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Title: Ionospheric effects of thunderstorms and lightning

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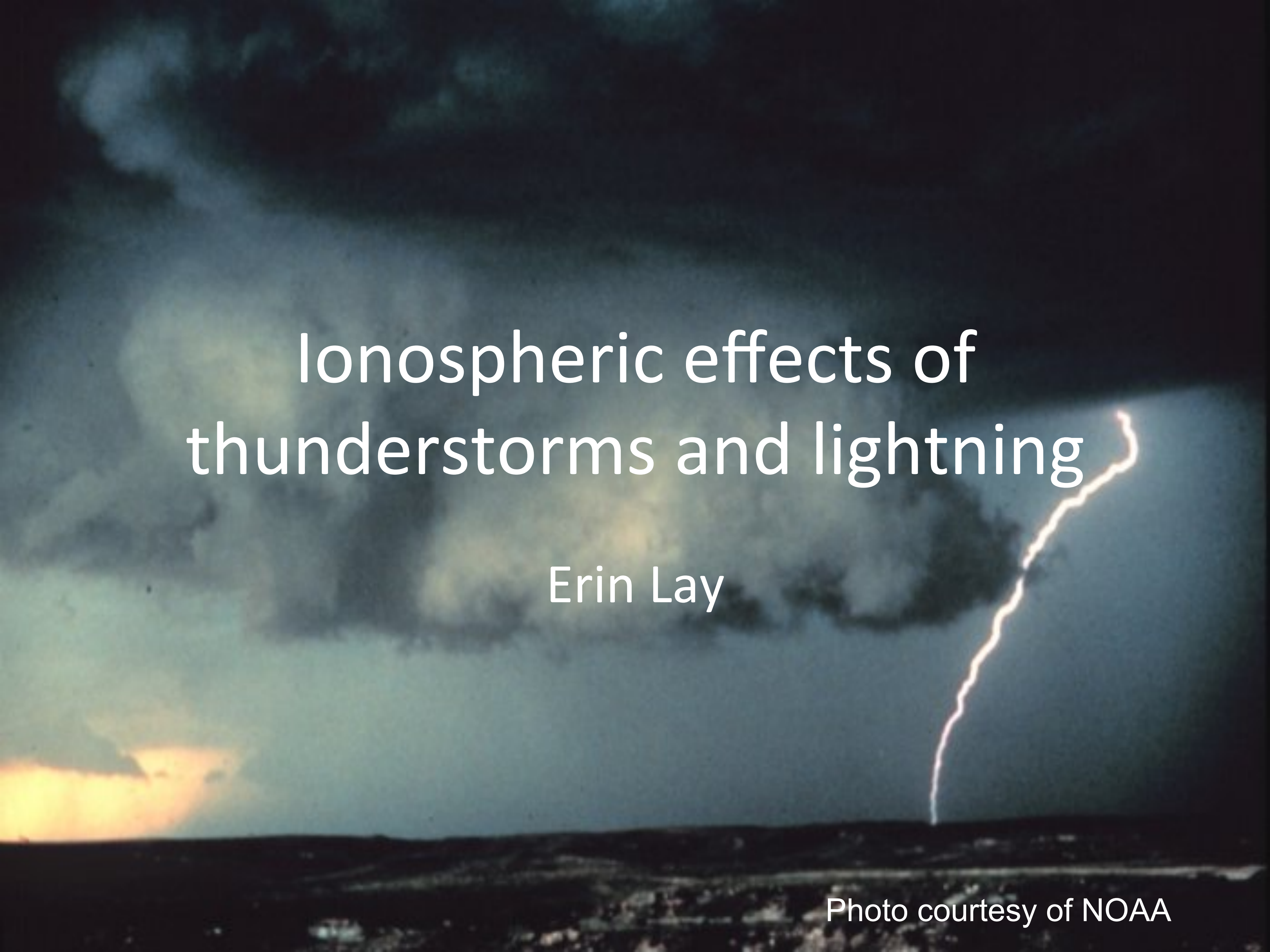


Ionospheric effects of thunderstorms and lightning

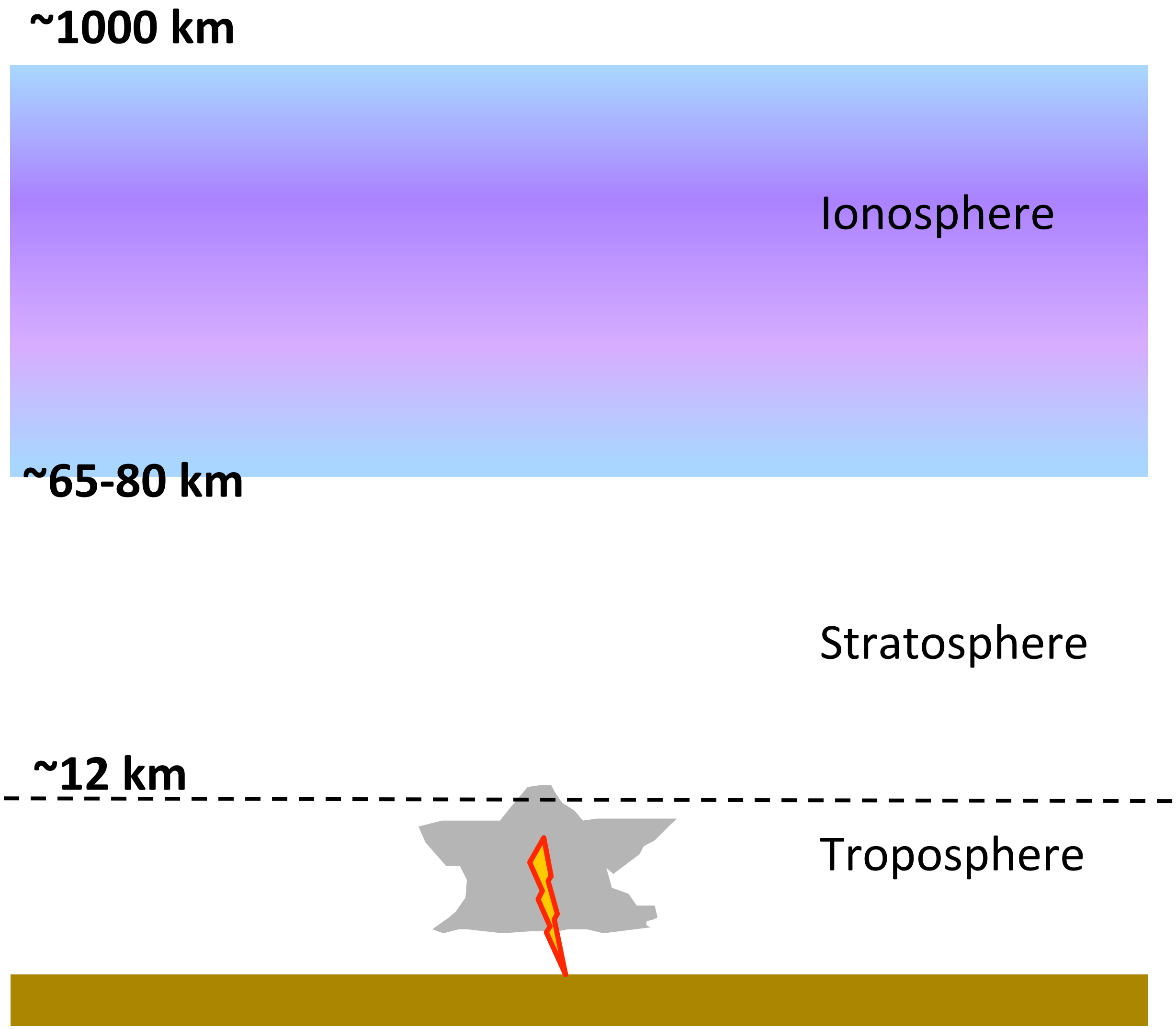
Erin Lay

Photo courtesy of NOAA

Outline

1. Background, science questions
2. D-region (65-90 km)
    a. LF/VLF probing technique
    b. Results
        1. D-region: Atmospheric gravity waves nearby large mesoscale storms
        2. D-region: Electrical effects nearby and above thunderstorms
    c. D-region Conclusions
3. F-region (200-400 km)
    a. GPS technique
    b. Results: Ionospheric acoustic wave variations near thunderstorms
    c. F-region Conclusions
4. Questions remaining / Future Work

Background



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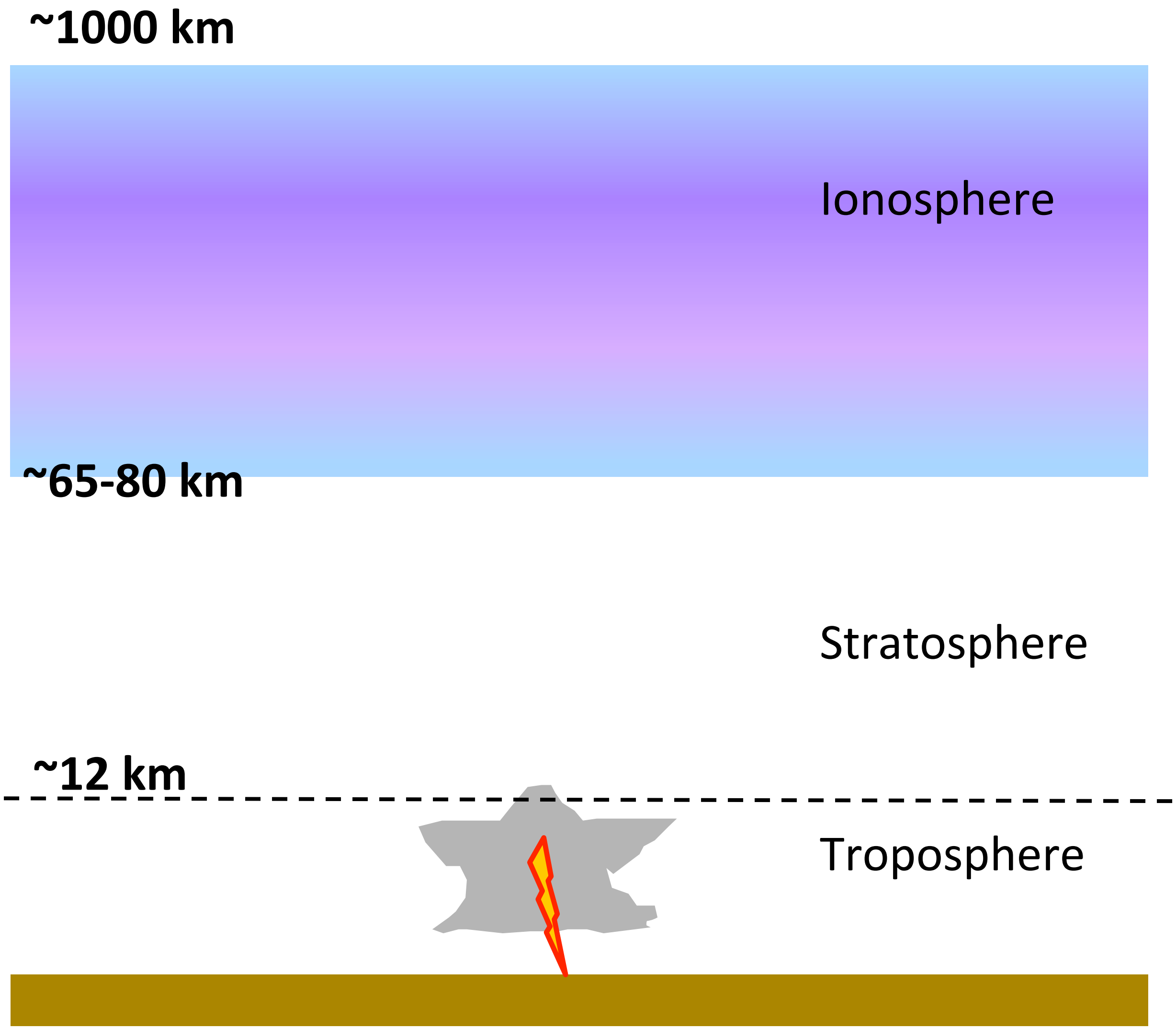
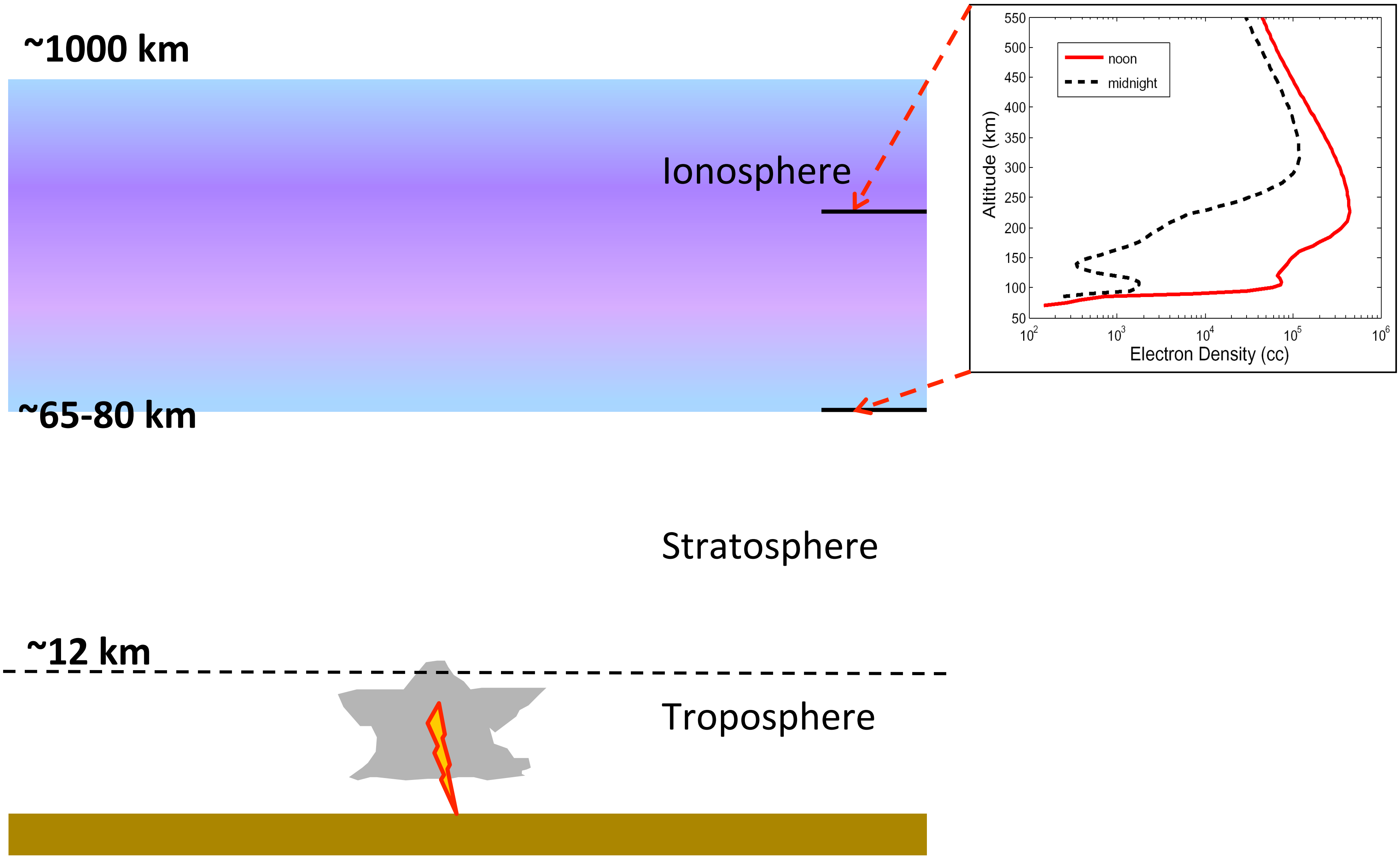
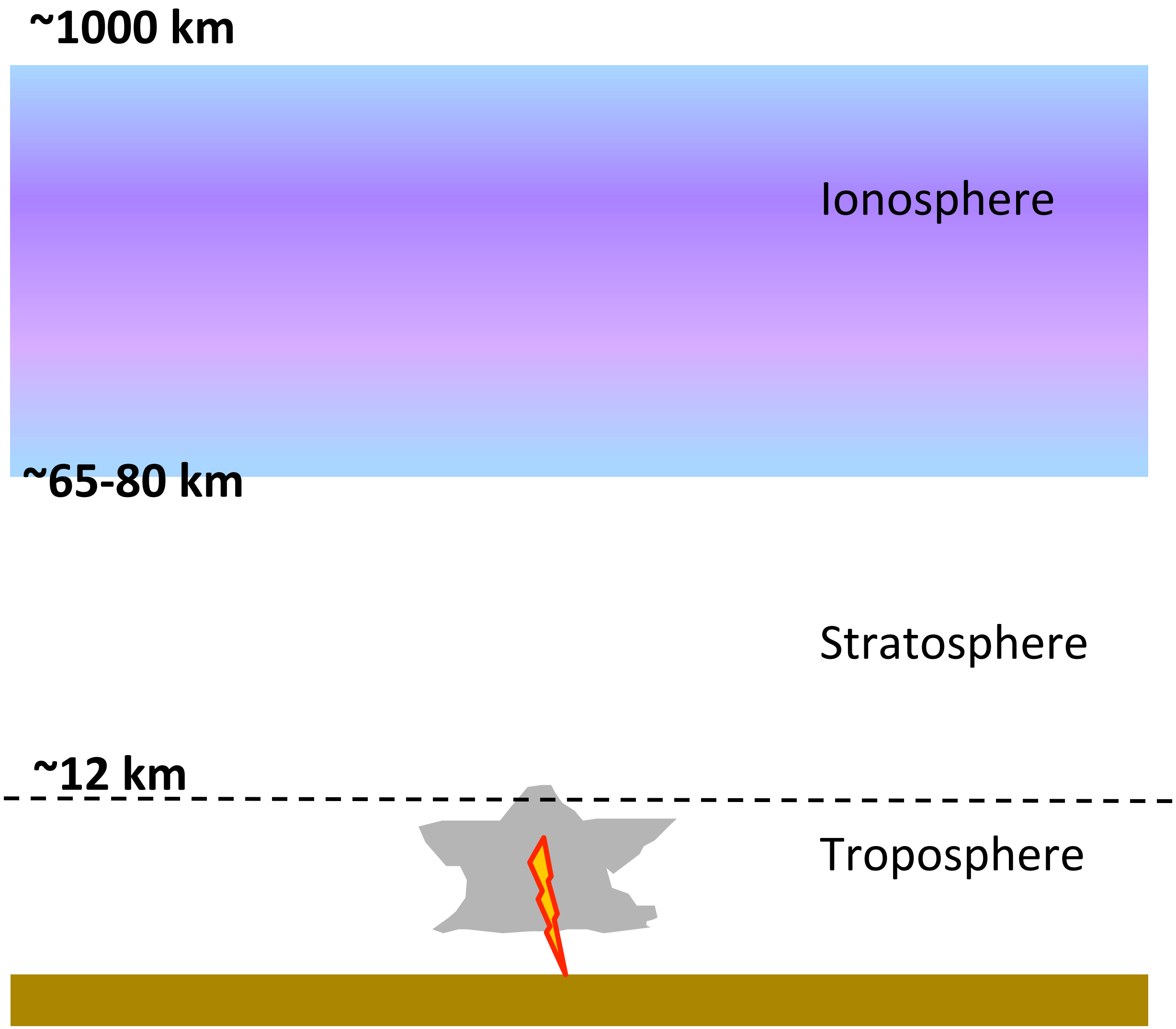


- Solar radiation ionizes atmosphere

Background

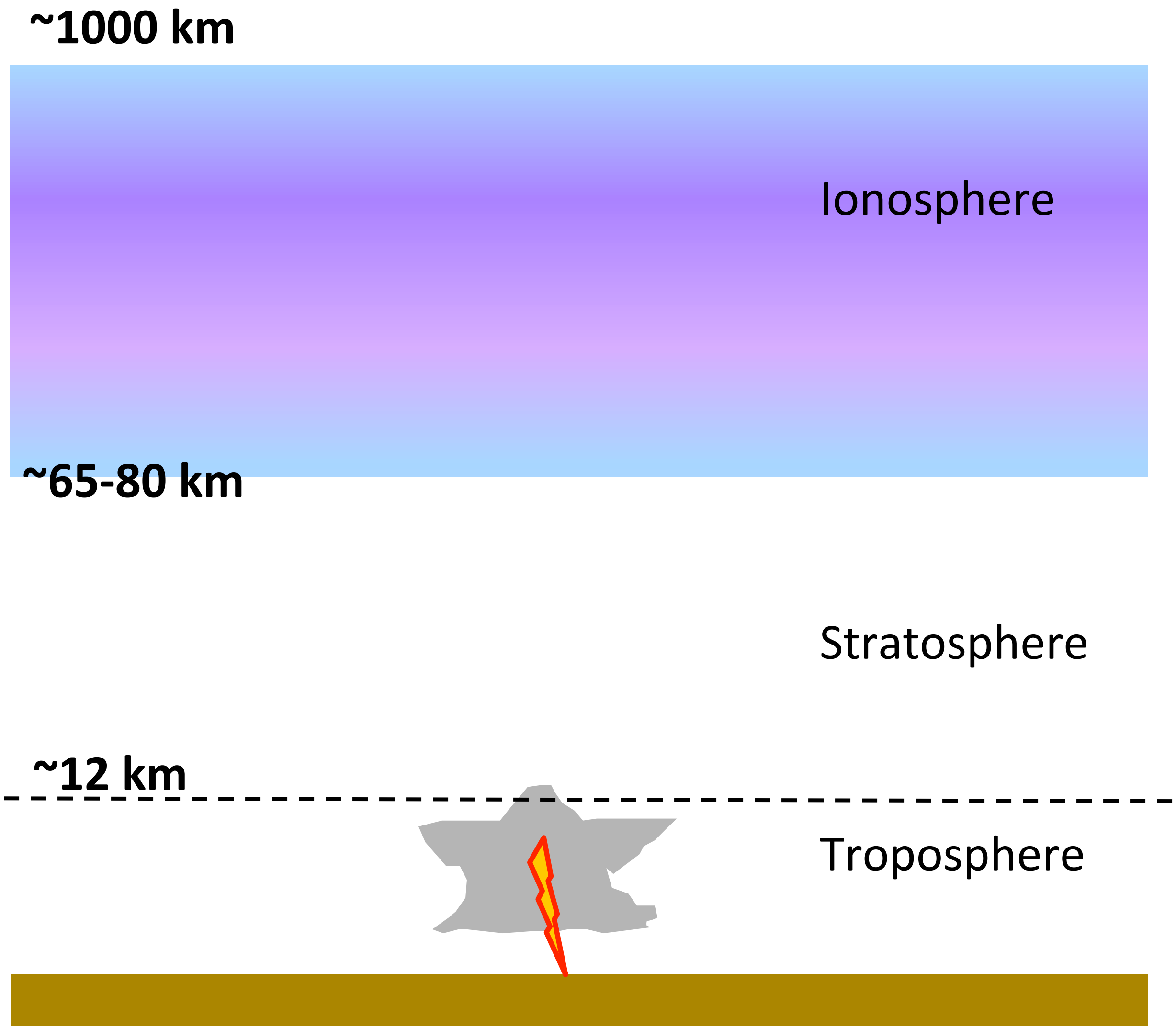

~1000 km
Ionosphere
~65-80 km
Stratosphere
~12 km
Troposphere
noon
midnight
Altitude (km)
Electron Density (cc)
550
500
450
400
350
300
250
200
150
100
50
10^2
10^3
10^4
10^5
10^6

Background



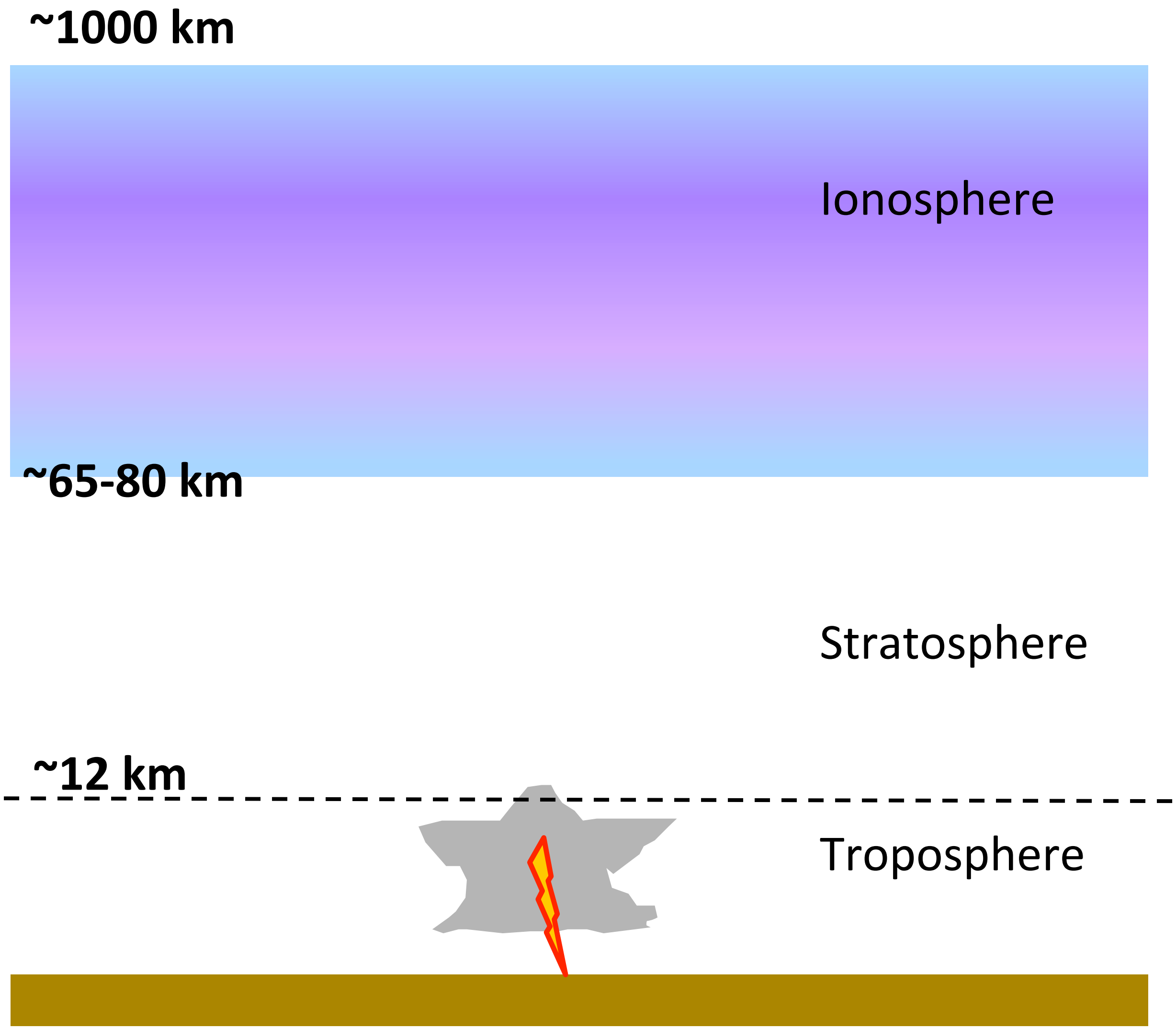
- Solar radiation ionizes atmosphere
- Affects EM wave propagation
- Large variations can affect communication and navigation.

Background



- Neutrals
- Some positively and negatively charged molecules
- Intermediate region

Background

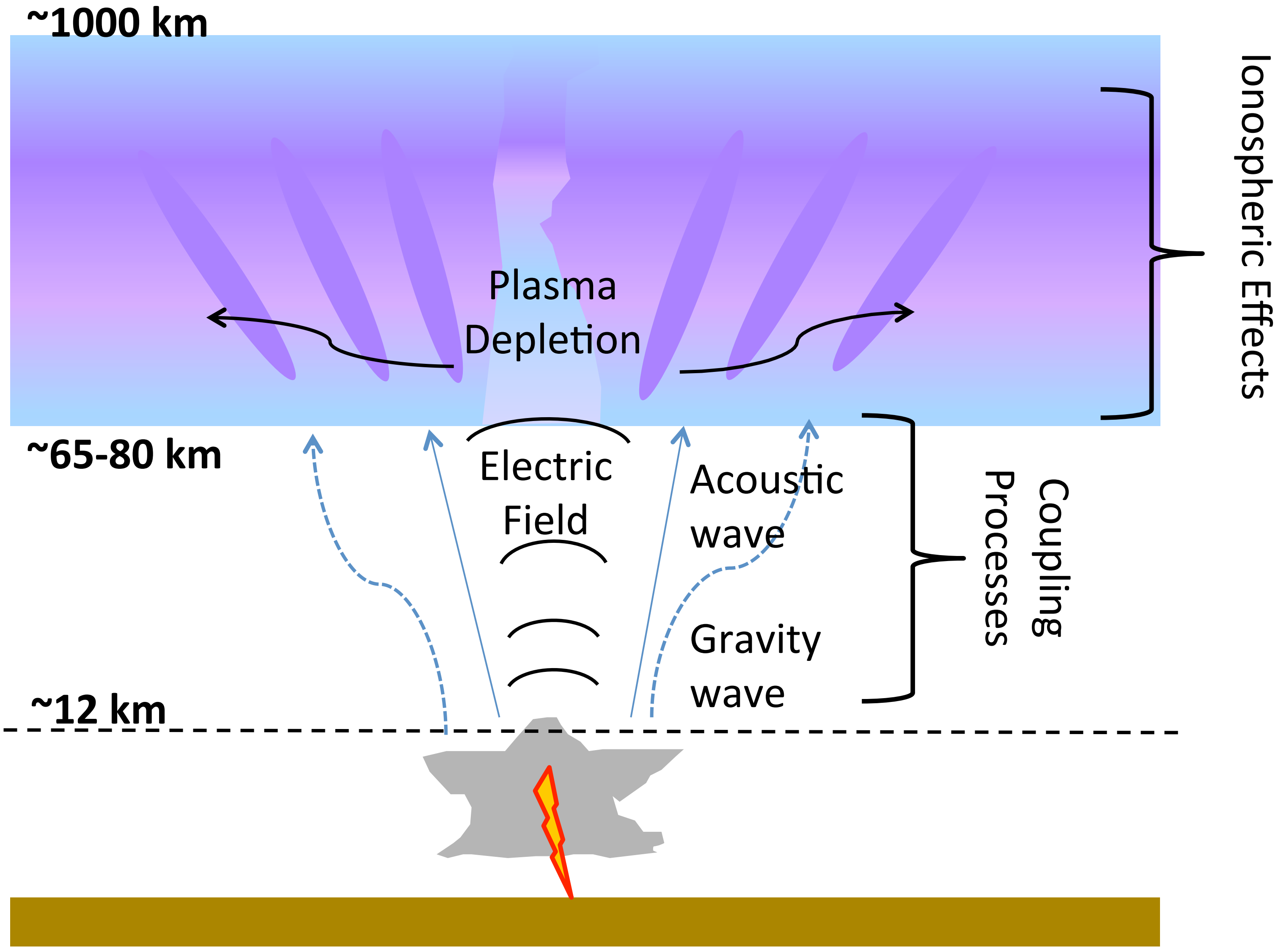


- Weather
- Thunderstorms can affect ionosphere from below

Background

- Most studies look at how ionosphere is affected from above (solar, geomagnetic activity)
  - Large scale variations (1000s km, several hours)
- Recent work has shown affects from below (troposphere) could be significant
  - Small scale (10s-100s km, several minutes – 1 hr)
  - Satellite communication problems (GPS navigation)
- How do thunderstorms disturb the ionosphere?
  - Electrical
  - Pressure/wave

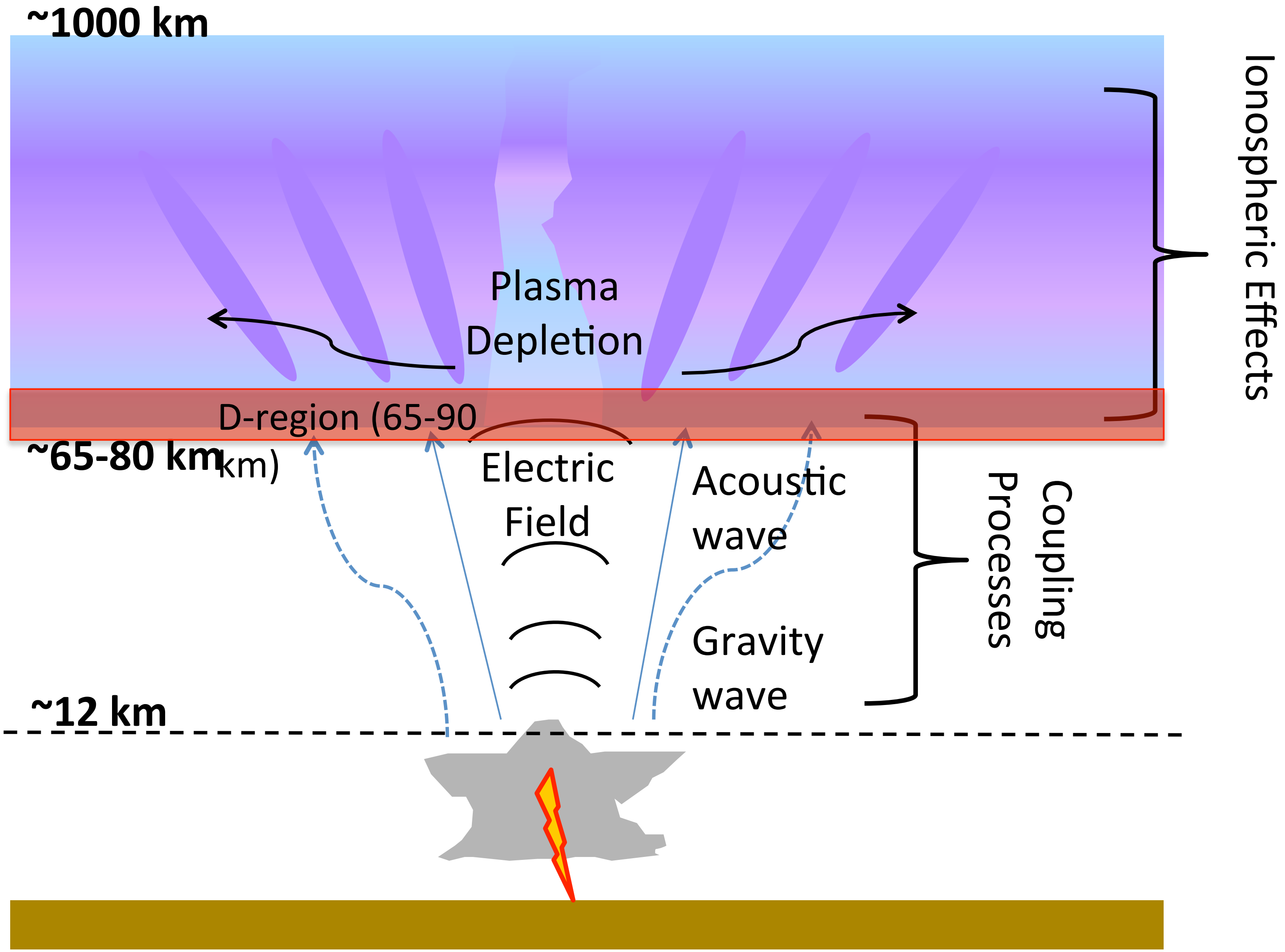
Thunderstorm/ionosphere coupling processes



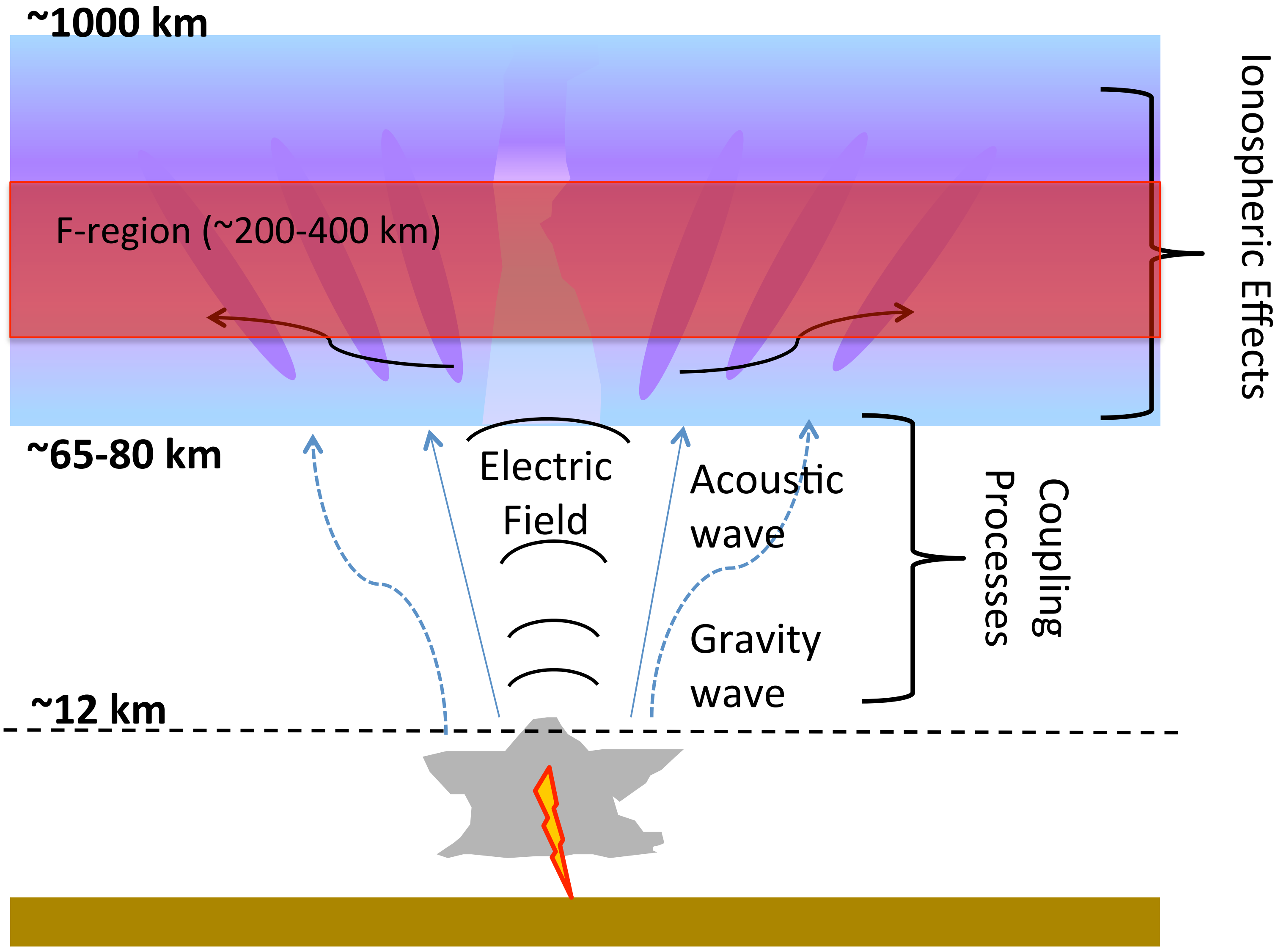
Measurements in the ionosphere

- In-situ
  - LEO Satellites (350 – 700 km), Rockets (80 – 500 km)
  - Coverage (90 secs – several minutes)
  - Fast moving
- Remote sensing (use radio signals)
  - Ionosondes, radars
  - Stationary
  - Long-term coverage
- What I do:
  - Innovative remote sensing
  - Find new ways to use existing radio signals to get better spatial and time coverage of ionospheric disturbances

Focus areas of my work



Focus areas of my work



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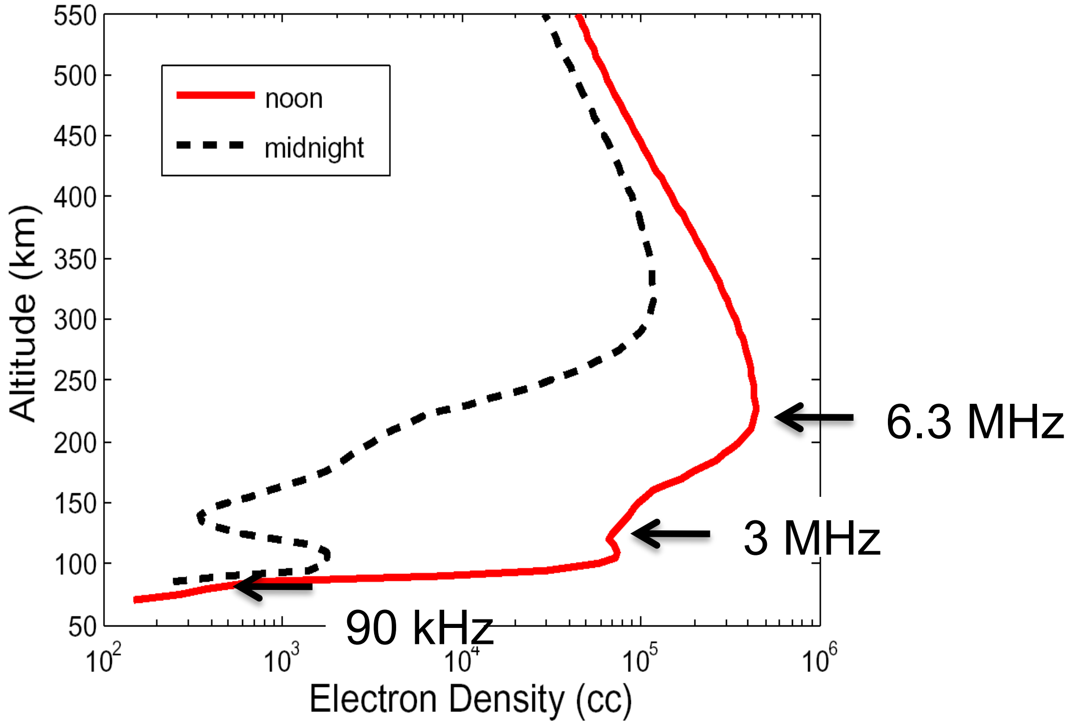
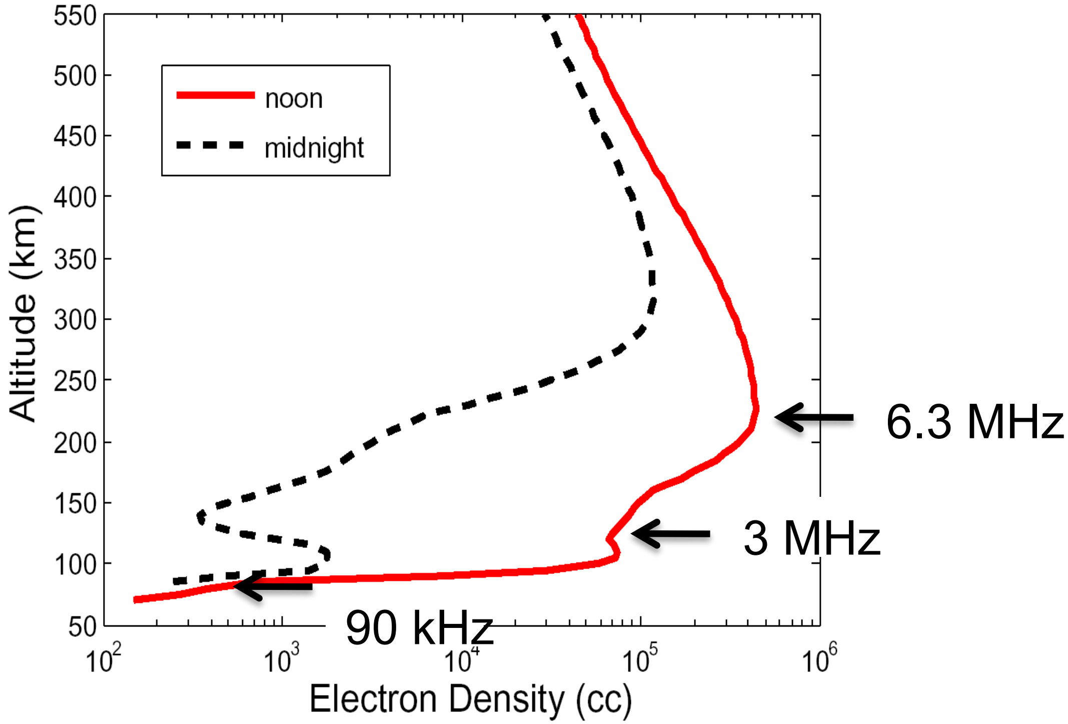
Probe D-region with kHz frequencies



EM signals will reflect from ionosphere when electron density is high enough to respond quickly to the particular frequency of wave

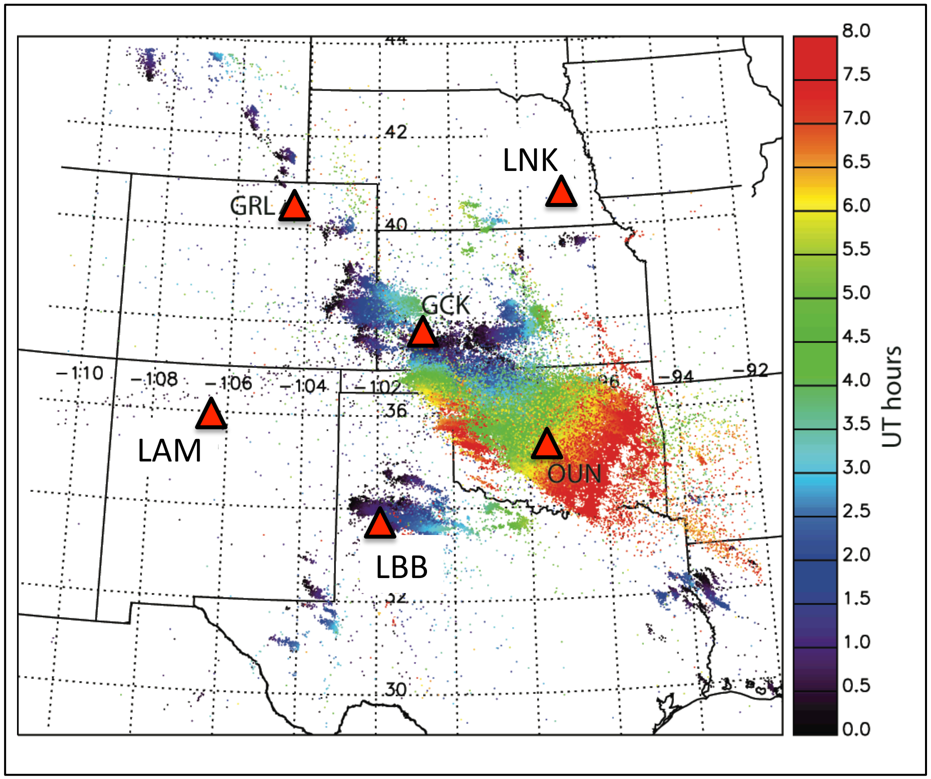
Probe D-region with kHz frequencies



EM signals will reflect from ionosphere when electron density is high enough to respond quickly to the particular frequency of wave

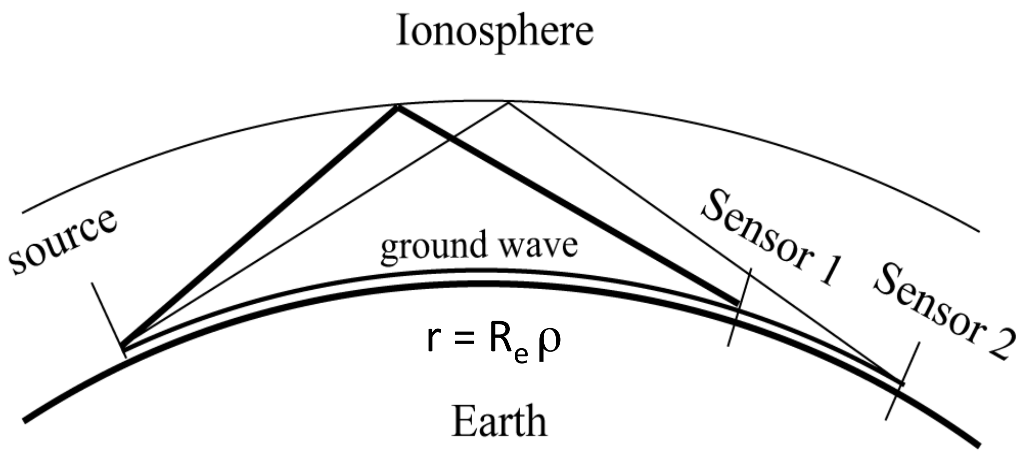
- We need kHz frequencies to reflect off 60-90 km!
- Hard to make an antenna big enough for kHz radiation
- Lightning is a very powerful transmitter of kHz frequencies!
- Use lightning as our “Radar”

Los Alamos Sferic Array (LASA)



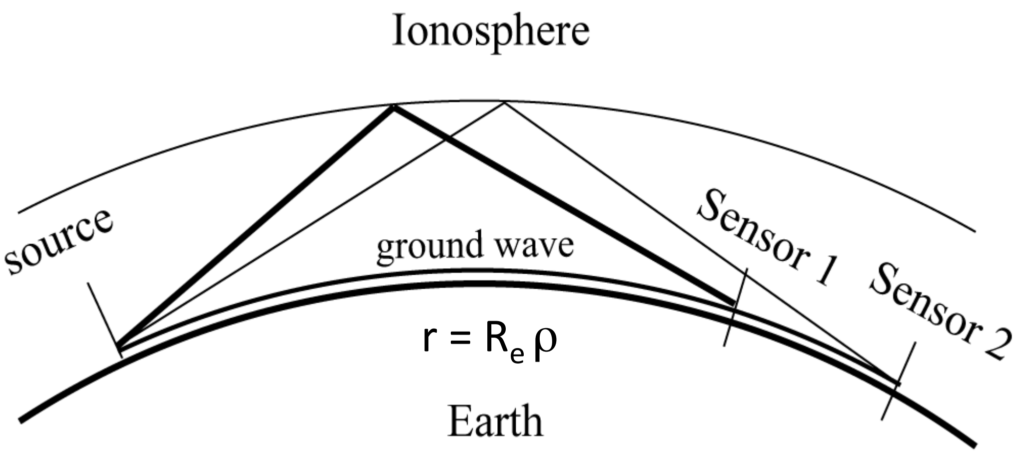
- 6 lightning receivers
- Detect, locate, characterize lightning activity
- Records and saves low frequency/very-low frequency (LF/VLF; 200Hz – 500 kHz) time waveforms.
- We use these waveforms as our “radar” signals!

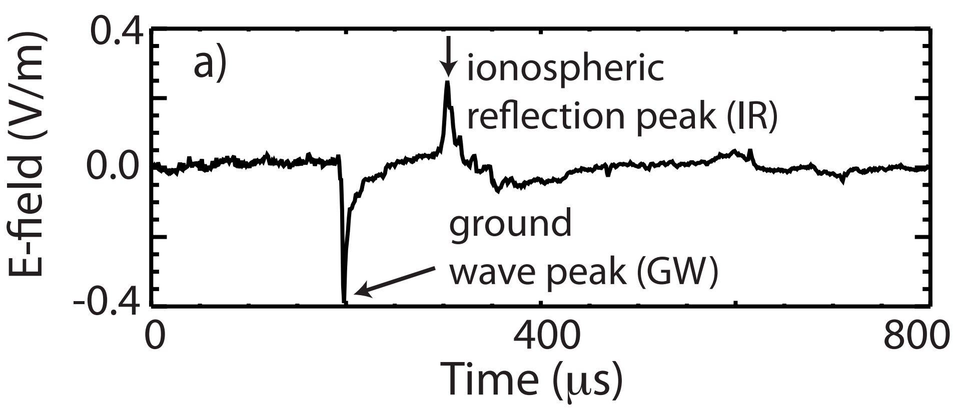
LF/VLF ionospheric probing technique using –CG lightning as probe source



- Ground wave from lightning arrives first at station, then ionospheric reflection
- One lightning can probe multiple ionospheric region depending on number of sensors

LF/VLF ionospheric probing technique using –CG lightning as probe source





[Lay and Shao, JGR, 2011]

- Ground wave from lightning arrives first at station, then ionospheric reflection
- One lightning can probe multiple ionospheric region depending on number of sensors

Measurements:

- Peak ratio ($R=E_{iono}/E_{ground}$) related to D-layer reflectivity
- Peak delay ($\Delta t = t_{iono} - t_{ground}$) related to D-layer height

Get electron density profile from propagation model

- Ground wave and D-layer reflection model for radiation VLF/LF propagation *[Jacobson et al.; Shao and Jacobson, 2009]*

$n_e = n_0\, e^{q(z-z0)}$

z0: scale height

q: steepness

1. Assume exponential increasing electron profile
2. Solve for best-fit parameters by comparison to data (R, Δt)

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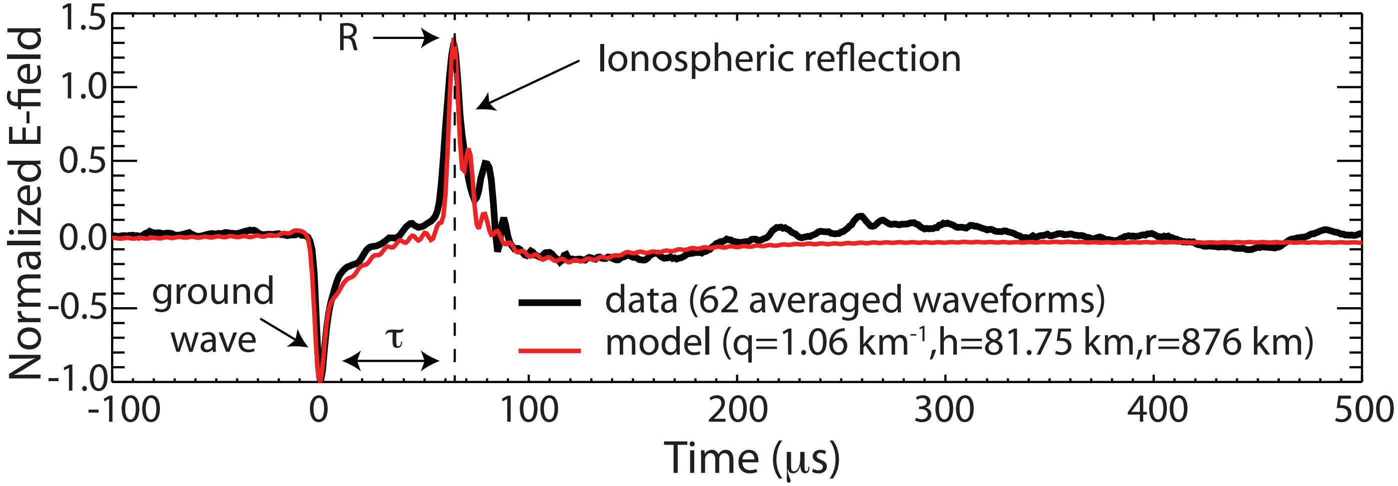
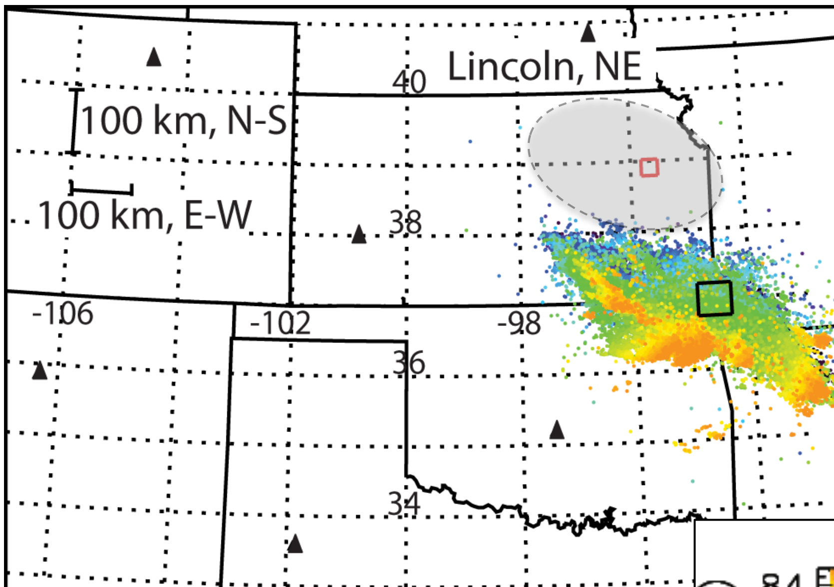
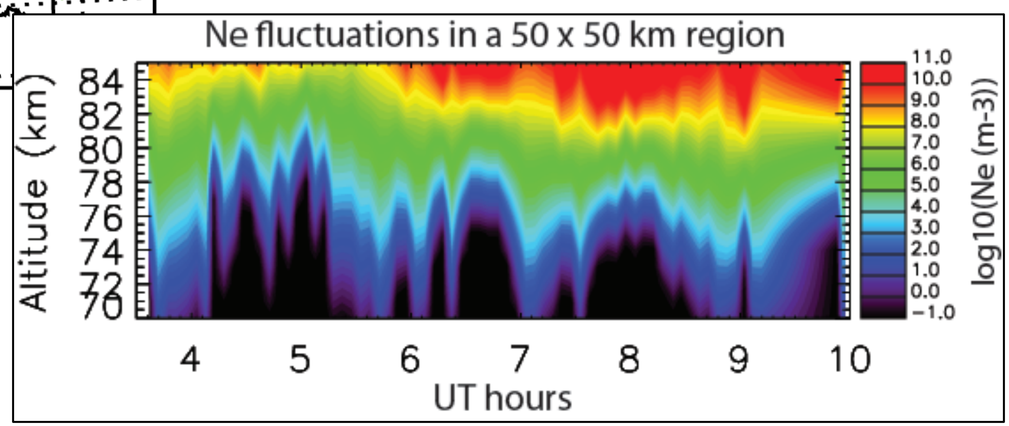


D-region perturbations north of a large thunderstorm

2005/05/23, 3:30 - 9:30 UT (22:30 – 4:30 LT)



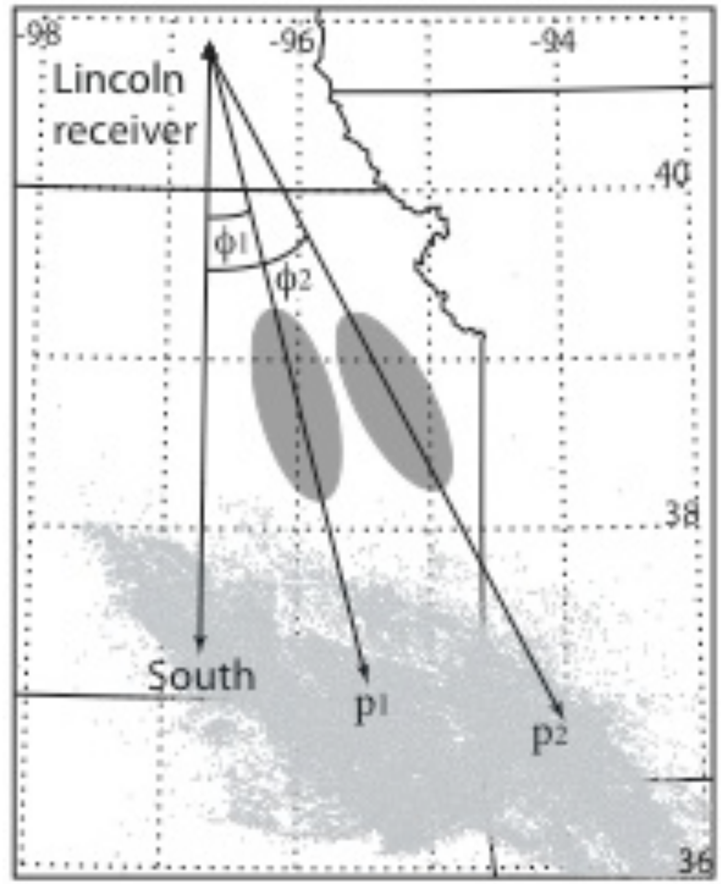
- Date: 23 May 2005
- 65,000+ negative CG lightning strokes
- Probe regions using Lincoln receiver



Example fluctuation in ionospheric height in a 50 x 50 km spatial area

Measuring D-region wave motion with lightning signals

- Each measurement has a range (p) and azimuthal angle (ϕ)



[Lay and Shao, JGR, 2011]

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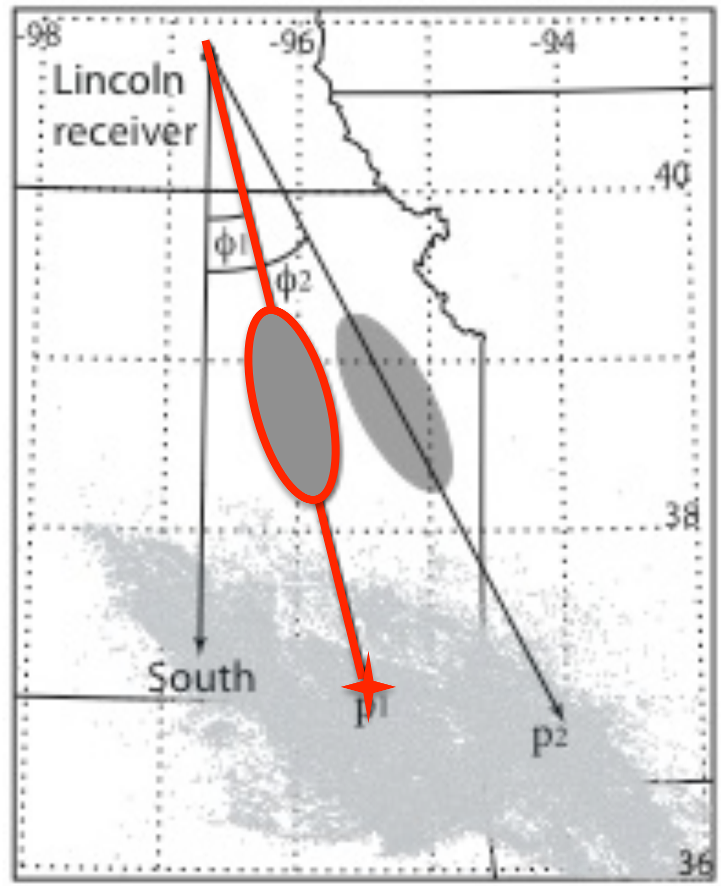

[Lay and Shao, JGR, 2011]

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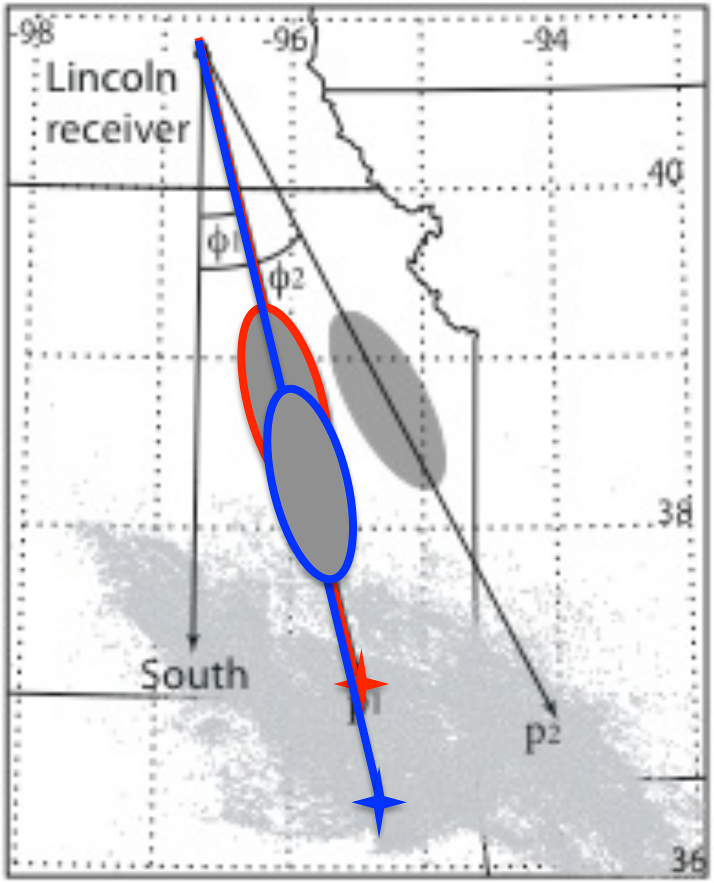
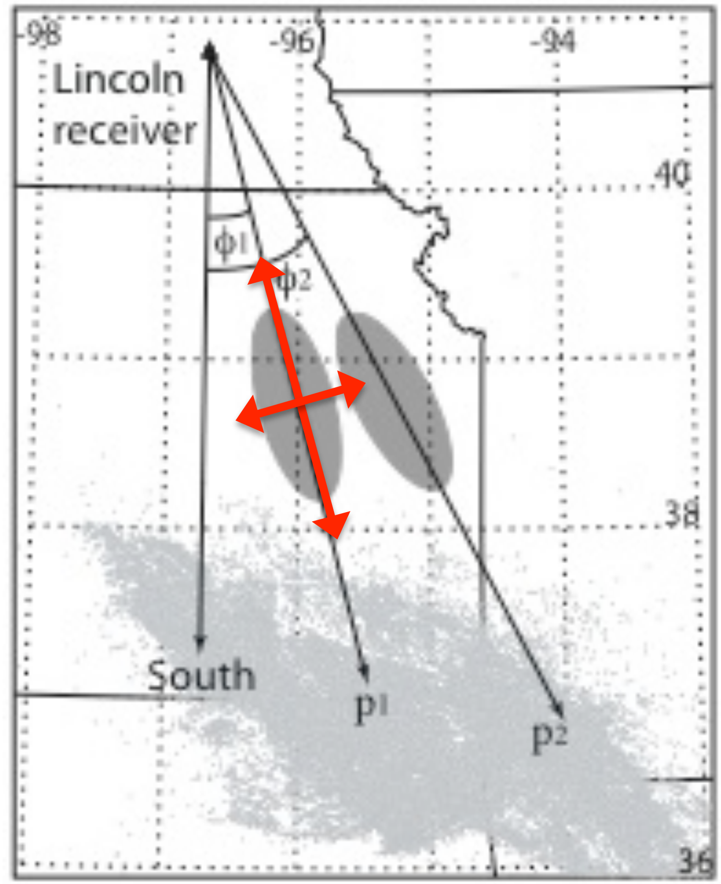


[Lay and Shao, JGR, 2011]

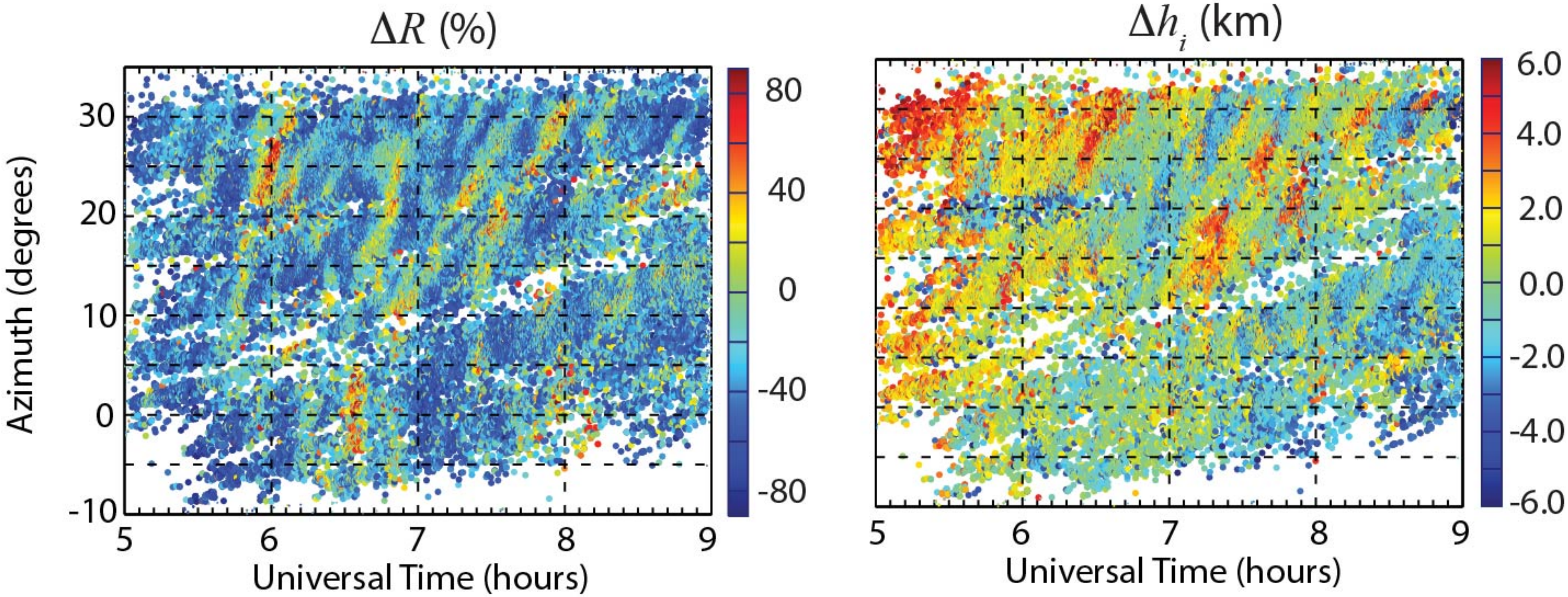
Measuring D-region wave motion with lightning signals

- Each measurement has a range (p) and azimuthal angle (ϕ)
- Many measurements together give sensitivity to D-region azimuthal or radial components of moving waves.



[Lay and Shao, JGR, 2011]

Wave signatures from lightning data



[Lay and Shao, J. of Geophys. Res., 2011]

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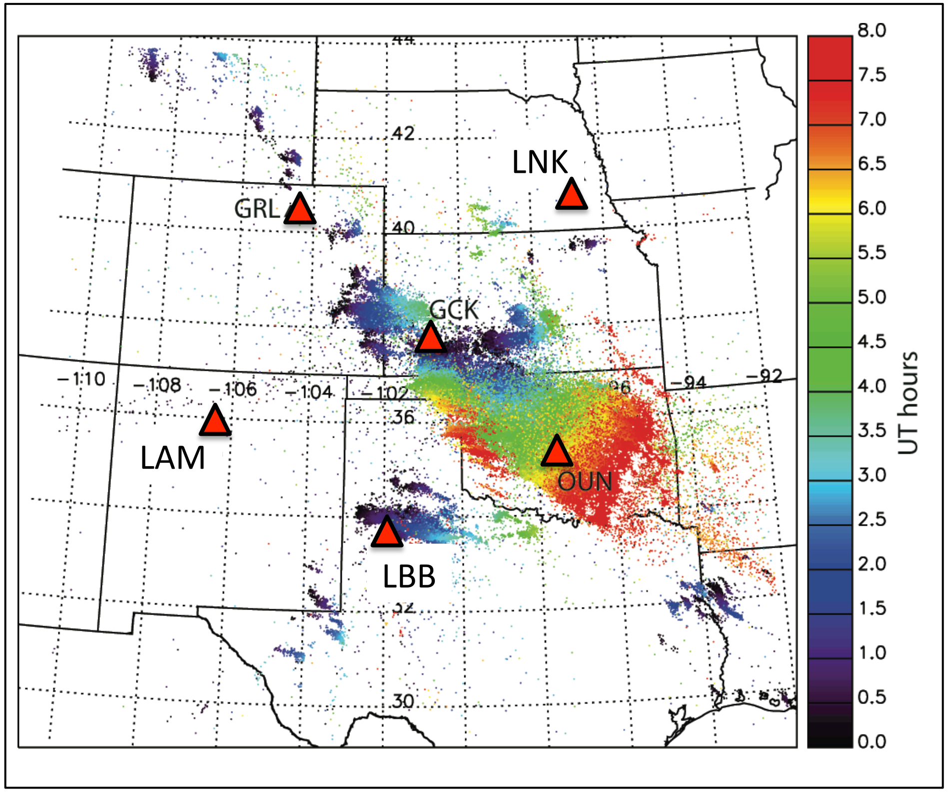
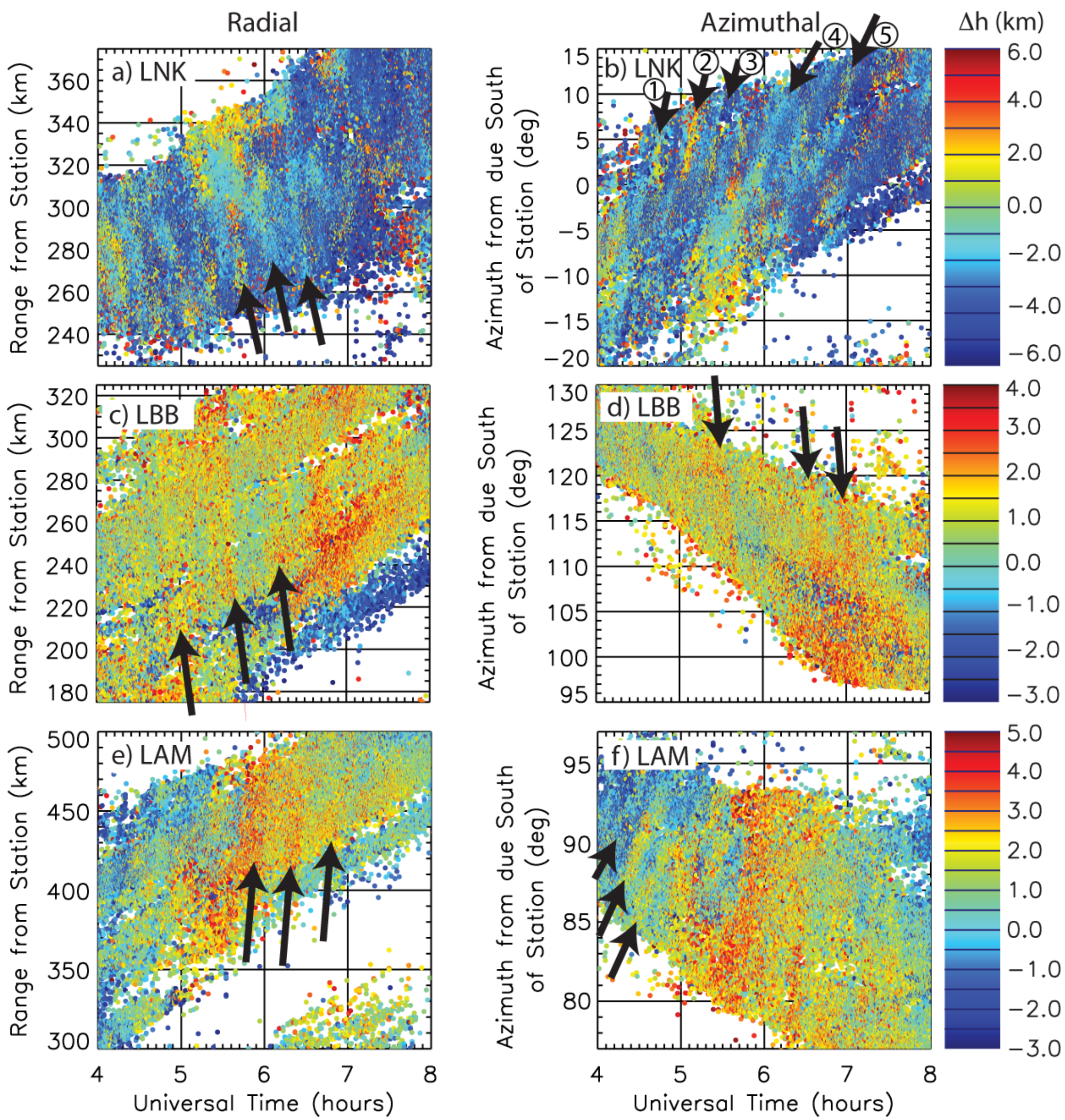
Are ionospheric waves originating from thunderstorms?



- Date: 17 June 2005
- 100,000+ negative CG lightning strokes
- Probe regions using LNK, LAM, LBB

Are waves originating from thunderstorms?



LNK station

N of storm

N & E propagation

LBB station

SW of storm

SW & SE propagation

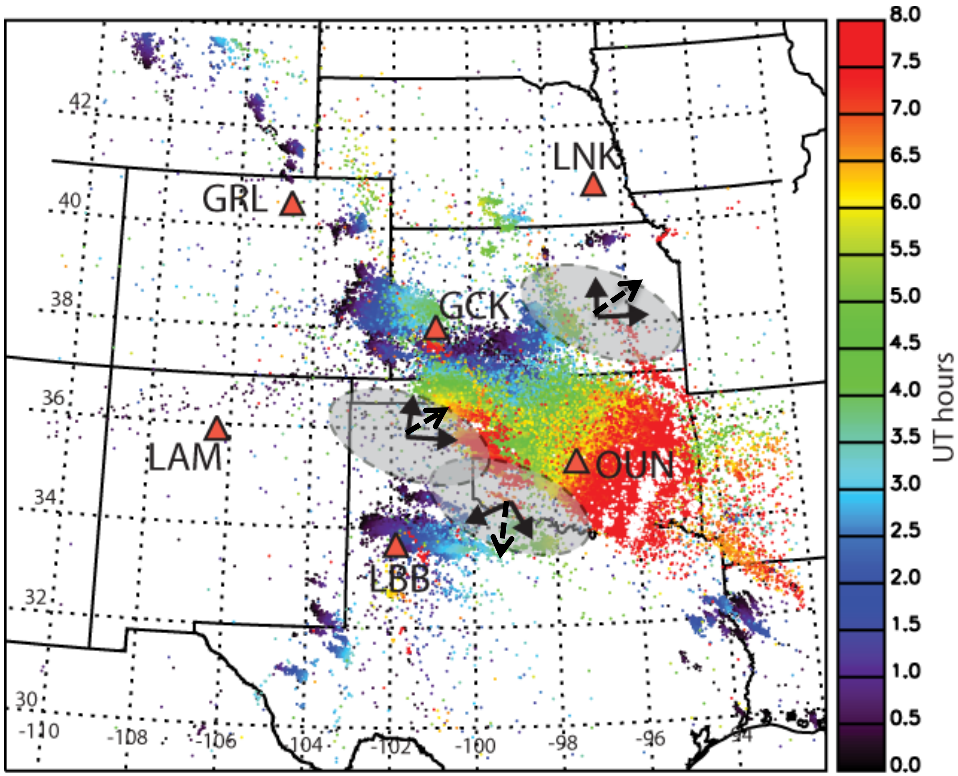
LAM station

W of storm

N & E propagation

[Lay and Shao, GRL, 2011]

Are waves ionospheric originating from thunderstorm?



[Lay and Shao, GRL, 2011]

1. Waves propagate away from storm as seen in LNK and LBB probing region
2. Background wave propagates eastward as seen from LNK and LAM.

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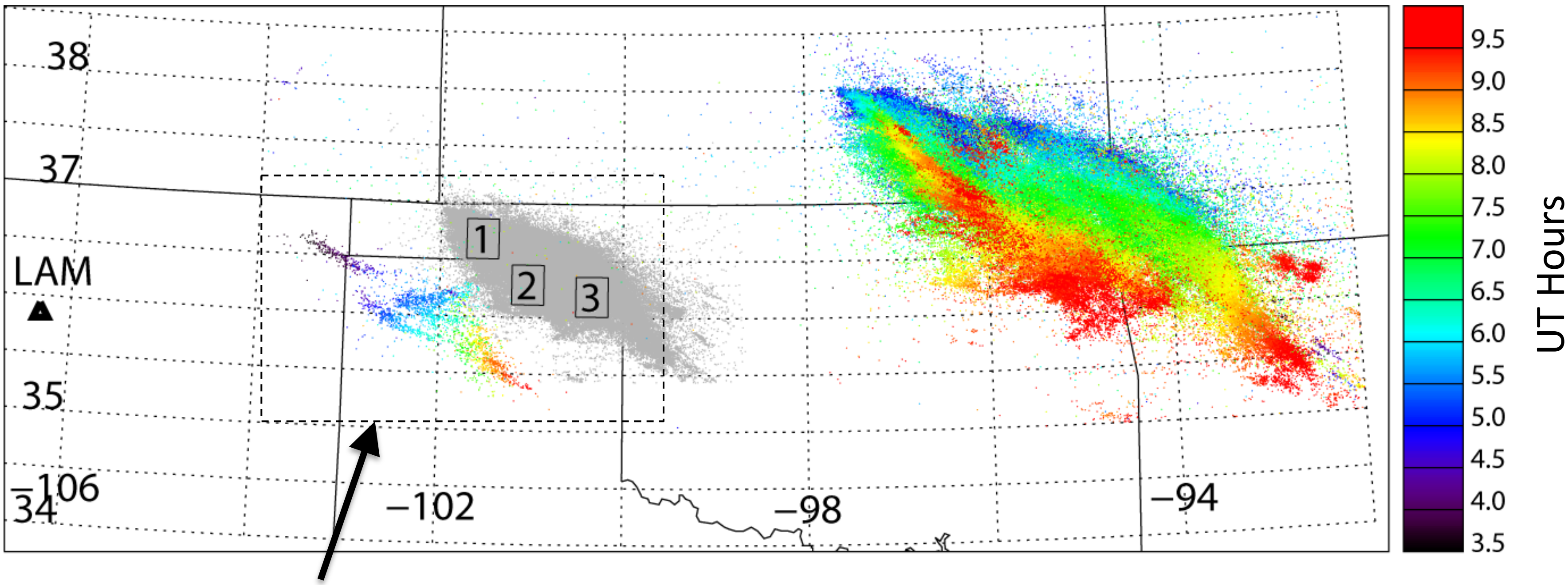
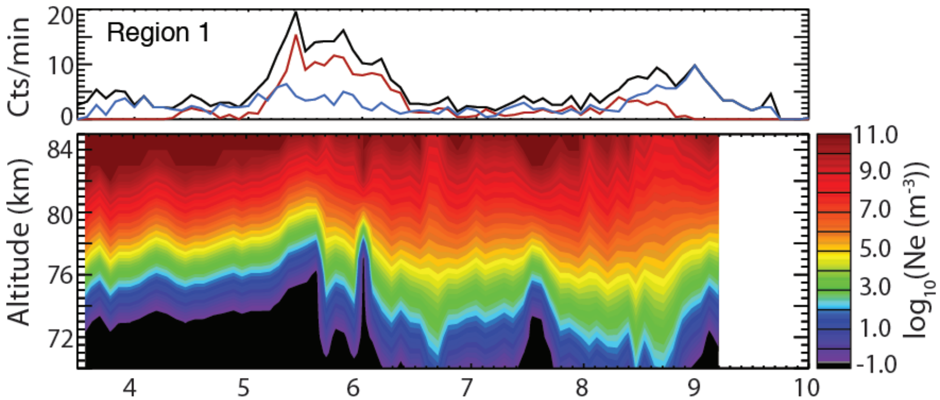
How do thunderstorm electrical effects disturb ionosphere?



Small storm and probing area

[Shao, Lay, Jacobson, Nature Geoscience, 2013]



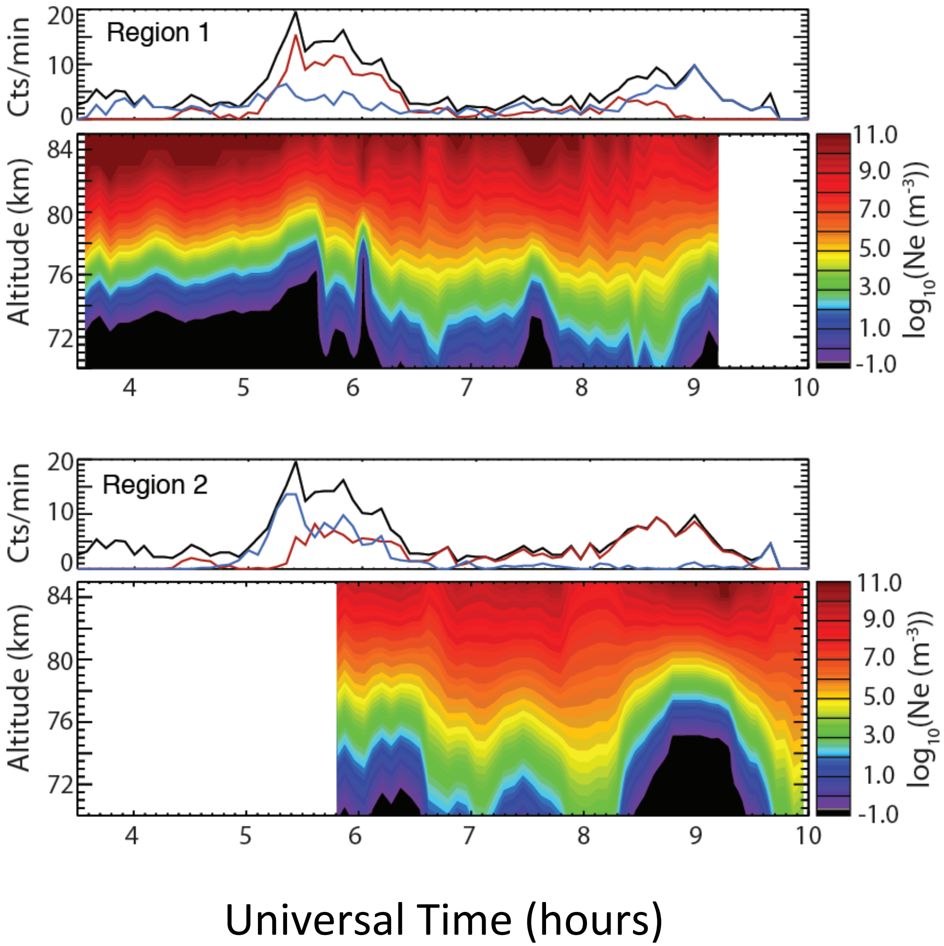
Universal Time (hours)

Top panel: Lightning count rates

- Black: total in small storm
- Red: within 100 km of region center
- Blue: 100 km < d < 150 km of region center

Bottom panels: Electron density profiles in time

[Shao, Lay, Jacobson, Nature Geoscience, 2013]



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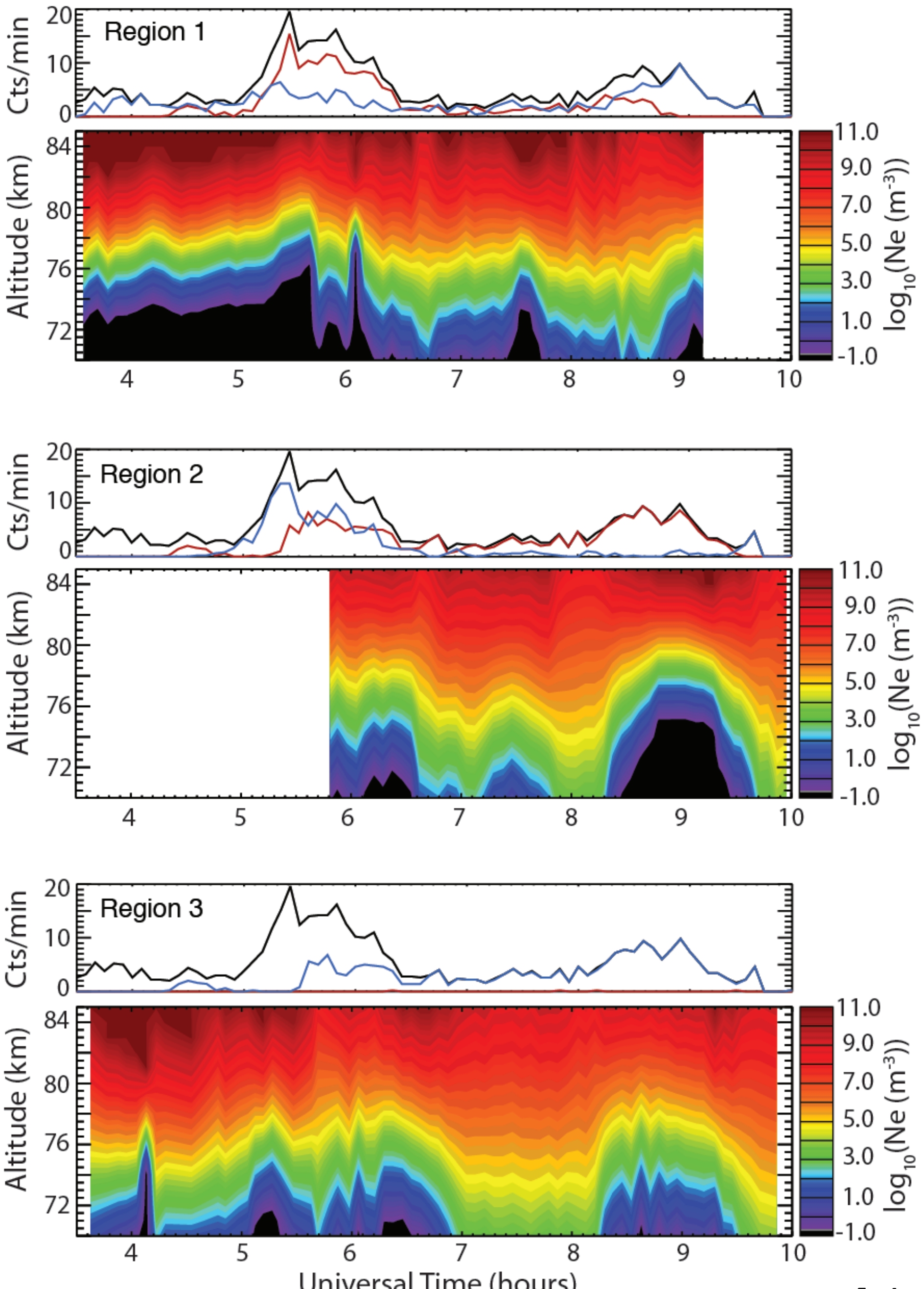

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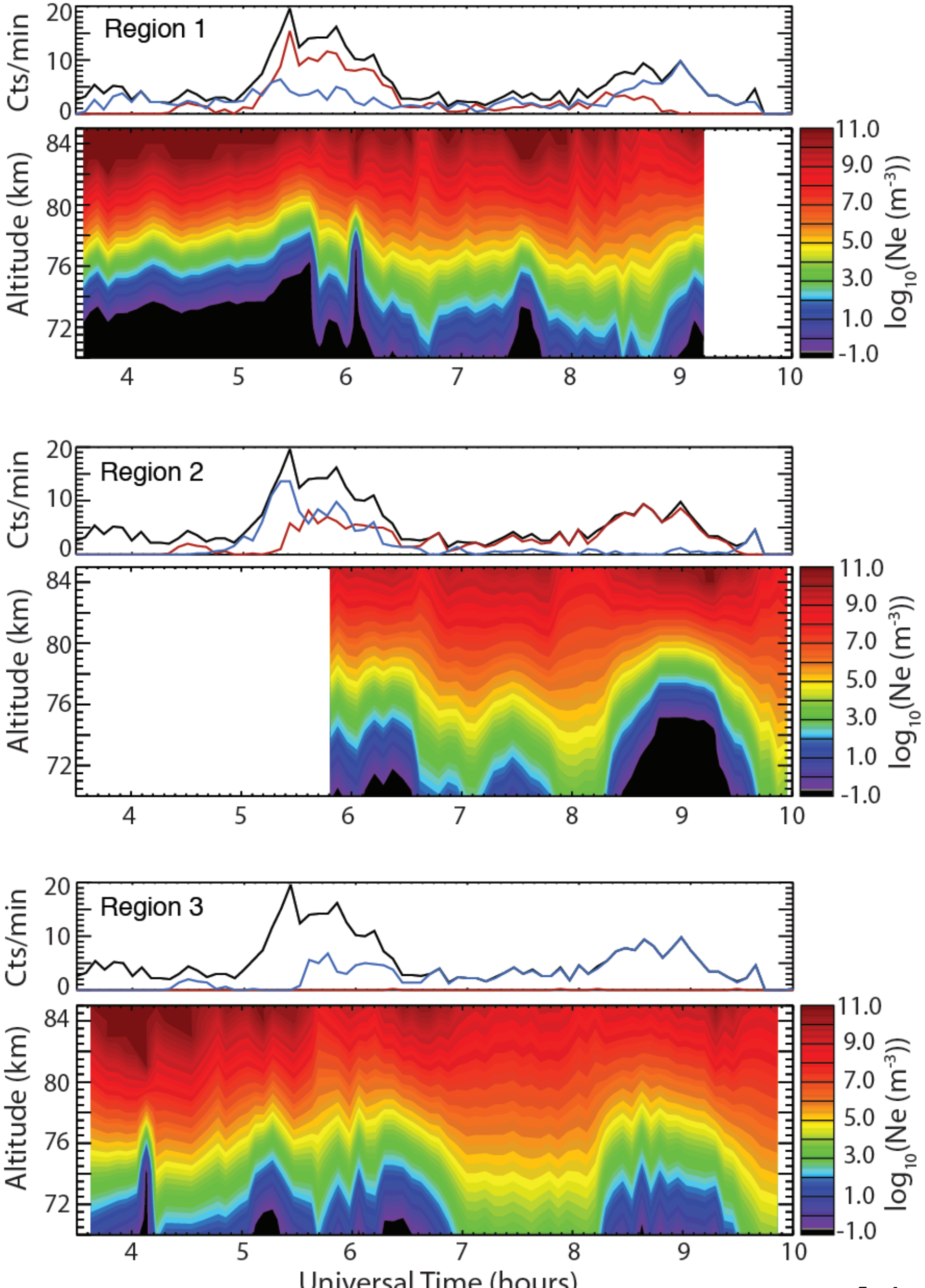

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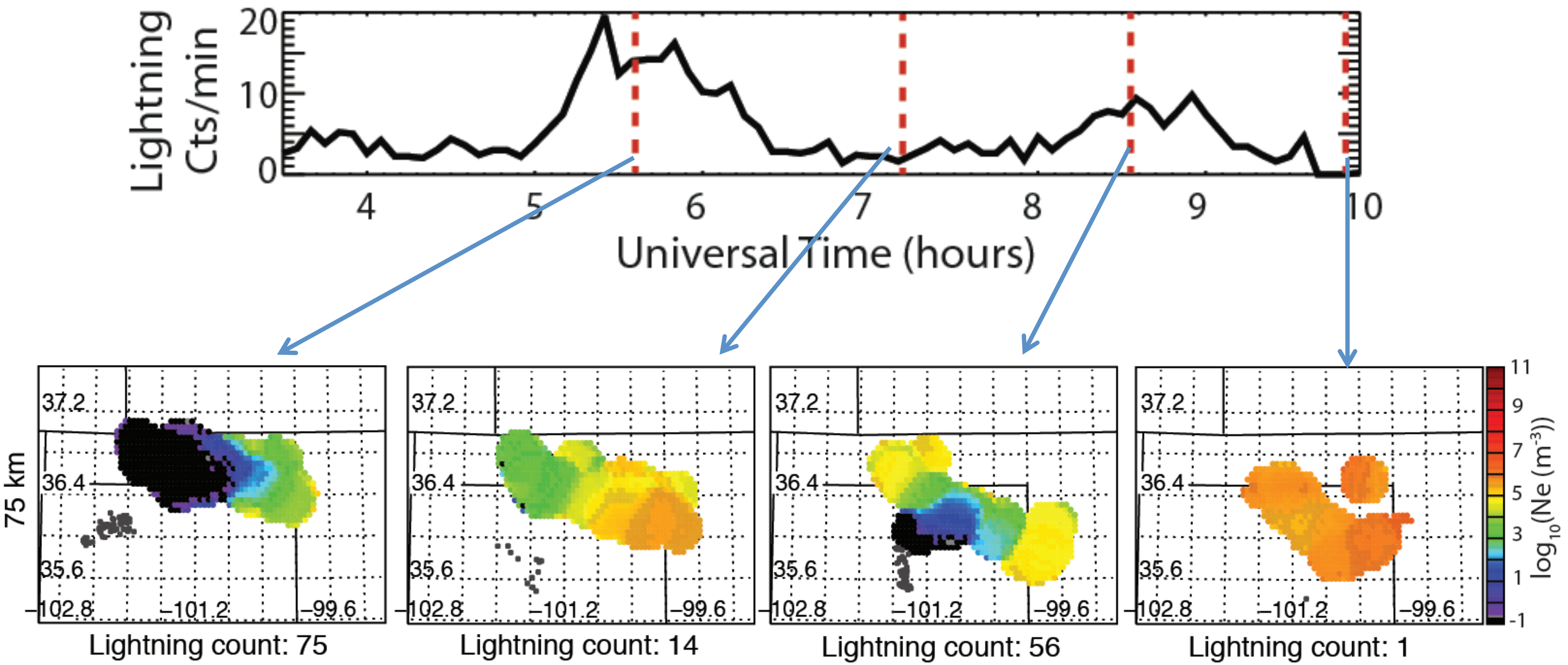
Bottom panels: Electron density profiles in time

1. Ionospheric height closely and positively related to lightning rate over time (heating and attachment)
2. Quiet times: electrons 'refill' the lower altitudes
3. Greater distance from lightning leads to smaller effects.

[Shao, Lay, Jacobson, Nature Geoscience, 2013]

Electrical effects above a small storm



1st lightning peak

Quiet period

2nd lightning peak

Storm dying out

[Shao, Lay, Jacobson, Nature Geoscience, 2013]

D-region conclusions

Atmospheric gravity waves

- Periods of 10s of minutes to ~1 hour.
- Speeds of 50-100 m/s
- Multi-station analysis suggests propagation away from storms

Electrostatic effects above thunderstorms

- Electron density variations closely associated in space and time with electrical activity of storm
- Suggests electron heating increases electron attachment.

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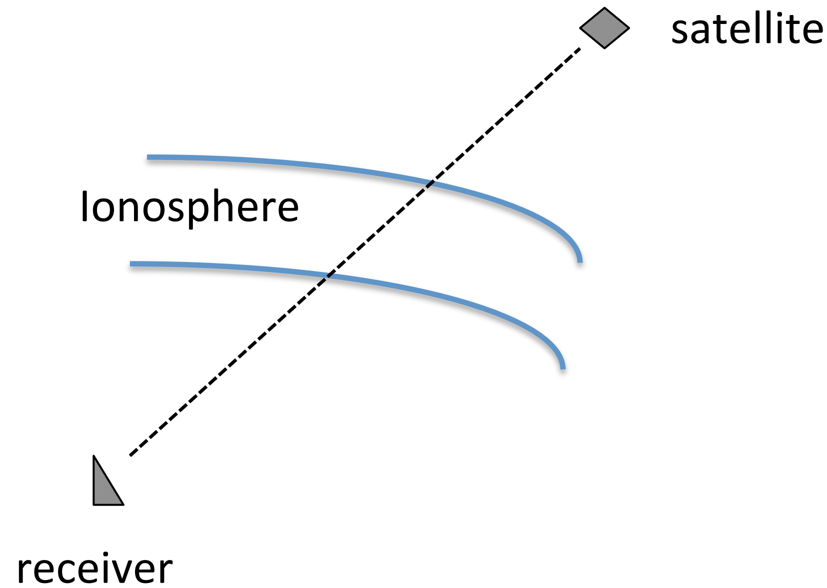
GPS Total Electron Content (TEC)

- GPS frequencies: 1.22 GHz, 1.57 GHz
- Measure phase delay and group delay due to the ionospheric plasma
- Determine total integrated electron density based on those delays

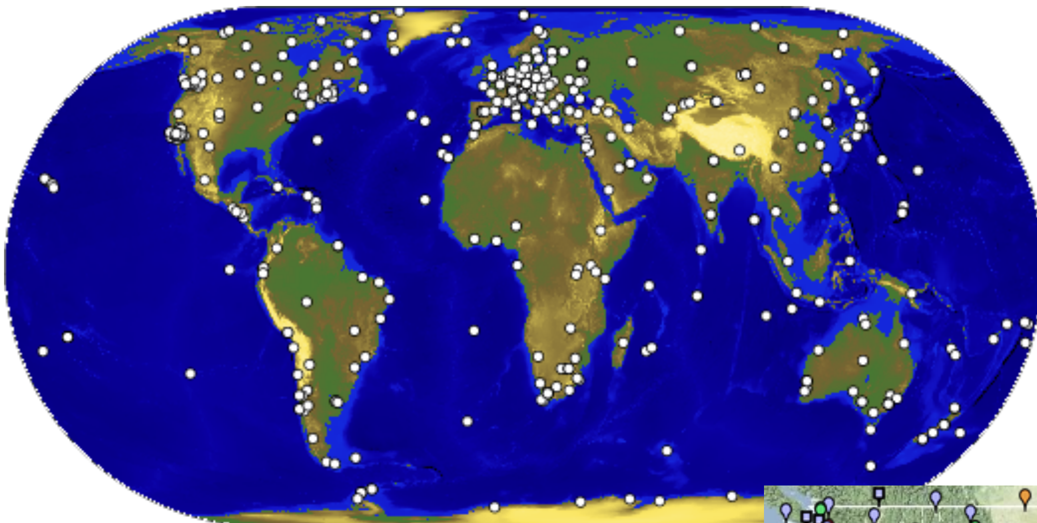


$$TEC = \int_{ground}^{satellite} N_e ds$$

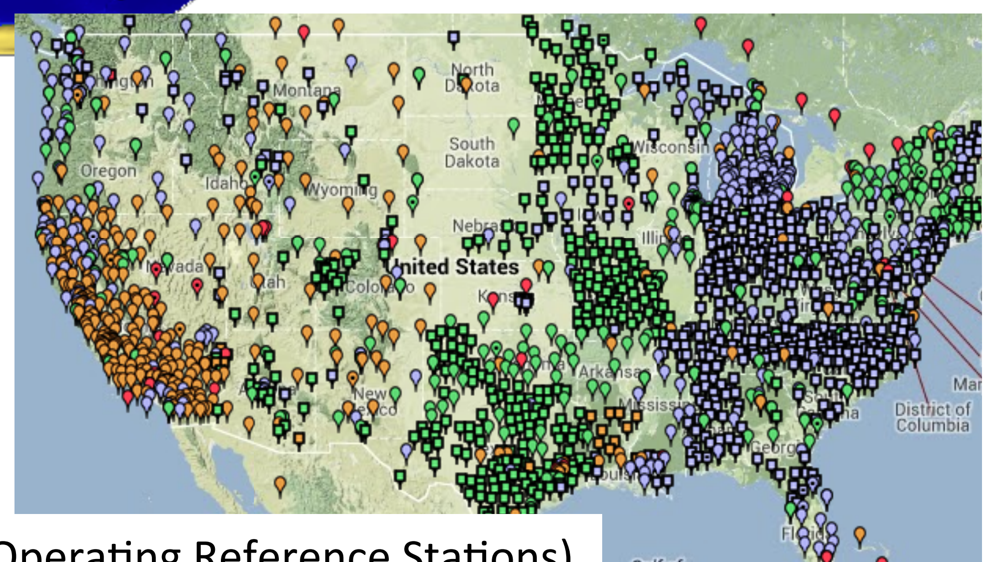
Integrated electron density along line-of-sight from ground receiver to satellite: electrons/m^2 (TECU = 1 x 10^{16} electrons/m^2)

Electron density (electrons/m^3)

GPS receivers world-wide

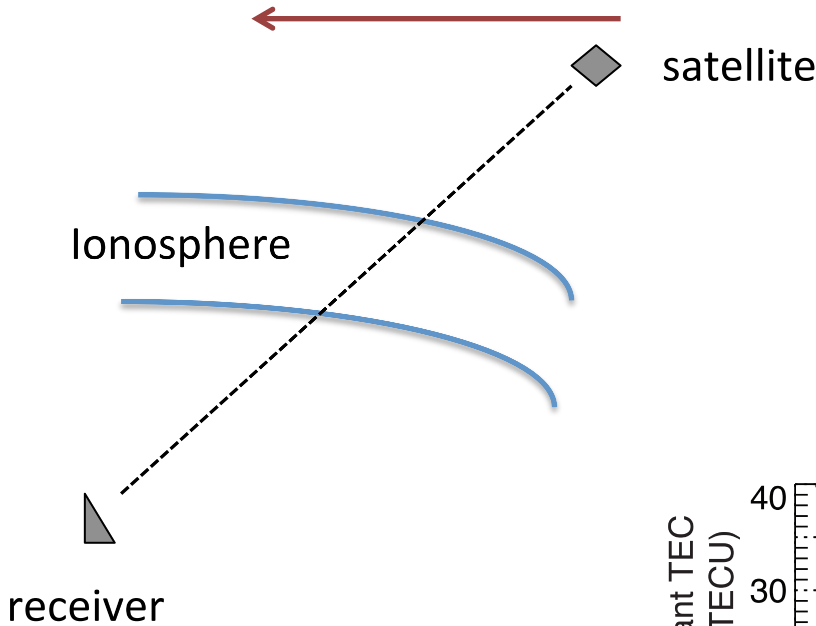


IGS (International GNSS Service)

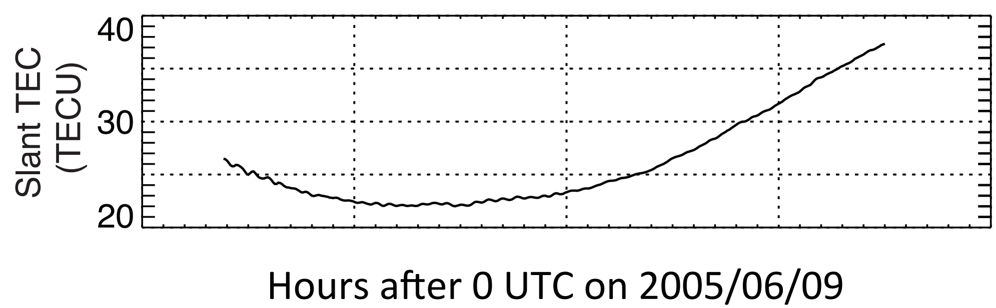


CORS (Continually Operating Reference Stations)

GPS TEC ‘arc’

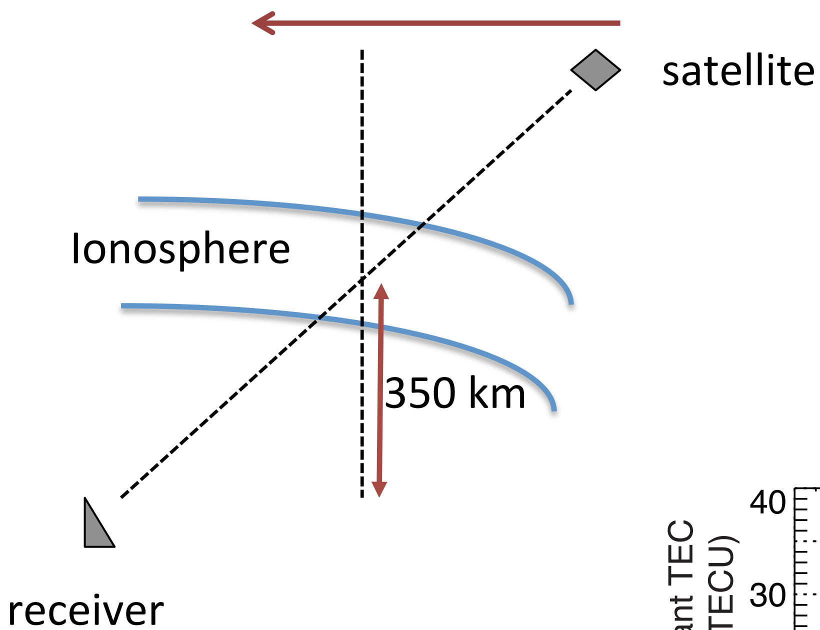


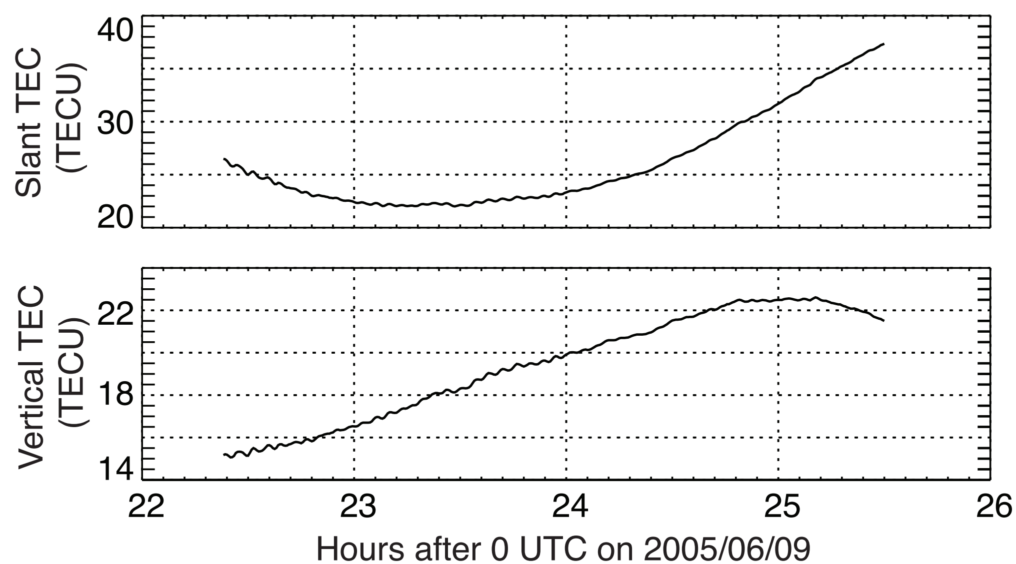
satellite
Ionosphere
receiver



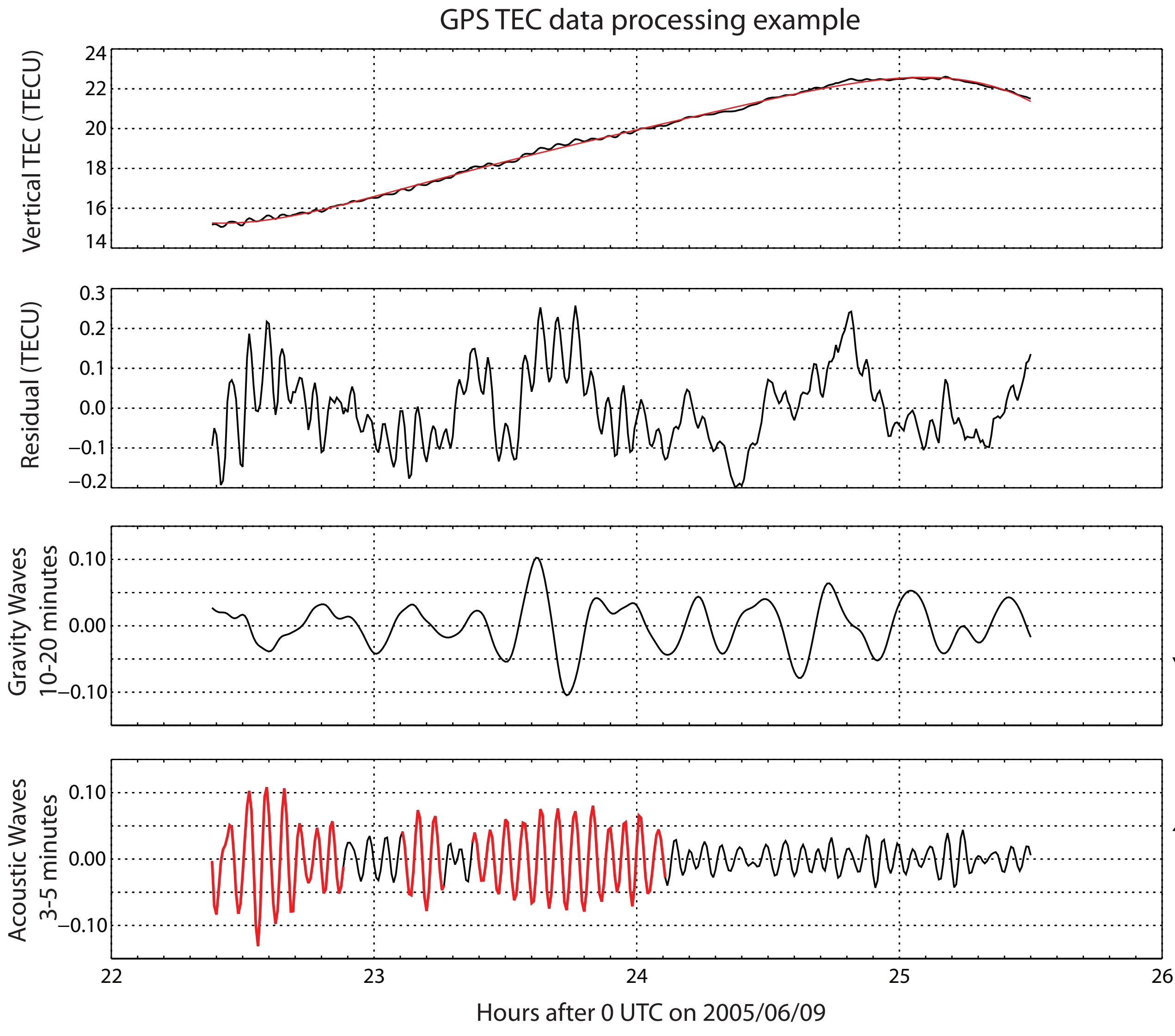
Slant TEC (TECU)
40
30
20
Hours after 0 UTC on 2005/06/09

GPS TEC ‘arc’


satellite
Ionosphere
350 km
receiver


Slant TEC (TECU)
40
30
20
Vertical TEC (TECU)
22
18
14
22
23
24
25
26
Hours after 0 UTC on 2005/06/09

GPS TEC data processing

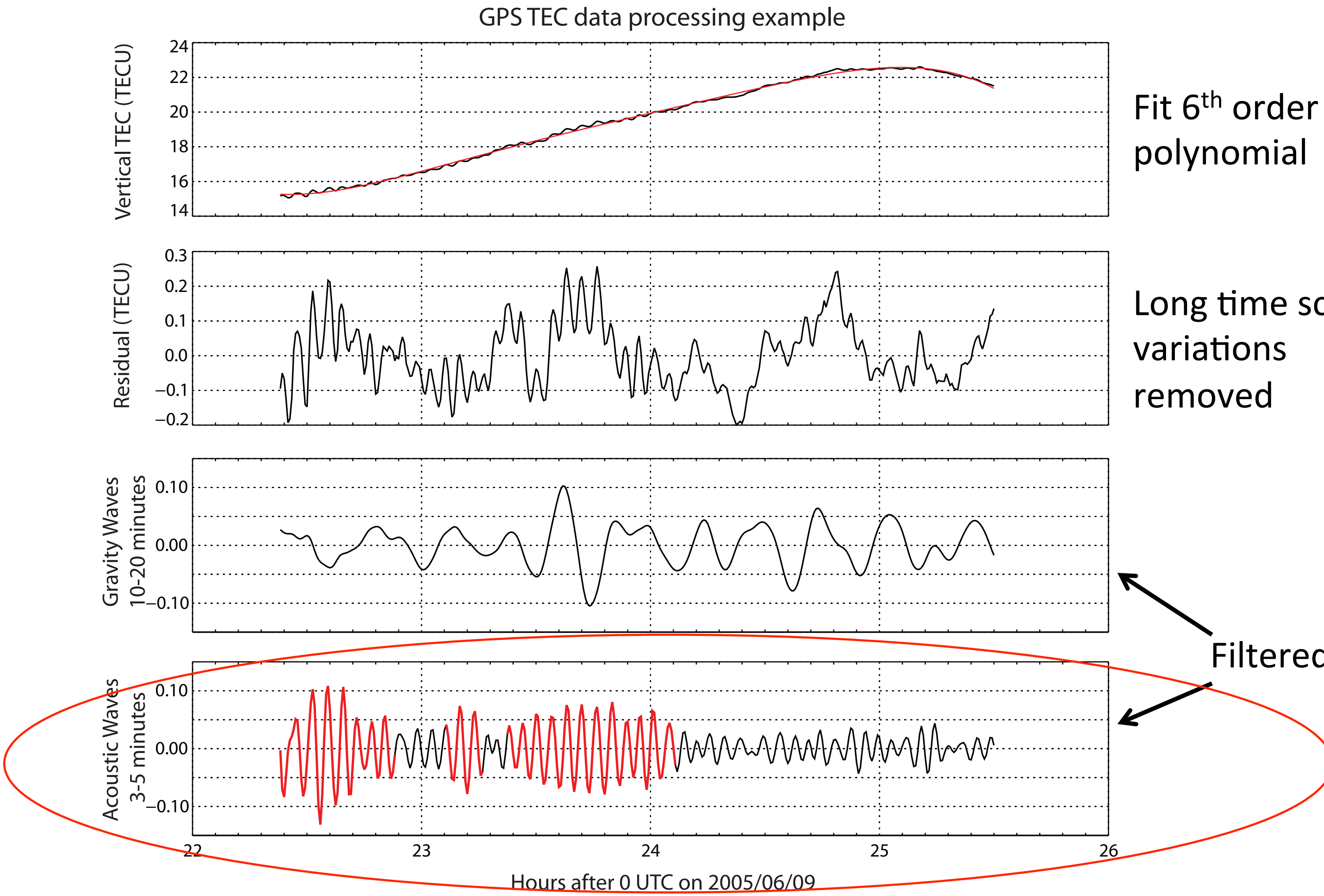


Fit 6th order polynomial

Long time scale variations removed

Filtered

GPS TEC data processing



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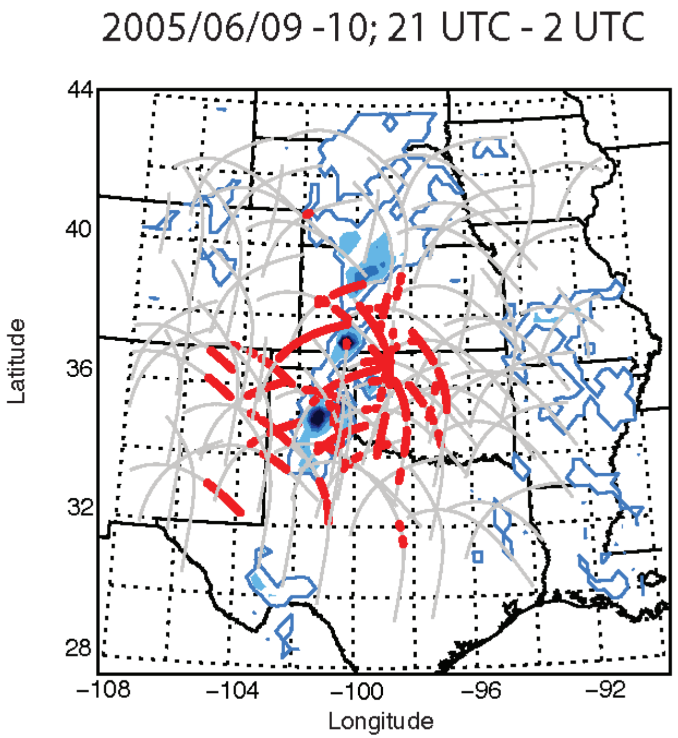
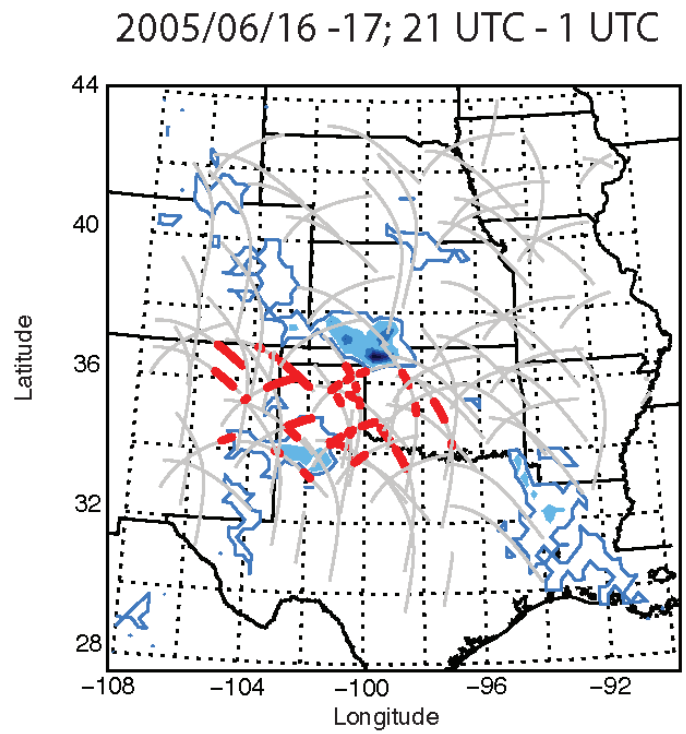
Acoustic waves near thunderstorms





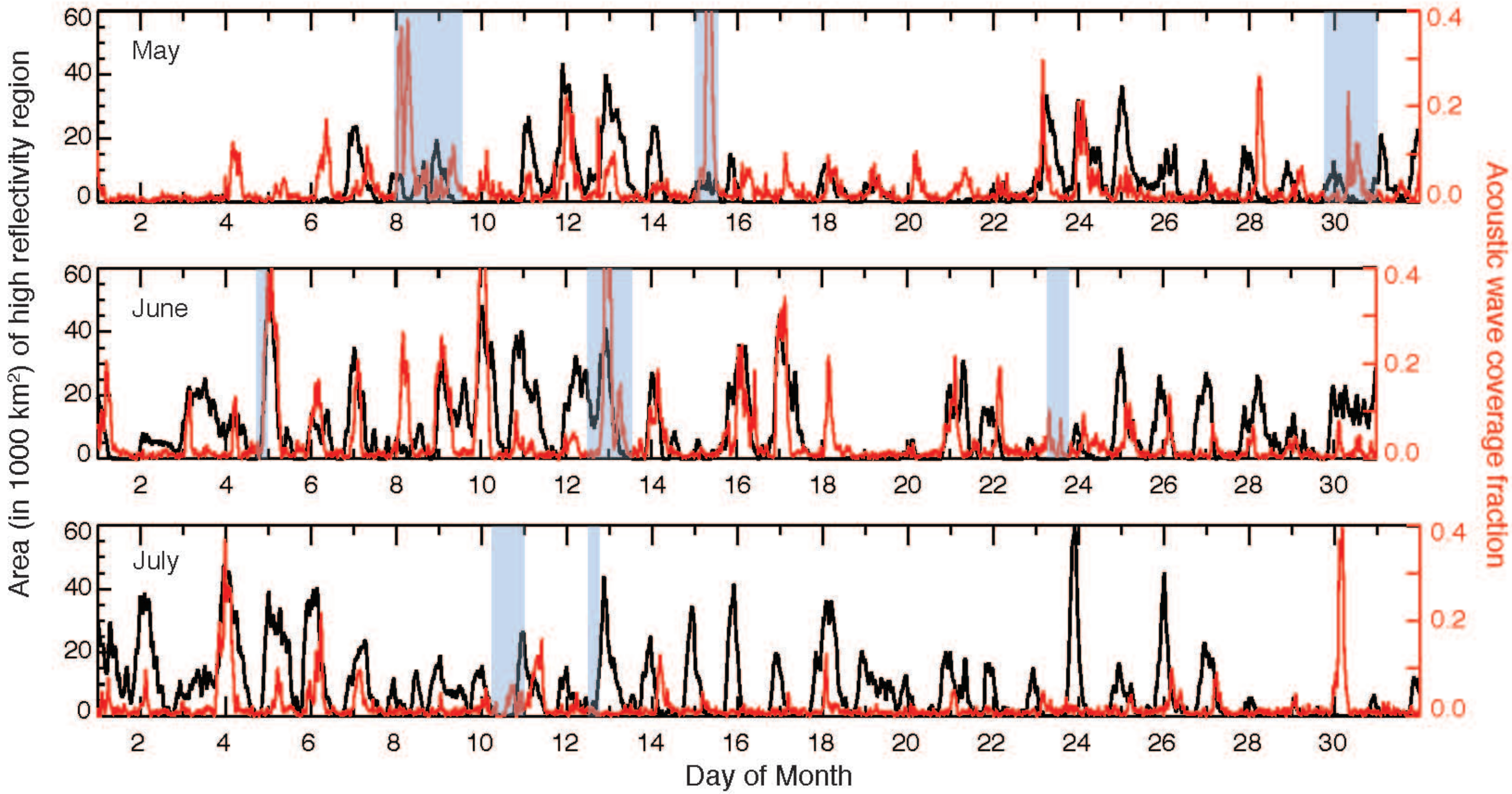
Red: Acoustic waves

Blue: Lightning activity

Gray: GPS tracks

Acoustic waves almost always occur near thunderstorms

Statistical comparison between thunderstorms and ionospheric acoustic waves



Shaded areas: high geomagnetic activity (Kp > 5.5)

F-region Conclusions

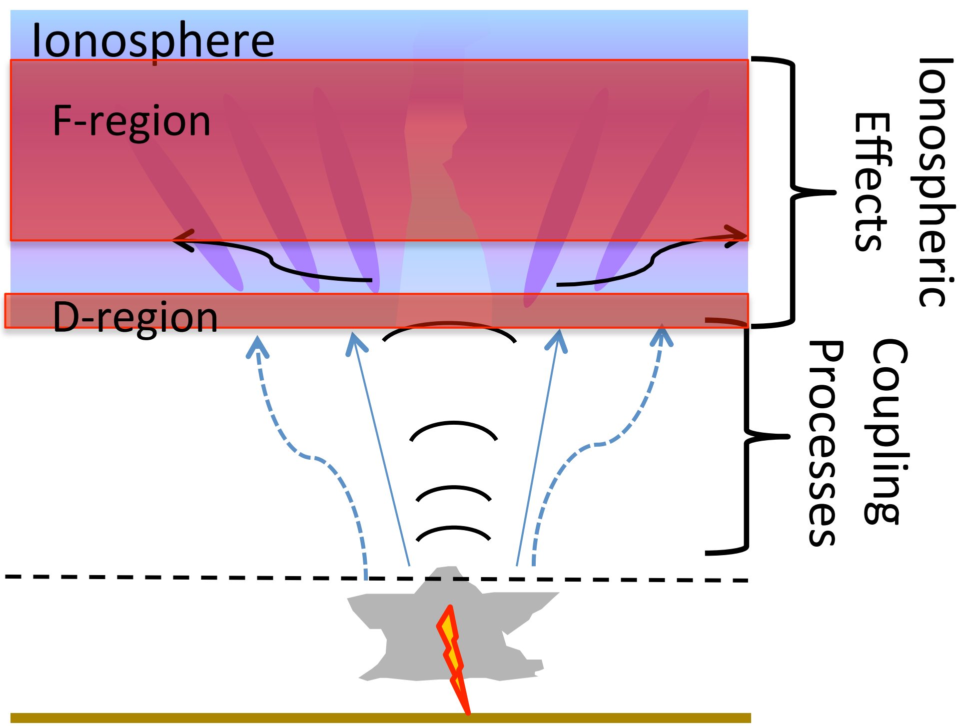
- Technique developed to process GPS TEC for acoustic and gravity wave perturbations in ionosphere.
- Case studies and initial statistical study show ionospheric acoustic waves associated in time and space with thunderstorms.

Outline

1. Background, science questions
2. D-region (65-90 km)
    a. LF/VLF probing technique
    b. Results
        1. D-region: Atmospheric gravity waves nearby large mesoscale storms
        2. D-region: Electrical effects nearby and above thunderstorms
    c. D-region Conclusions
3. F-region (200-400 km)
    a. GPS technique
    b. Results: Ionospheric acoustic wave variations near thunderstorms
    c. F-region Conclusions
4. Questions remaining / Future Work

Questions to address

What storm characteristics (size, energy) are associated with ionospheric acoustic waves?

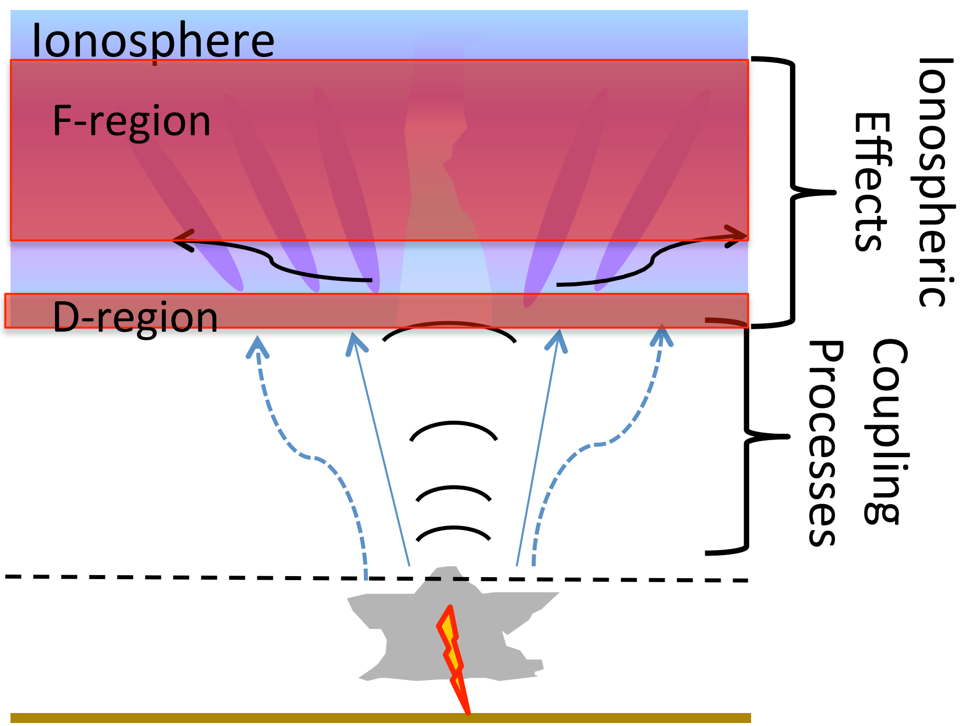


How to address:

- Continue statistical analysis
- Phase differential location technique under development for ionospheric acoustic waves
- Simultaneous ground infrasound measurements

Questions to address

Are these findings of D-region/F-region waves near thunderstorms similar in other regions of the world (different magnetic field, ionosphere conditions)?

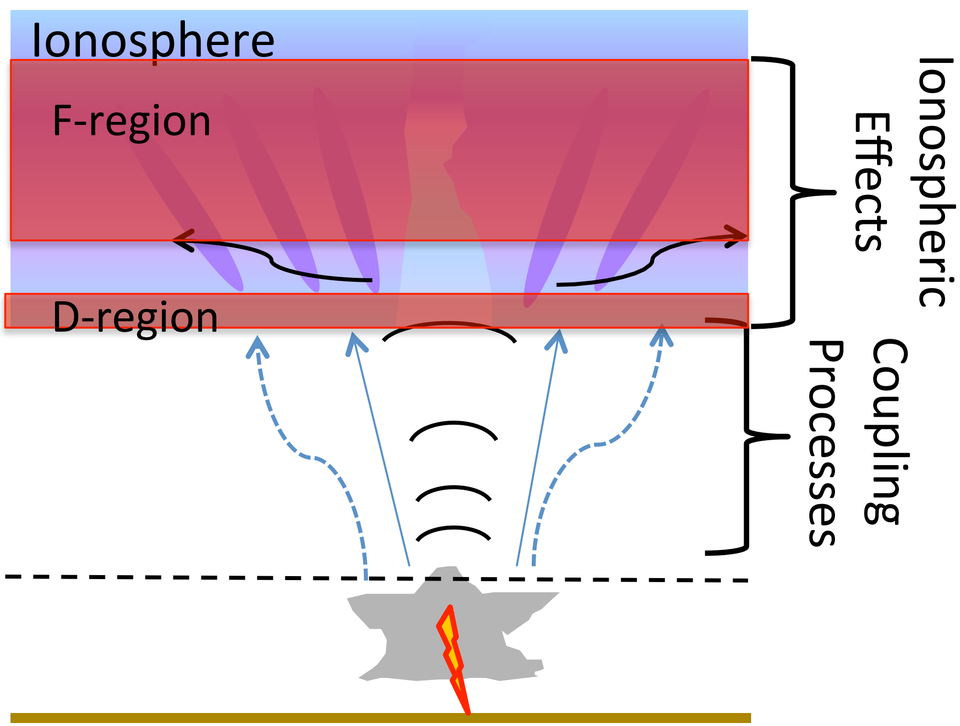


How to address:

- Global lightning network (ENTLN) saves lightning waveforms from 700 stations around the world – learn to process and analyze these data for global D-region.
- Use IGS GPS for global TEC.
- Data analysis comparisons for various regions globally.

Questions to address

How are D-region perturbations associated with F-region acoustic and gravity waves?



How to address:

- Case studies of combined D-region/F-region measurements
- Work with modelling community (Embry-Riddle Aeronautical University)

Thank you for your attention!

Questions?

Abstract

Abstract: Tropospheric thunderstorms have been reported to disturb the lower ionosphere (~65-90 km) by convective atmospheric gravity waves and by electromagnetic field changes produced by lightning discharges. However, due to the low electron density in the lower ionosphere, active probing of its electron distribution is difficult, and the various perturbative effects are poorly understood. Recently, we have demonstrated that by using remotely-detected time waveforms of lightning radio signals it is possible to probe the lower ionosphere and its fluctuations in a spatially and temporally-resolved manner. Here we report evidence of gravity wave effects on the lower ionosphere originating from the thunderstorm. We also report variations in the nighttime ionosphere atop a small thunderstorm and associate the variations with the storm's electrical activity. Finally, we present a data analysis technique to map ionospheric acoustic waves near thunderstorms.