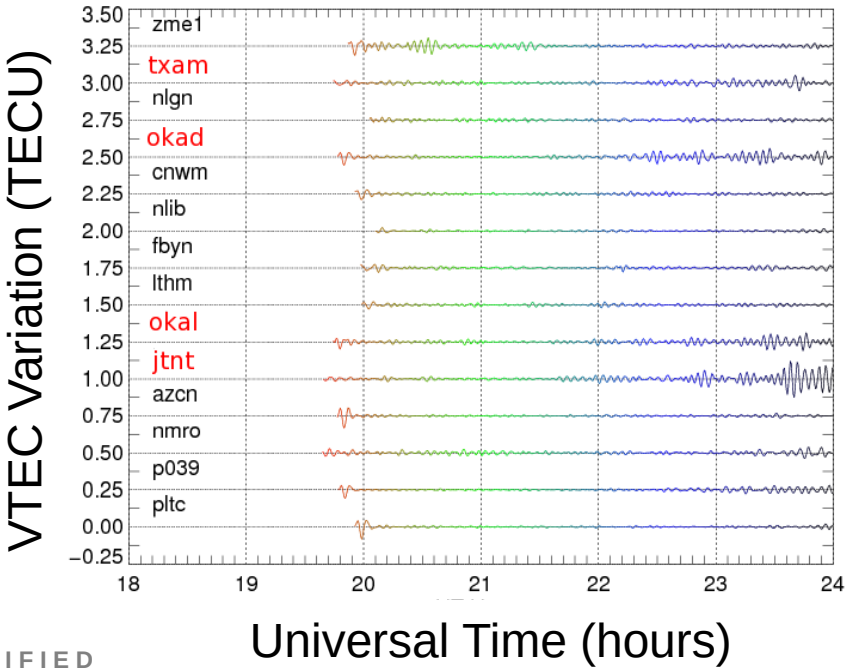
High Pass Filtered VTEC variation(prn 25)



Map of Satellite Arcs (prn 25)

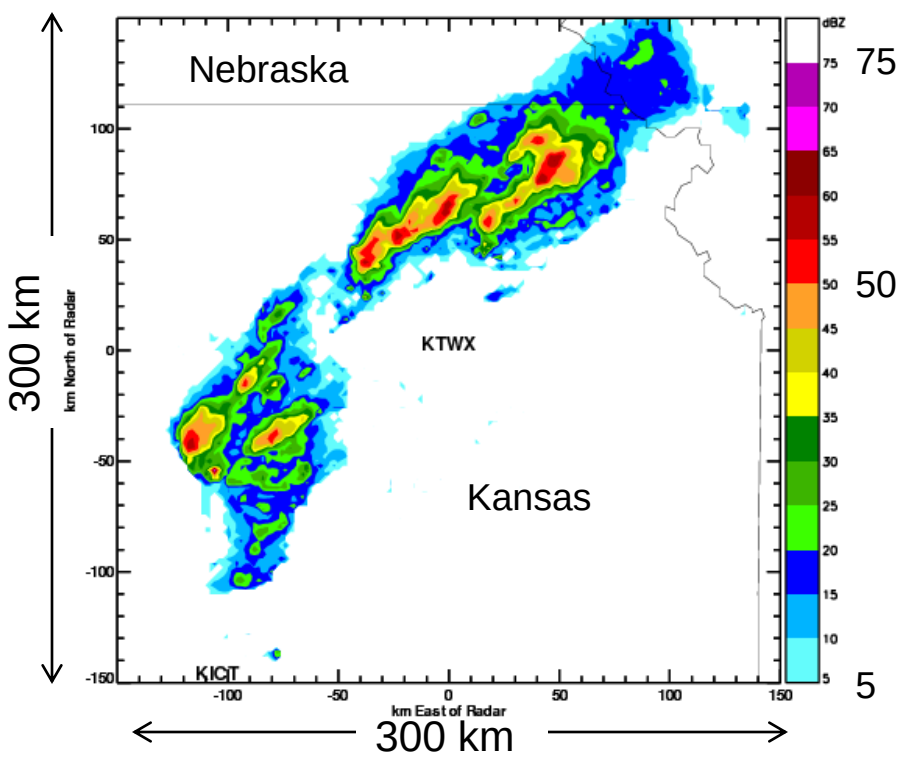


High Frequency Variation (prn 25)

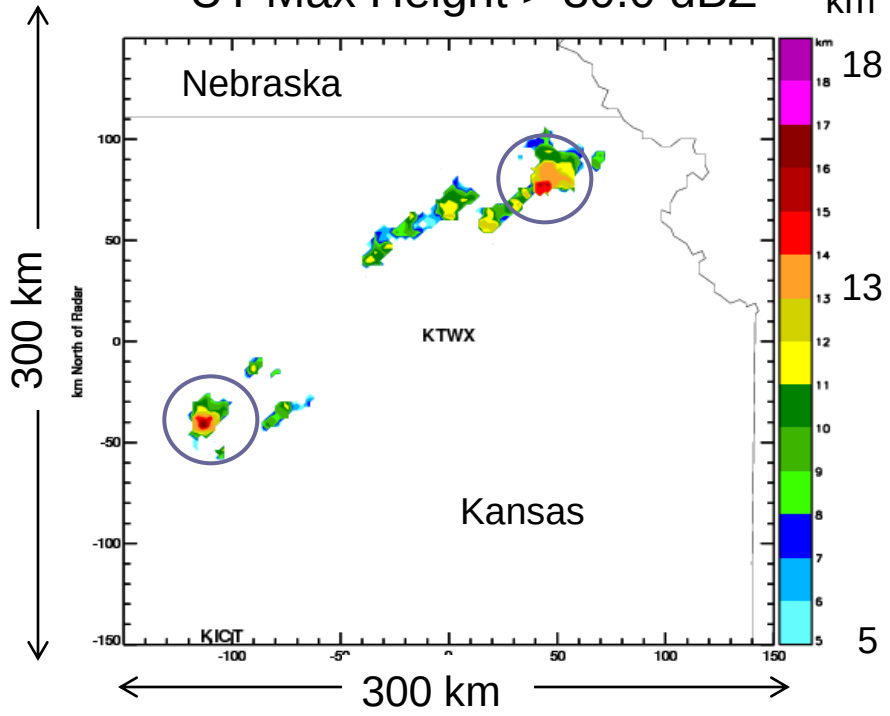


Meteorological Analysis (6/04/2005)

Topeka, KS NEXRAD (6/04/05) 20:47-20:52 UT Composite Reflectivity



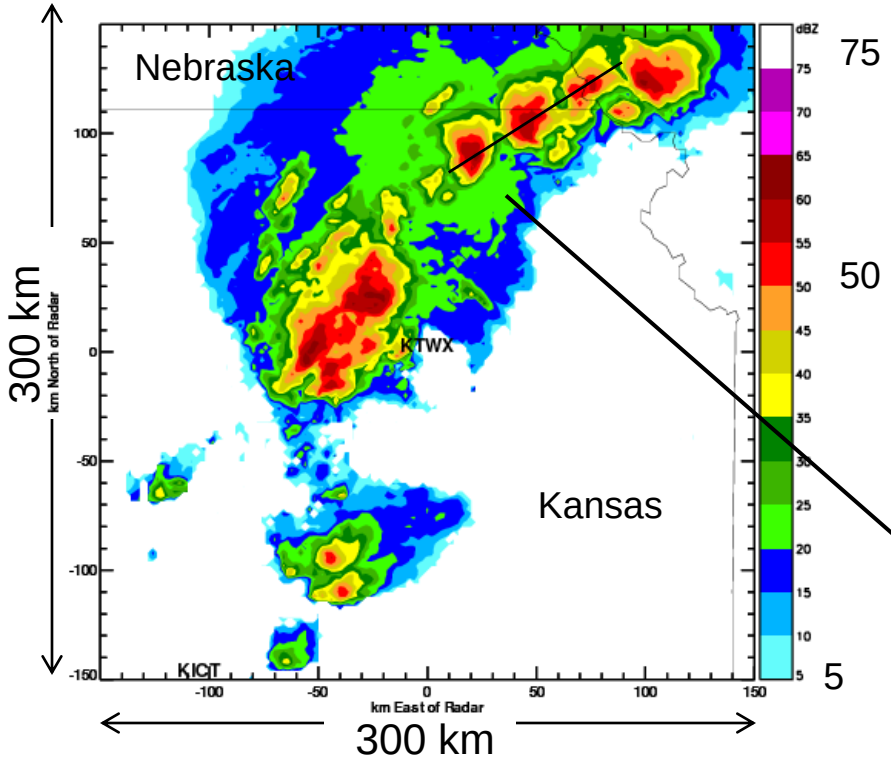
Topeka, KS NEXRAD 20:47-20:52 UT Max Height > 30.0 dBZ



First timestamp with storm tops above 15km (~20:50 UT)
GW TEC variation starts at about 21:10 UT
HF TEC variation starts at about 21:40 UT

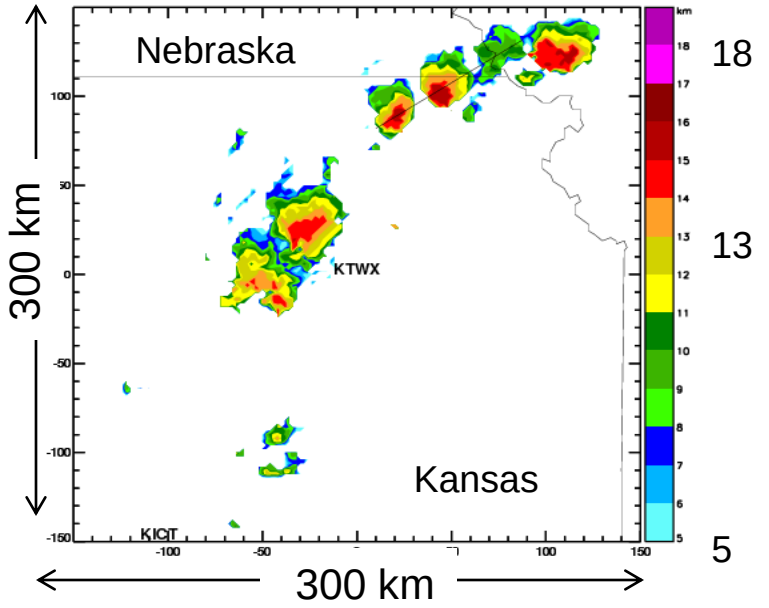
Meteorological Analysis (6/04/2005)

Topeka, KS NEXRAD (6/04/05) 22:22-22:26 UT Composite Reflectivity dBZ

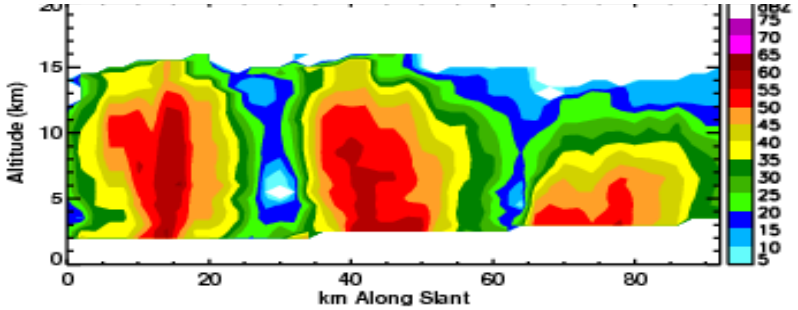


More drastic HF variation at 22:20-22:30 UT

Topeka, KS NEXRAD 22:22-22:26 UT Max Height > 30.0 dBZ

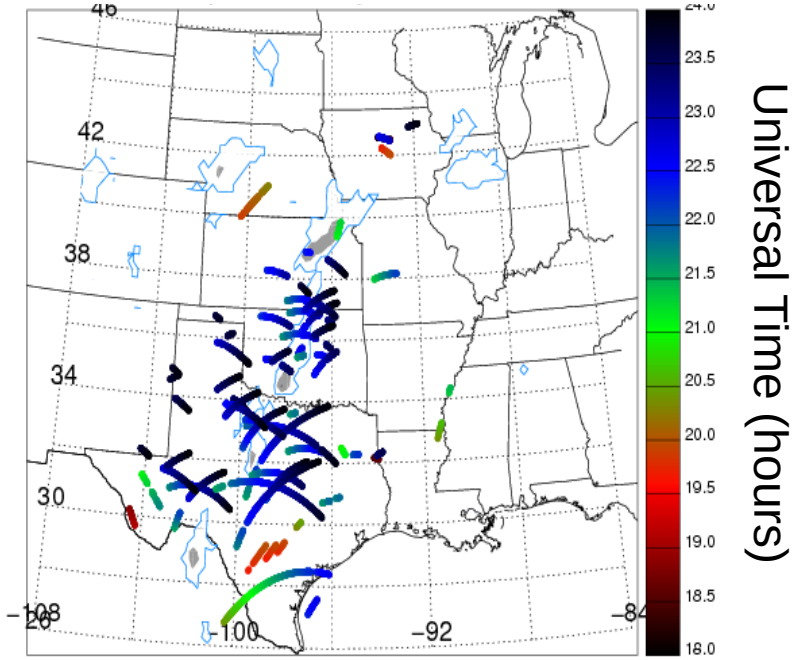


Reflectivity Along Slant



Take Away Points (6/04/2005)

Total HF variation over all satellites and numerous stations

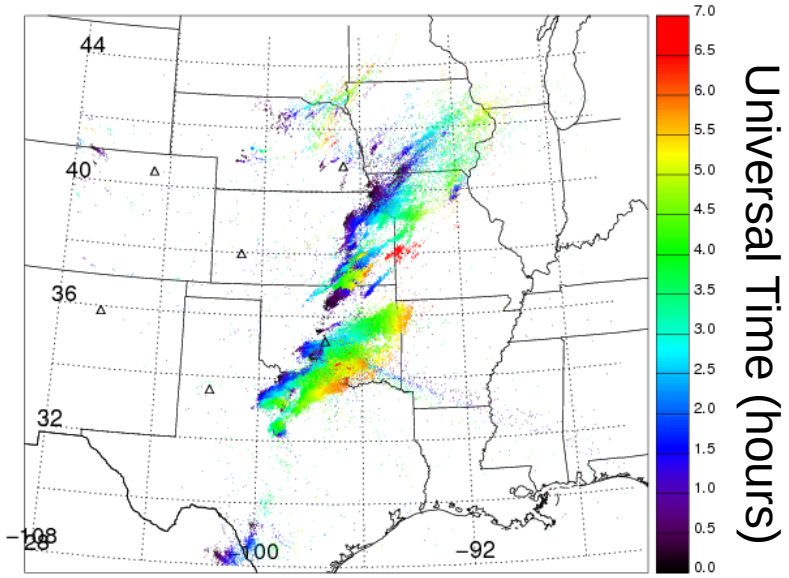


- **5 tornadoes active in NE Kansas and NW Missouri**
- **Multiple storm tops above 15 km for a long duration**
- **Both gravity waves and acoustic waves visible in TEC variation data**
- **Most of the variation concentrated over N Oklahoma and N Texas**

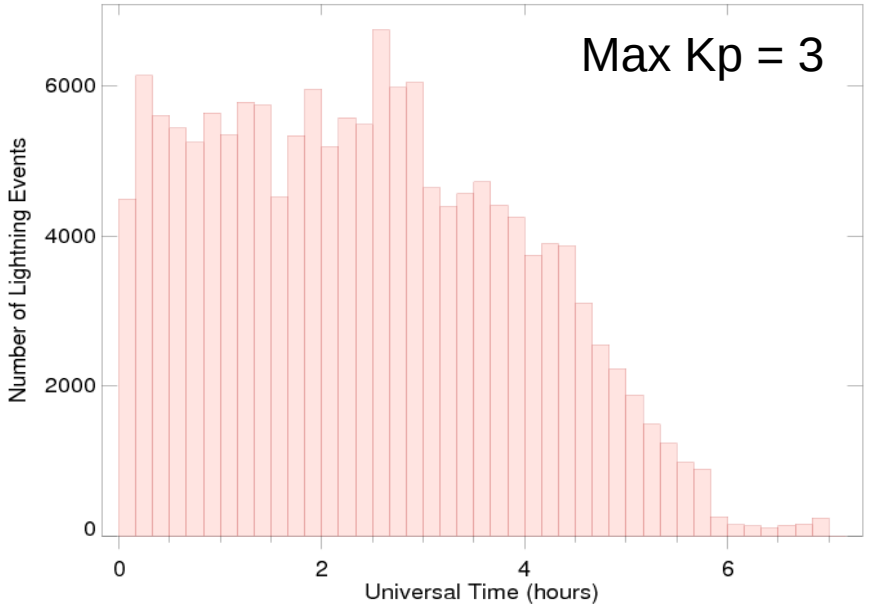
Lightning Data (6/05/2005)

Continuation of 6/04/2005 Storm into the night

Lightning Location Map



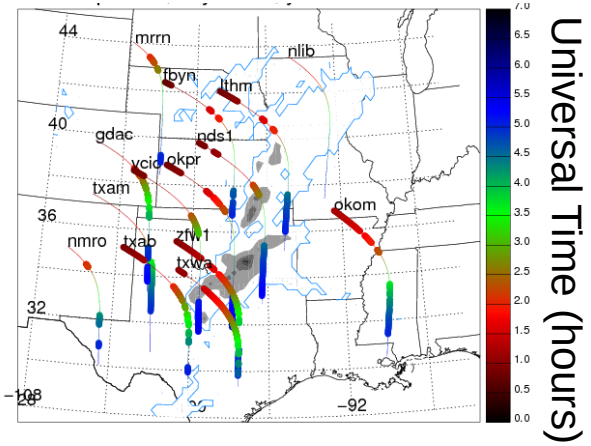
Histogram of Lightning Events



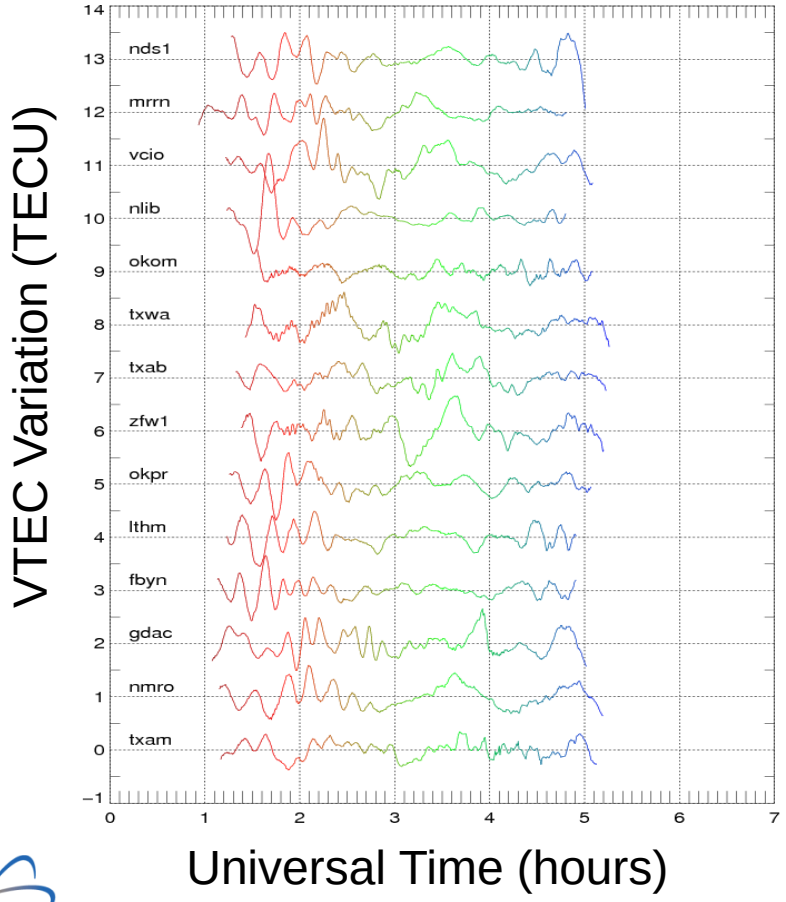
- Large developed and electrically active storm front with active tornadoes in northern Texas
- 0-7 UT is 19-2 CDT (7 PM – 2 AM)

TEC Results (6/05/2005)

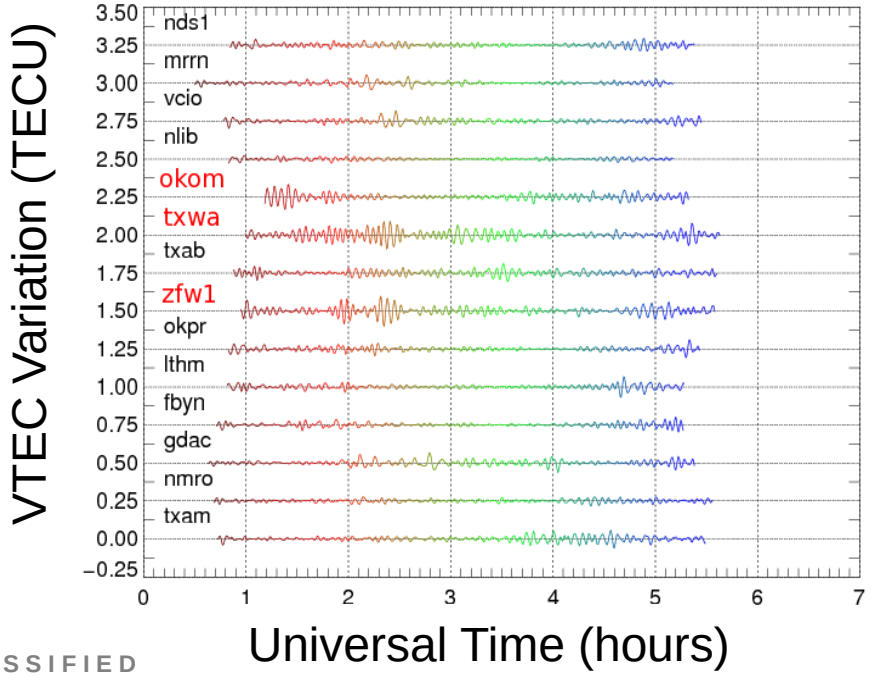
Map of Satellite Arcs (prn 13)



VTEC variation from fitted curve (prn 13)

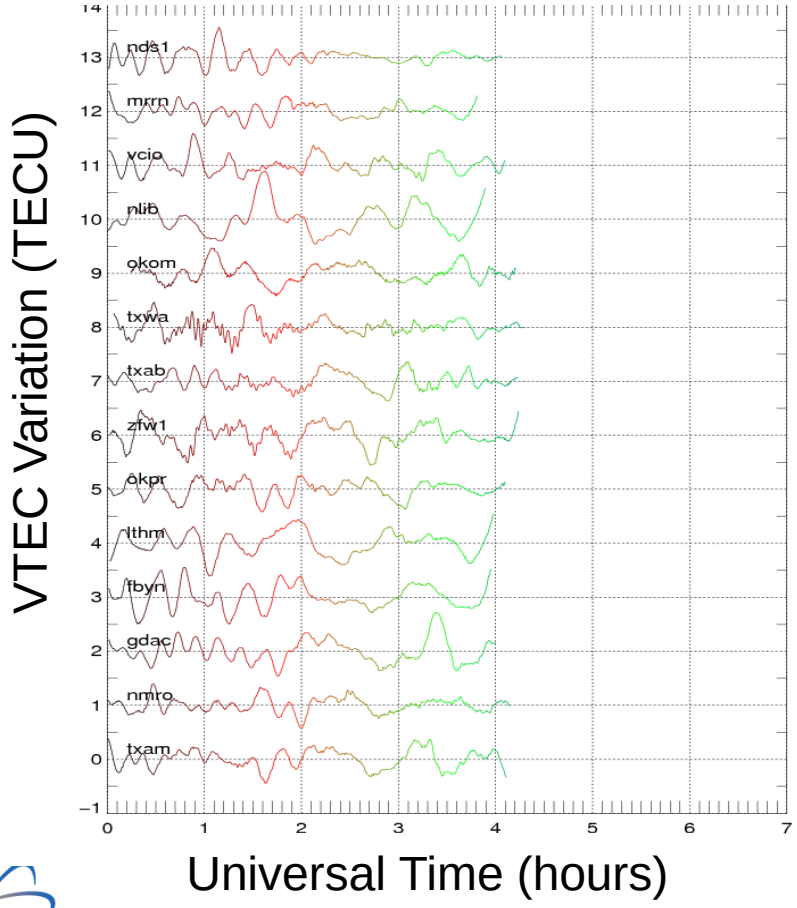


High Frequency Variation (prn 13)

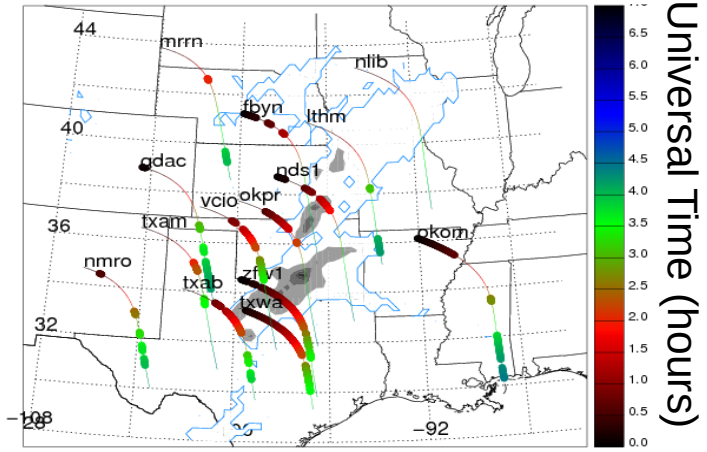


TEC Results (6/05/2005)

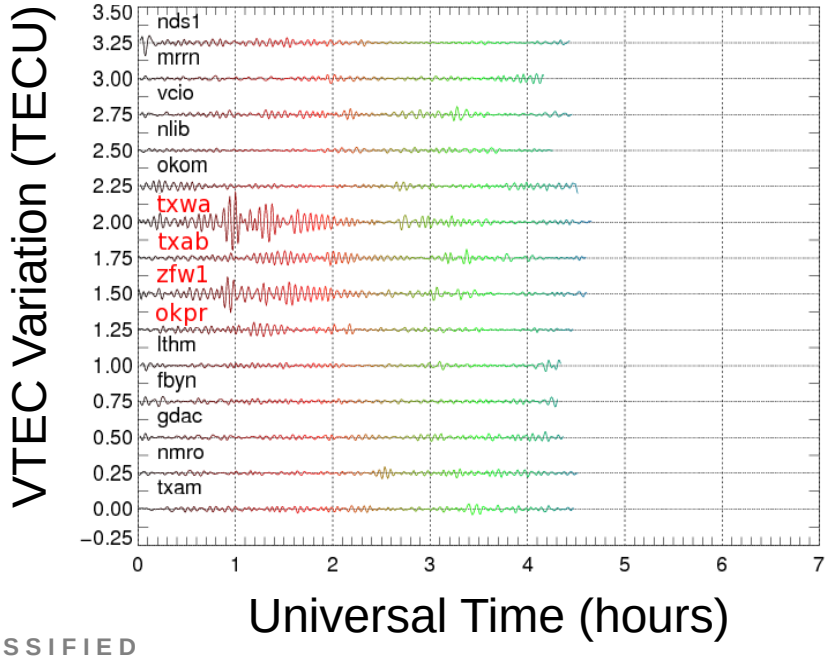
VTEC variation from fitted curve (prn 23)



Map of Satellite Arcs (prn 23)

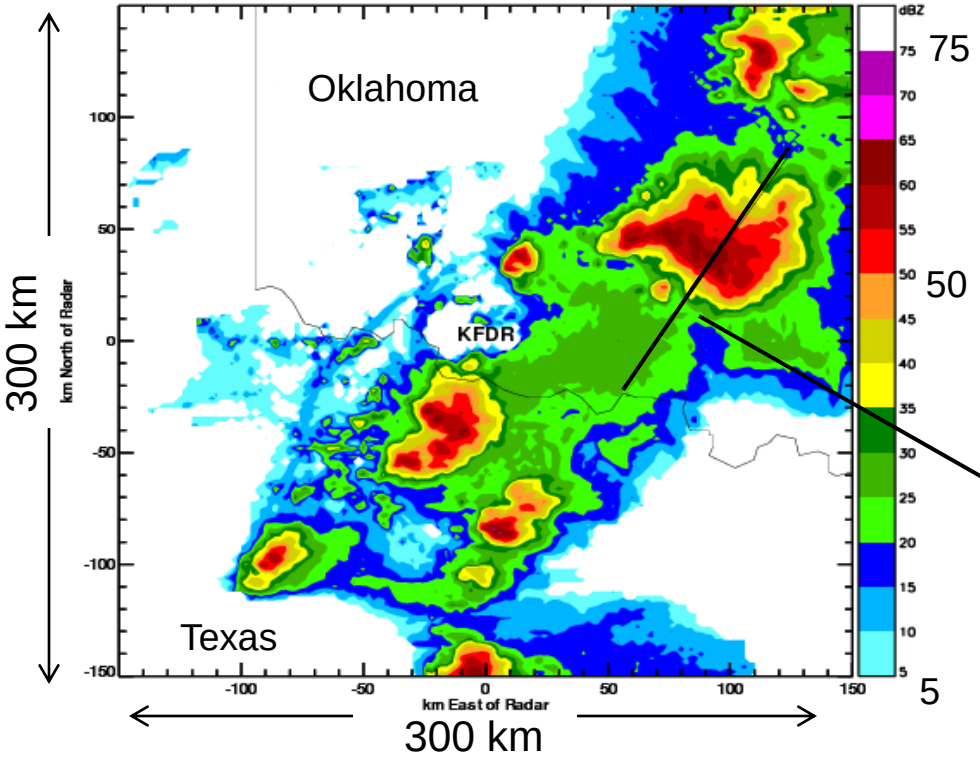


High Frequency Variation (prn 23)

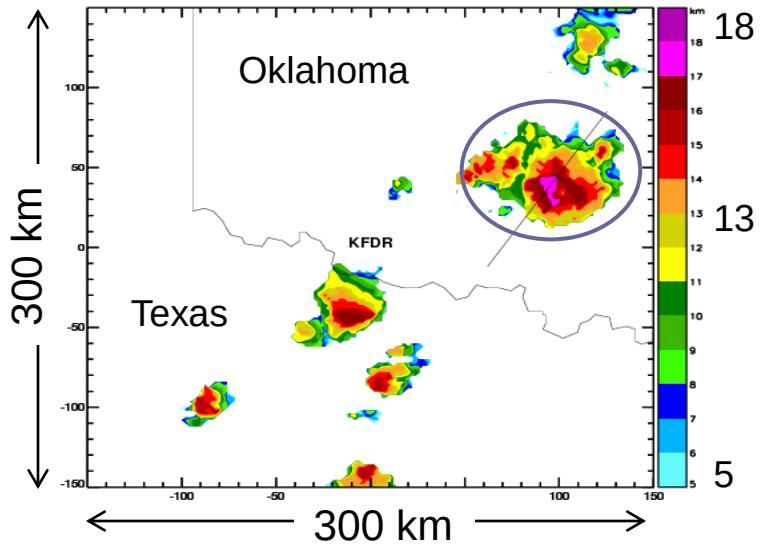


Meteorological Analysis (6/05/2005)

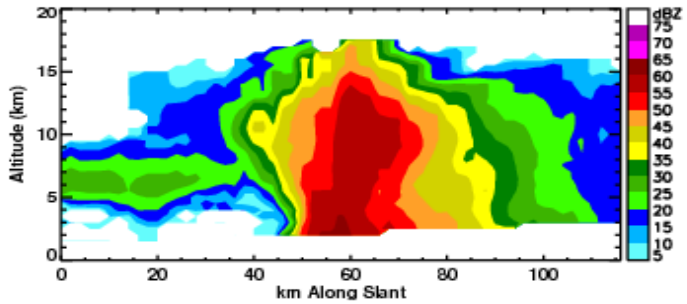
Frederick, OK NEXRAD (6/05/05) 00:02-00:06 UT Composite Reflectivity dBZ



Frederick, OK NEXRAD 00:02-00:06 UT Max Height > 30.0 dBZ



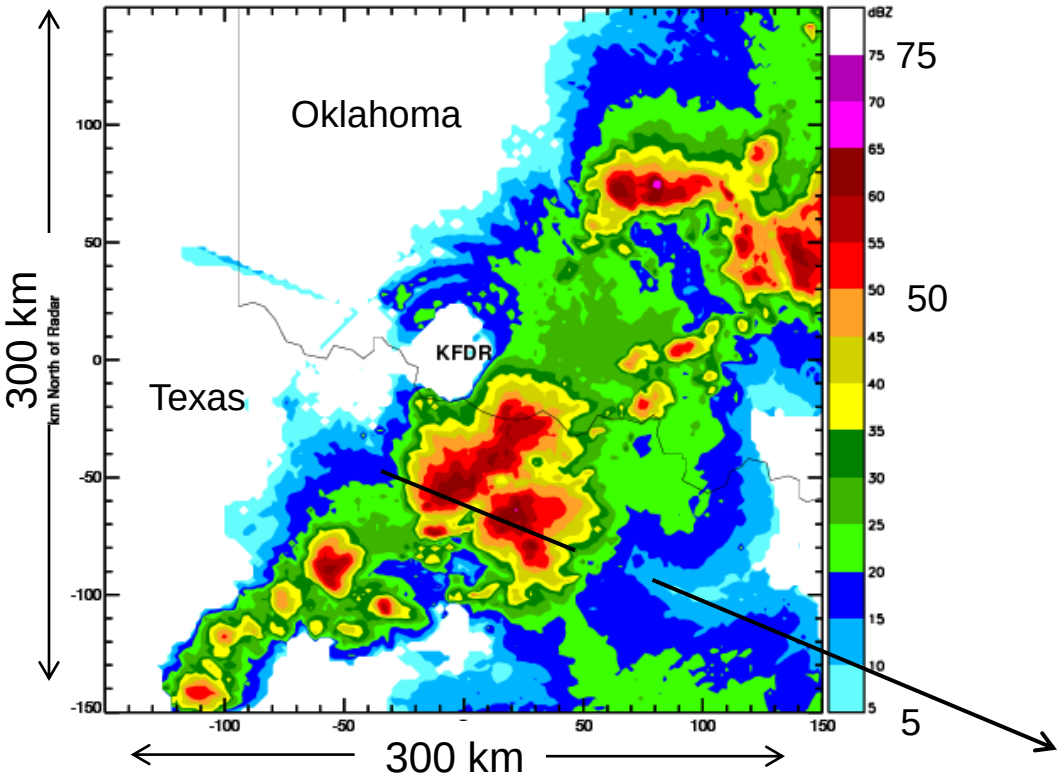
Reflectivity Along Slant



Multiple cells above 15km, both GW and HF variation present at the start of 0 UT

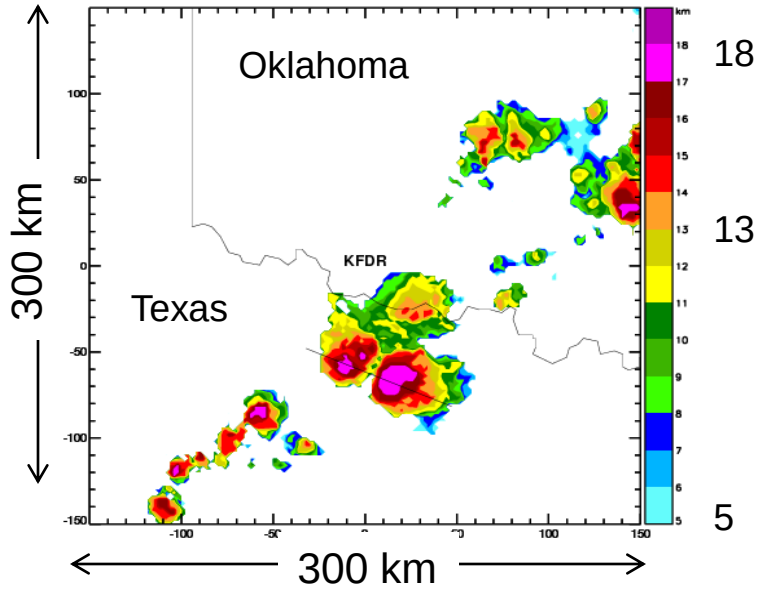
Meteorological Analysis (6/05/2005)

Frederick, OK NEXRAD (6/05/05) 00:54-00:58 UT Composite Reflectivity

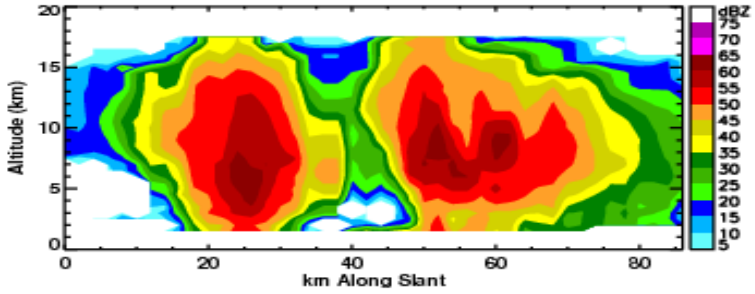


Larger magnitude HF variation at 00:50 UT

Frederick, OK NEXRAD 00:54-00:58 UT Max Height > 30.0 dBZ

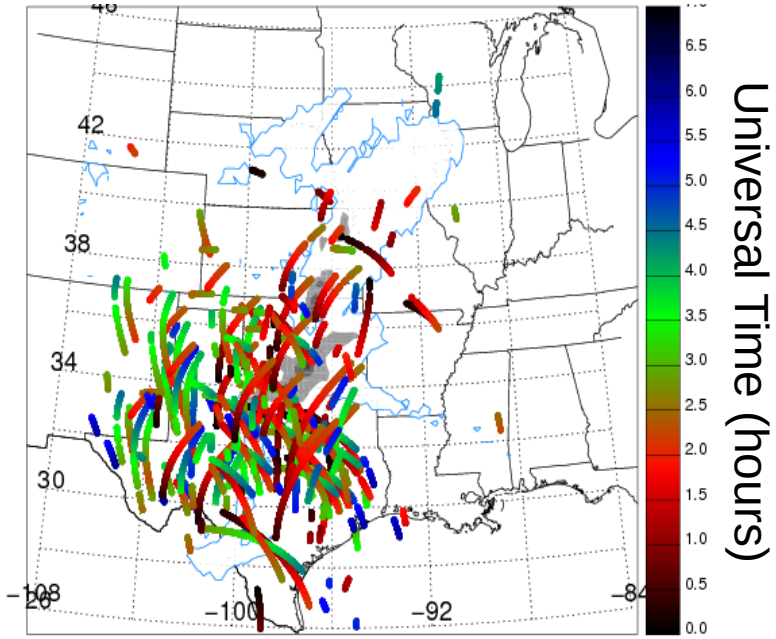


Reflectivity Along Slant



Take Away Points (6/05/2005)

Total HF variation over all satellites and numerous stations



- **Most widespread HF variation observed so far**
- **11 tornadoes reported in Texas and Oklahoma from 0-4 UT**
- **Many large storm cells significantly above 15 km**
- **Both gravity waves and acoustic waves are observed as TEC variations**

Event Statistics

Event Classification	May	June	July	August
No Event	4	0	0	0
GW Only	9	0	1	2
HF Only	1	0	0	0
Both	2	7	2	0
Total	16	7	3	2

- Atmospheric conditions in June/July could be potentially more favorable for acoustic wave propagation but more June/July events need to be investigated
- Significant storm systems in May did not show as well defined HF acoustic wave variation when compared to HF events in June and July
- Most HF variation in May appears to be more transient, less periodic and different in shape than the June/July HF variation

Conclusions

- After studying multiple storm systems and quiet days, it is clear that increased acoustic wave and gravity wave activity is associated with thunderstorms, although coupling mechanisms remain unclear
- HF TEC variations from acoustic waves appear to require mesoscale convective storm systems suggesting sprites may play a role in HF TEC variations
- Tornadoes are generally active though not always when HF TEC variations are observed
- Lower frequency TEC variations from gravity waves are observed often when there is a large volume of the storm system at significant heights
- Localized storm systems do not generate significant HF TEC variations though lower frequency gravity wave variations may be present
- Verified model predictions of detectable TEC variations from gravity waves

Acknowledgements

- **Tim Hamlin**
- **Erin Lay**
- **Xuan Min-Shao**

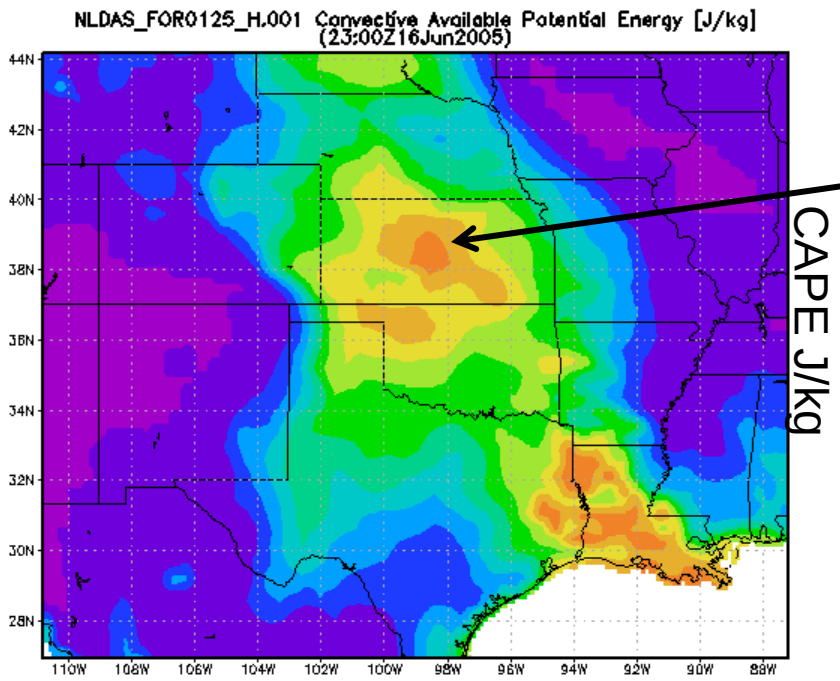
Questions?

Abstract

Solar and geomagnetic activity are considered to be the main drivers of ionospheric variation, but recent findings have suggested that tropospheric weather could also have a significant effect in terms of tides, generation of atmospheric gravity waves, and seeding of spread-F. A recent study has shown anomalous TEC fluctuations nearby large mesoscale thunderstorms in the U.S. Great Plains [Lay et al., GRL 2013]. In this study, we examine additional GPS TEC data from the Continuously Operating Reference Station (CORS) network during the summer of 2005 to further analyze the connection between TEC variations and thunderstorms in the Great Plains. We use Next-Generation Radar (NEXRAD) and additional data from NOAA to provide meteorological context for the events identified with TEC variations. Currently various coupling mechanisms between mesoscale thunderstorms and the ionosphere are being investigated as we attempt to correlate various meteorological phenomena to the generation of high frequency (3-5 mHz) TEC variations. Local storm systems in the New Mexico area were also investigated for TEC variations using a GPS receiver located at LANL. No significant variation was detected above these storms suggesting mesoscale convective systems are necessary for coupling to the ionosphere. We used the Los Alamos Sferic Array (LASA) and the World Wide Lightning Location Network (WWLLN) as an indicator of nearby thunderstorm activities.

Appendix:
Convective Available Potential Energy (CAPE)

NLDAS-1 CAPE 050616 23:00 UT



Updraft Velocity Approximation:

$Wmax = (2*CAPE)^{1/2}$

$Wmax = (2*4000)^{1/2}$

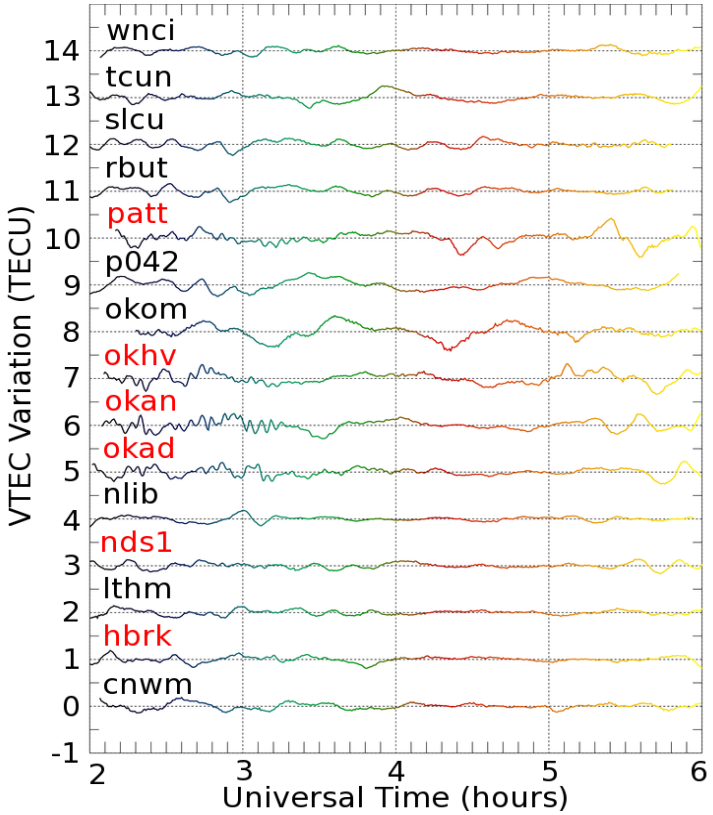
$Wmax = 89.44$ m/s

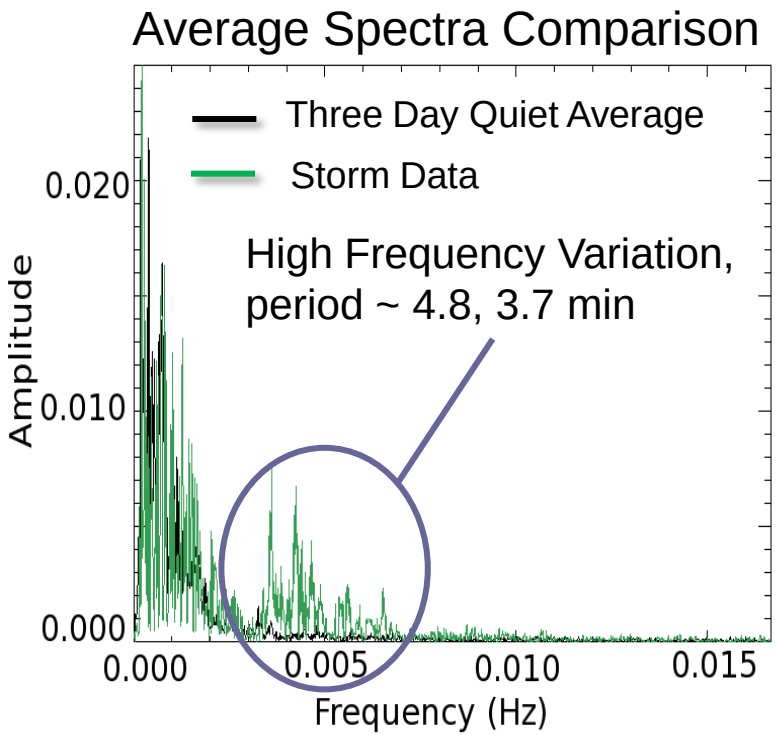
Allowing an overestimate of a factor of 2:

$Wmax = 44.72$ m/s

Appendix:
Average Spectra Comparison (7/04/2005)

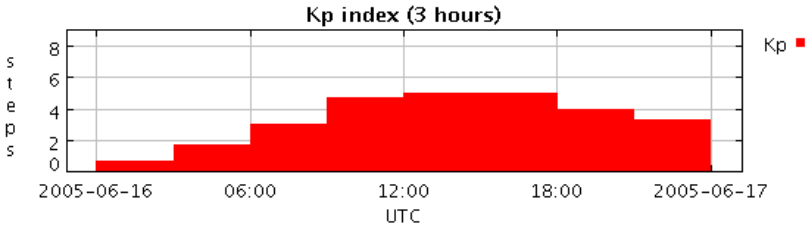
VTEC variation from fitted curve (prn 8)



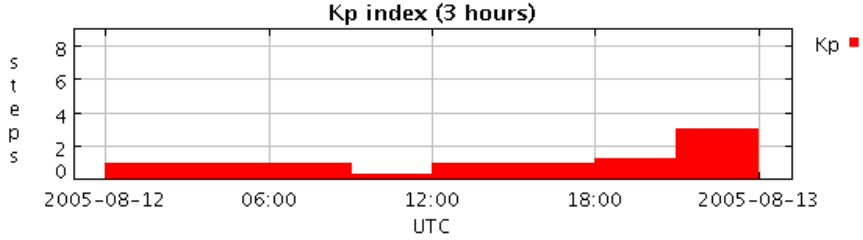


Appendix:
Kp Index Plots

050616



050812



050604-050605