Mid-Latitude Ionospheric Response to the Solar Eclipse of August 21, 2017: What do we learn from solar eclipse studies?

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From radio wave propagation to ionosphere

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Modifications of Electron Temperature and Concentration in Ionospheric *F* Region Due to Impact of High-Power Radio Waves

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Abstract. A decrease in the scatter cross-section was observed by incoherence scatter radar during an emission of high-power radio waves by the heating facility. It was shown that this phenomenon was caused by a temperature increase and a depletion of electron concentration in the *F* region.

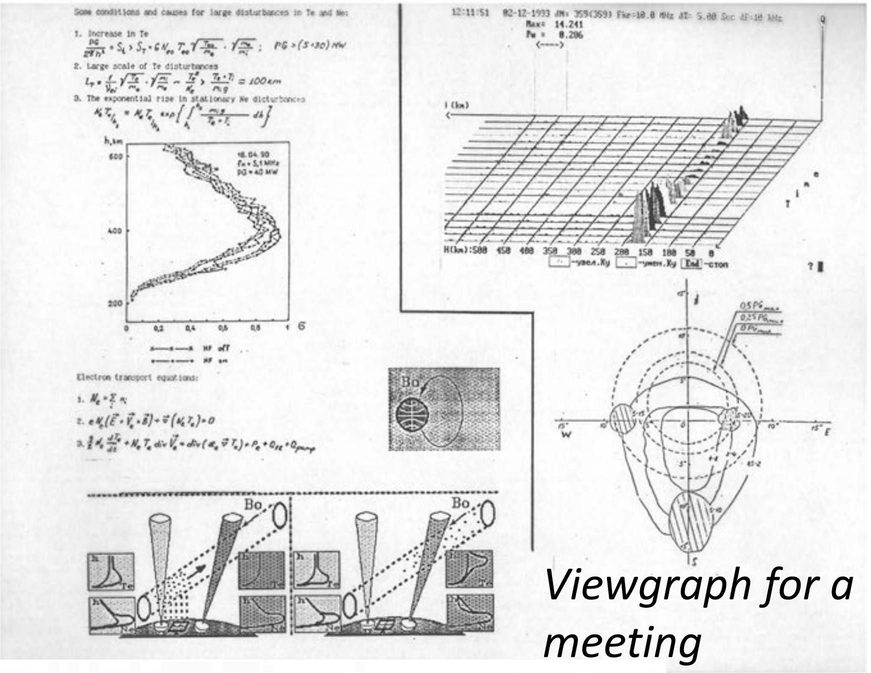
Introduction

During recent years, the impact of high-power radio waves on the ionosphere has been studied extensively. A number of experimental techniques have been developed for this purpose: test waves, Doppler delay, satellite measurements, etc. The major results have been obtained by the incoherent scatter radar technique, which provides details of spatial and temporal resolution. In particular, significant changes in ionospheric parameters due to high-power decametric wave emission are detected: the temperatures of electrons increase by 50-300%, and their concentrations decrease by 15-70% [*Duncan et al.*, 1988; *Hansen et al.*, 1992].

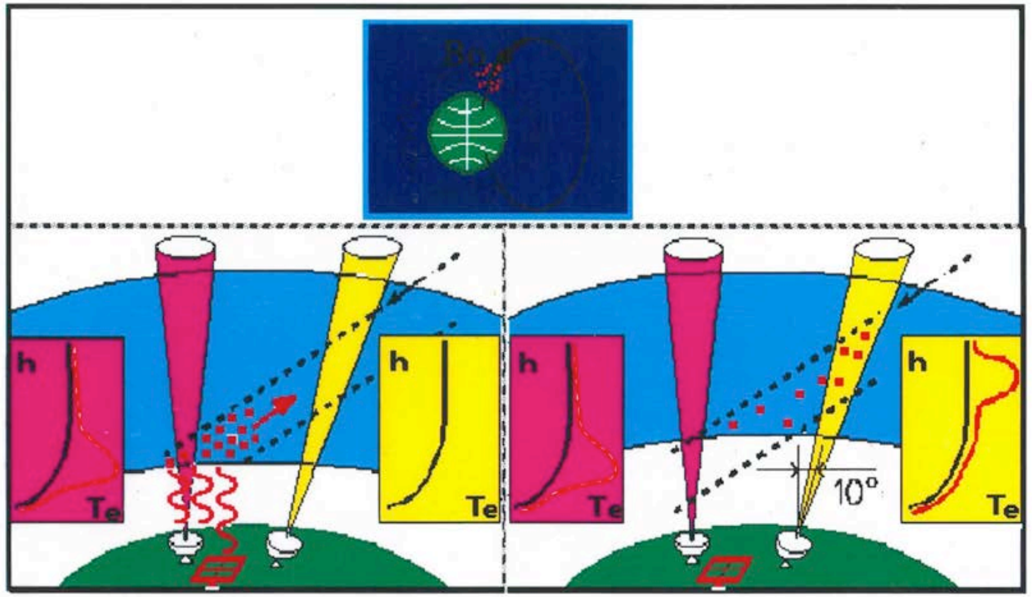
linear or circular polarization in both pulse and continuous modes.

Remote sensing of the artificially disturbed ionosphere is carried out by incoherent scatter radar and a vertical sounder. A two-mirror antenna (diameter, 100 m) with a fixed vertical directional pattern is used. The design width of the radar field-of-view is less than 1° and allows sounding of the plasma volume with a cross-sectional diameter of ~7 km at altitude 200 km. Figure 1 shows the experimental scheme. A few ope… modes of the radar are used to obtain altitude p… ionospheric parameters. These modes differ by… ration and recurrence frequency of the soundin… and the data processing technique. The durat…

Taran et al., Geomagnetism and Aeronomy, 1993



Viewgraph for a meeting



- My first computer program calculated HF wave propagation in a model ionosphere
- Very limited exposure to ham radio

- We study ionosphere to understand radio wave propagation
- We study radio wave propagation to understand ionosphere

What changes do we expect to see due to the eclipse?

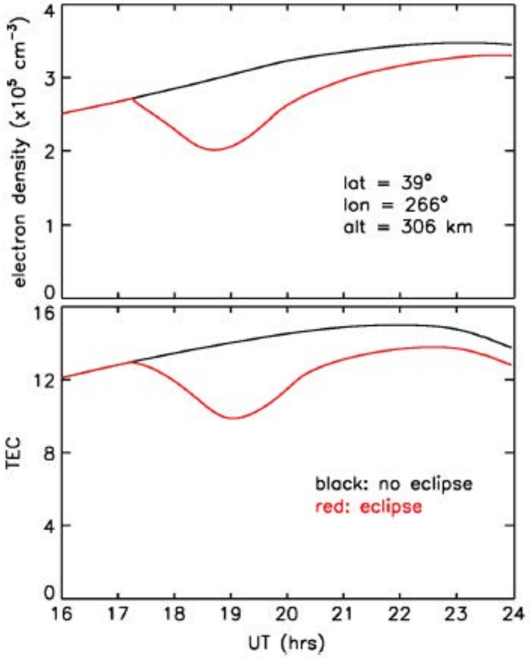
Ion (and electron) density continuity equation

transport

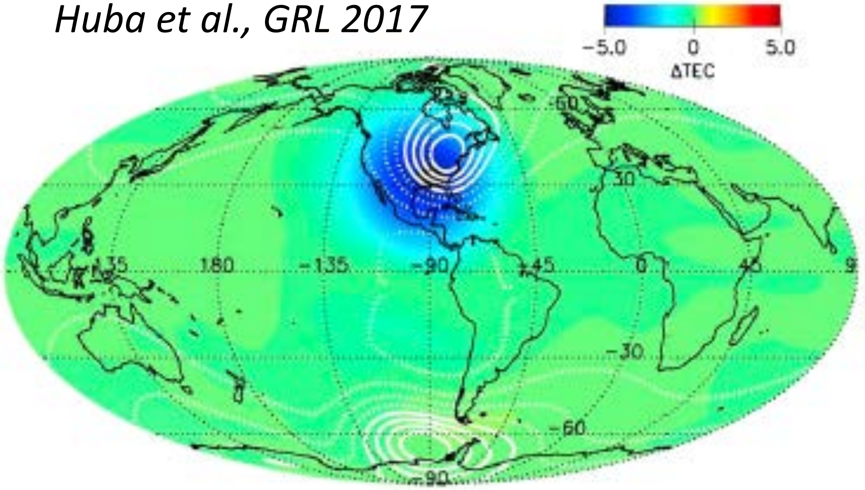
$$\frac{\partial N_i}{\partial t} = Q - L + \Delta \cdot (N_i V_i)$$

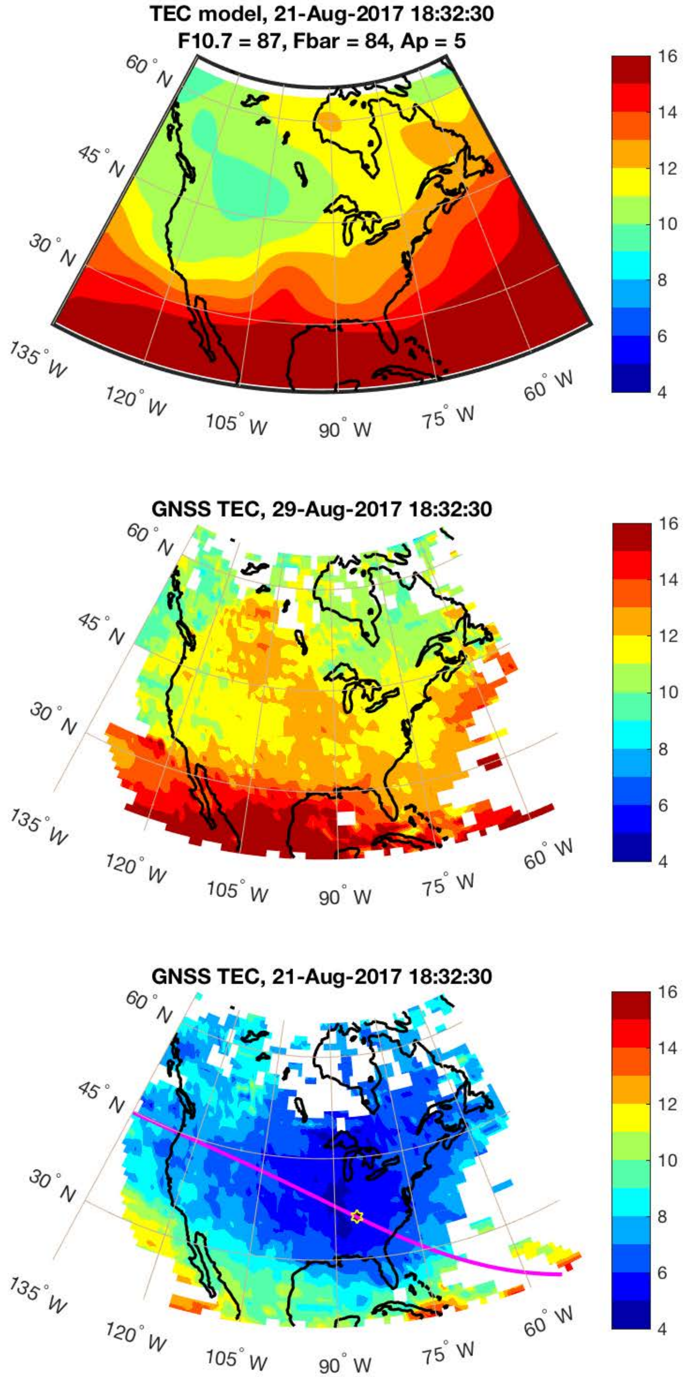
production loss

- **Production: proportional to solar radiation; decreases due to eclipse, decrease varies with height – *dominant role***
- Loss: depends on composition and temperature; varies with height – ***unknown role***
- Transport: depends on a wind system – ***unknown role***



SAMI3 simulations, Huba et al., GRL 2017



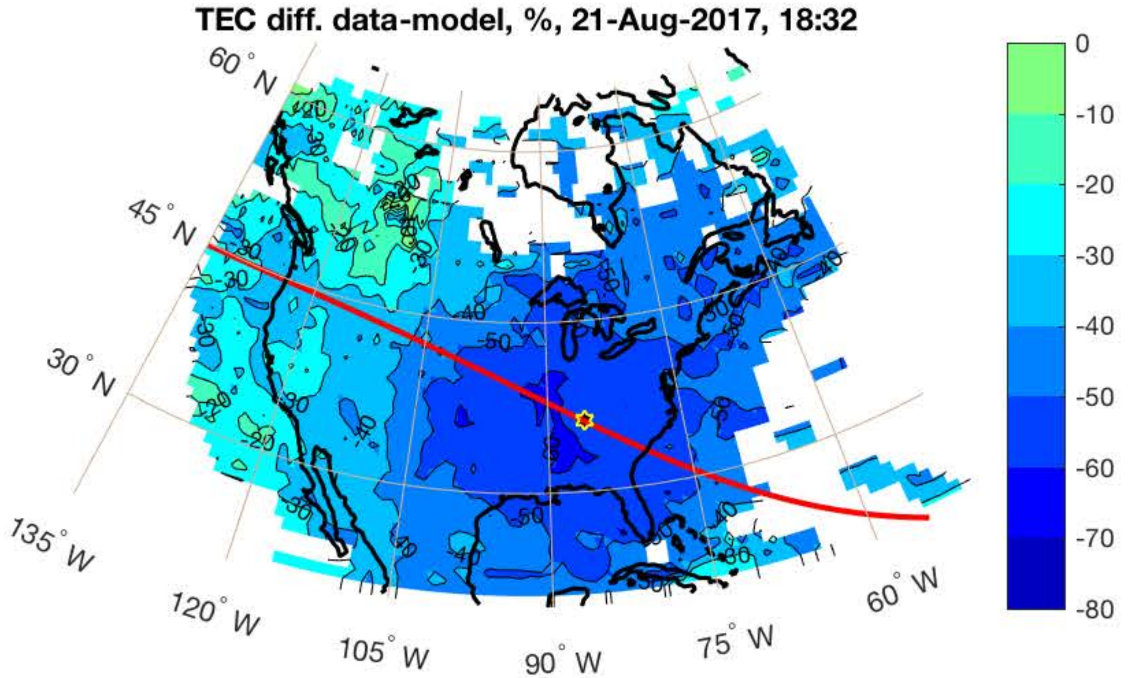


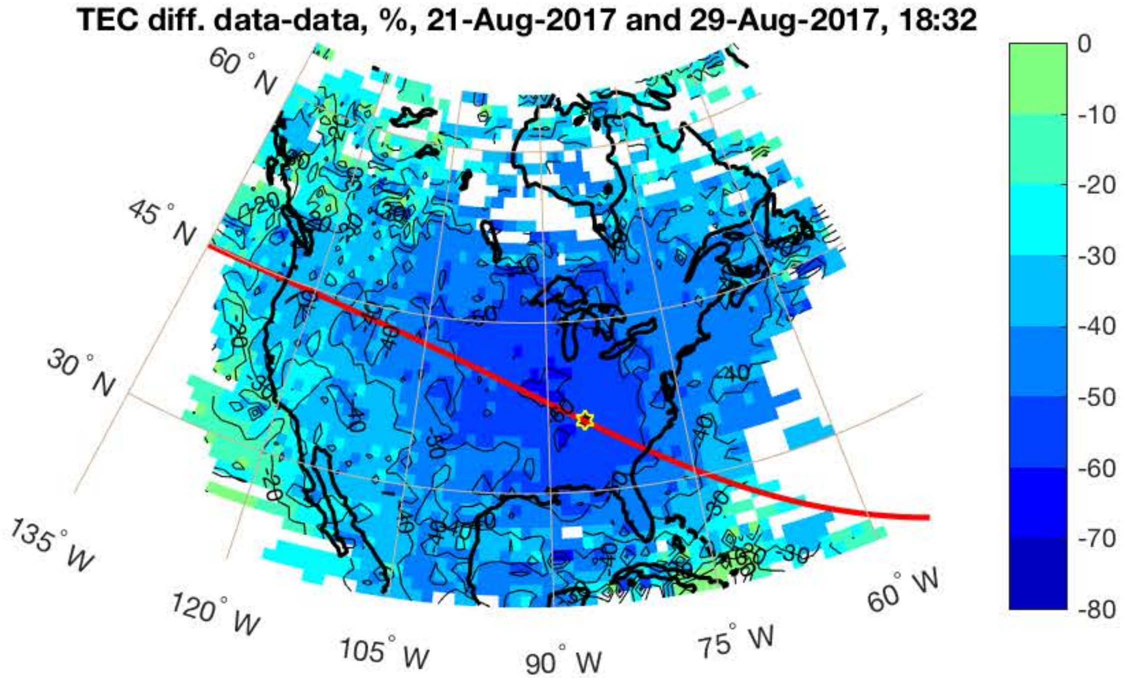
How large is the 'ionospheric hole' due to the eclipse?

- The answer depends on the selection of a baseline. We tried 2 methods, empirical TEC model (NATEC, Chen et al., 2015) and observations.
- Top panel: NATEC results (F10.7 = 87, Fbar = 84, Ap=5). North America TEC model works well and is a good indicator of expected behavior in TEC
- Middle panel: Observations for Aug 29, 2017, closest day with similar F10.7 (F10.7 = 84). Shows little lower TEC overall and a patch of higher TEC at 90-110W.
- Bottom panel: Observations for Aug 21, 2017; much lower TEC over entire continental US.

Coster et al., GRL, 2017

TEC change during Aug 21 eclipse





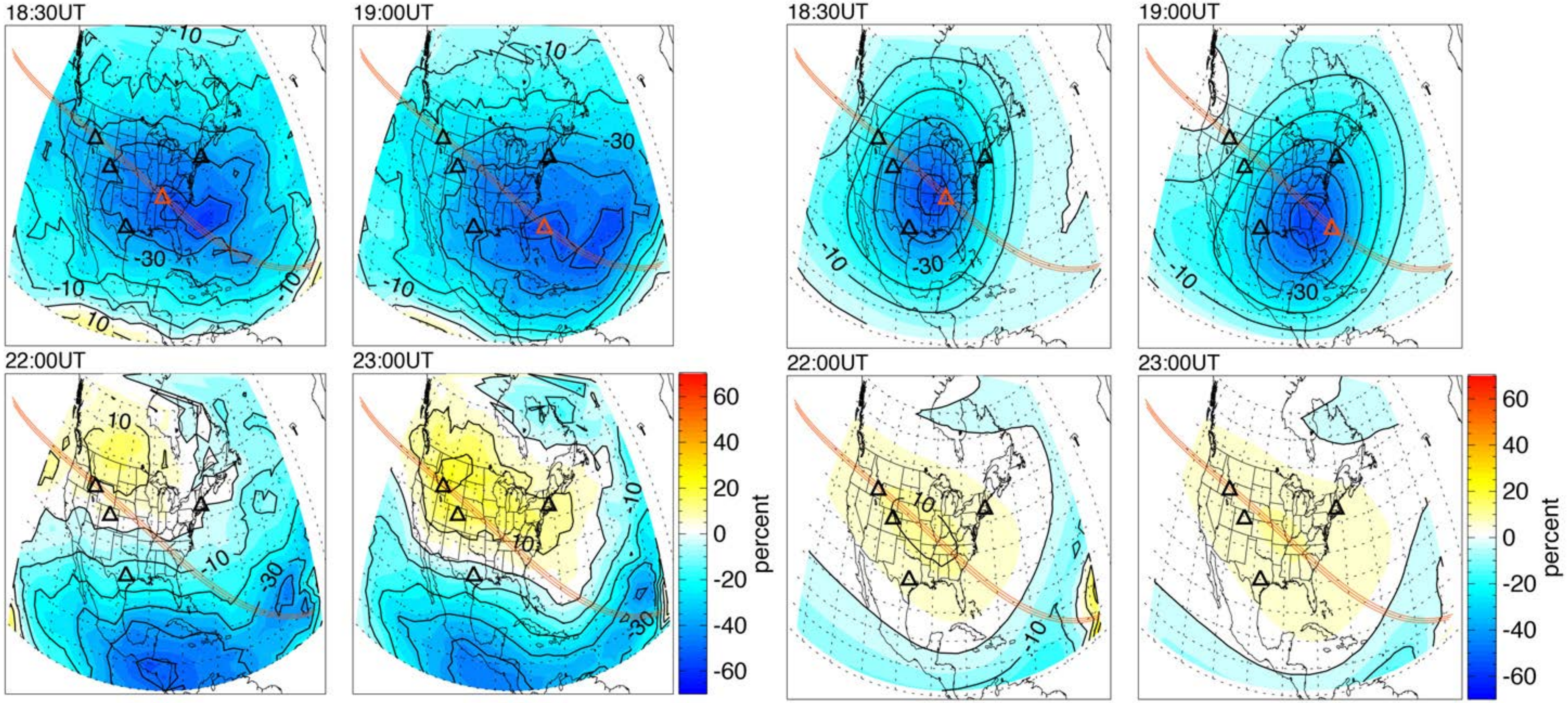
Coster et al., GRL, 2017

TEC **data-model** difference in % ;
Max decrease in TEC is 50-60%

TEC **data-data** difference in %;
Max decrease in TEC is 50-60%

- **Solar eclipse causes decrease in electron density & TEC over the entire continental US**
- Comparison of eclipse data (Aug 21) with NATEC model (left) and Aug 29, 2017 data (right)
- Results are very similar, regardless of a choice of background
- Largest decrease >60% is to the west of totality; shows nicely in model-data and data-data differences
- Strong depletions to the south of totality – see over Florida

Can theoretical models reproduce eclipse effects?

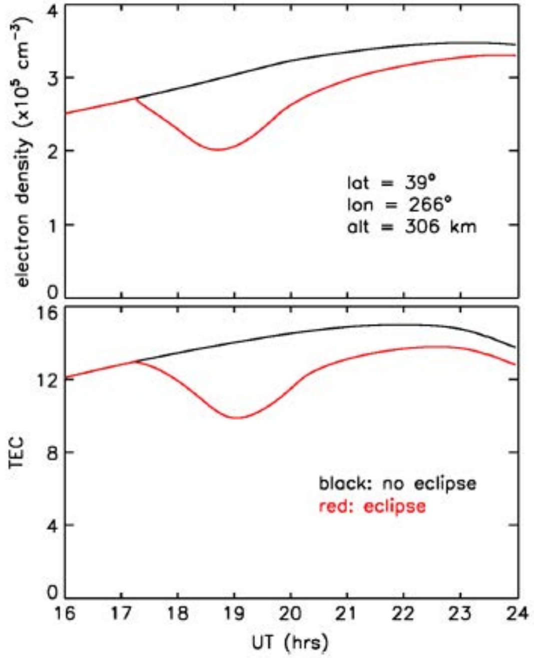


TEC data

GITM simulations: Wu et al., subm. to GRL, U. of Michigan

GITM model

…GITM simulation includes thermosphere and reproduces well the depth and the size of the 'eclipse hole'. It also reproduces well post-eclipse increase in electron density…



…Initial prediction with SAMI3 sees a 35% decrease in TEC. The model does not include thermospheric changes and misses some features, like recovery…

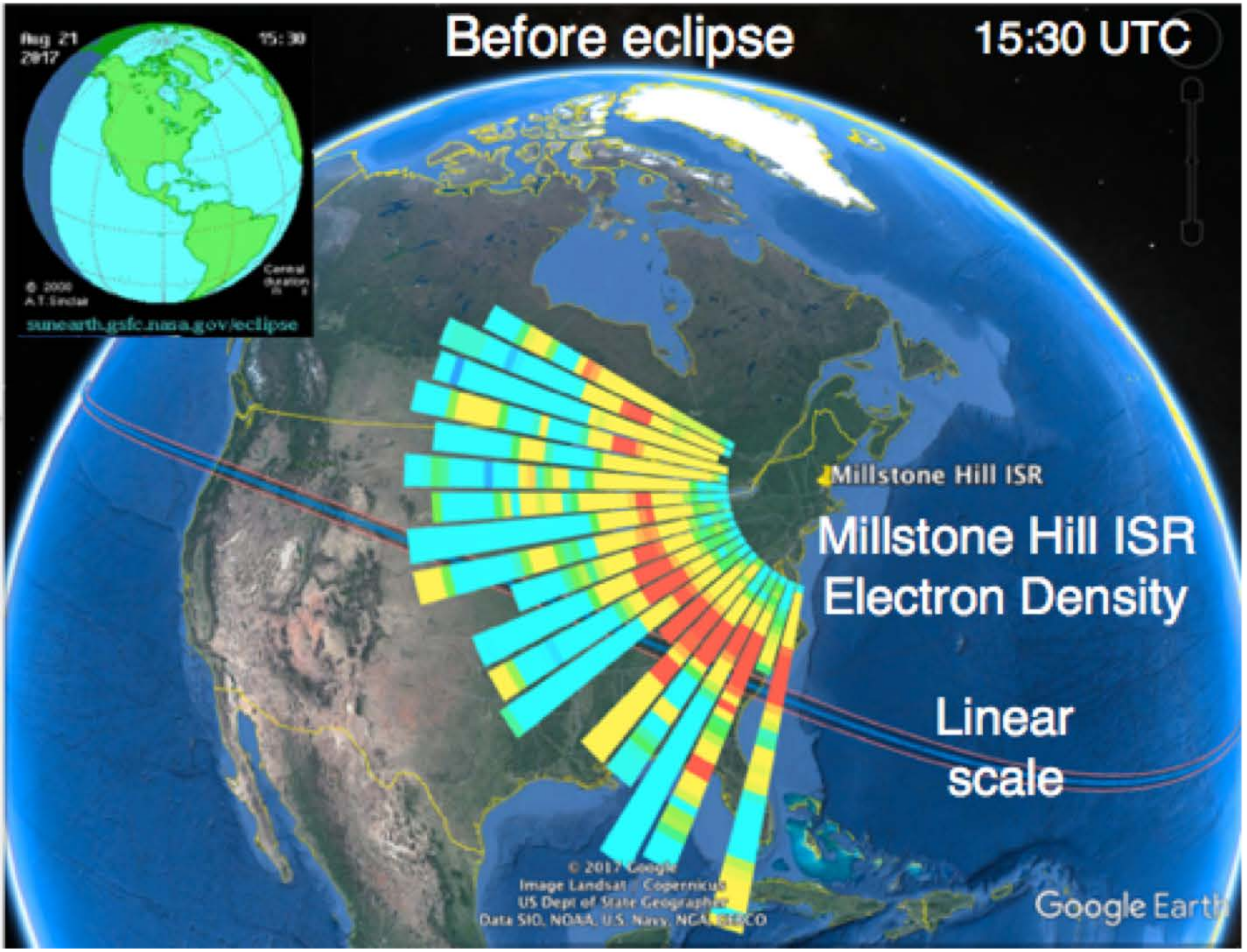
SAMI3 simulations, Huba et al., GRL 2017, NRL

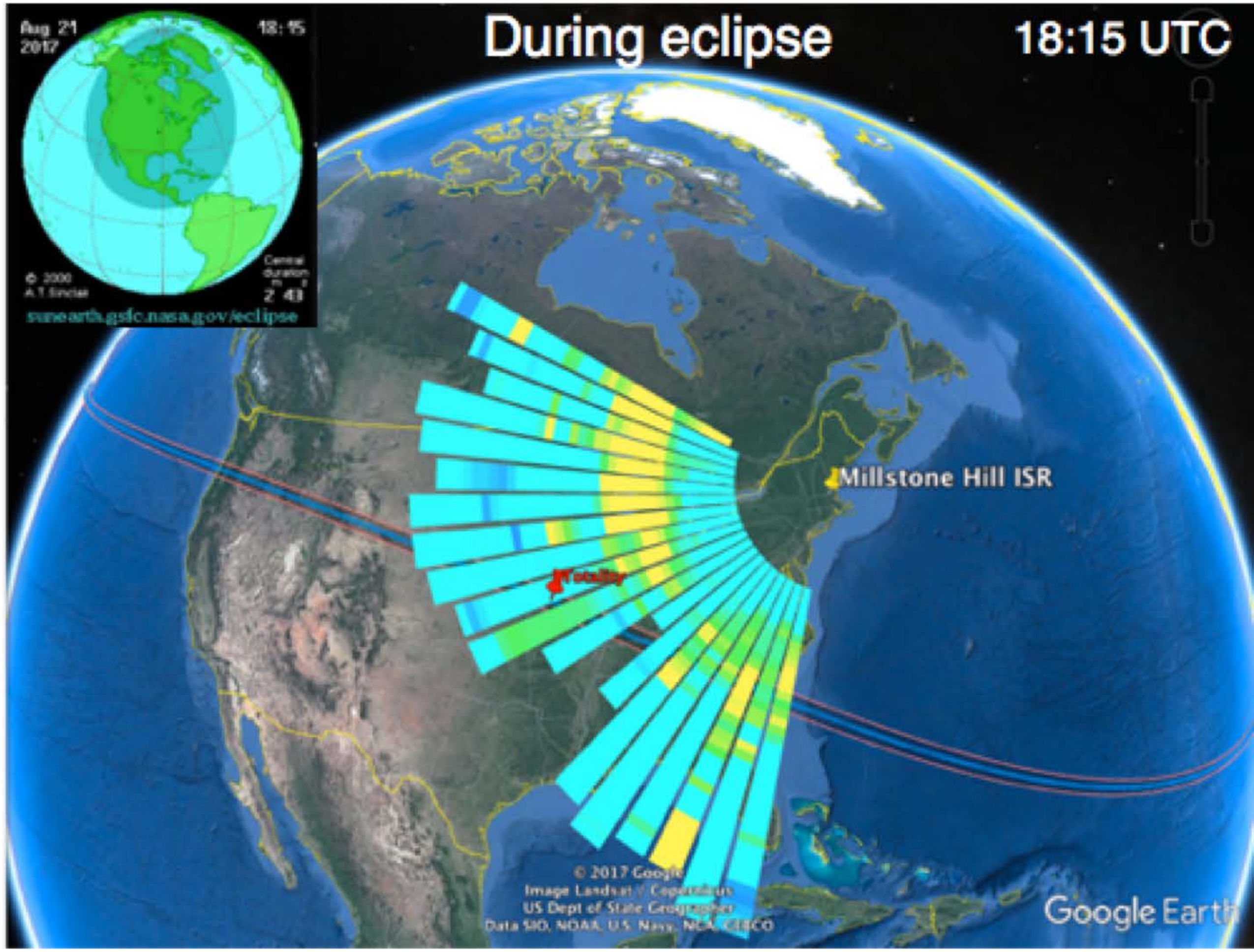
Fully coupled ionosphere-thermosphere models can better capture eclipse-induced changes than purely ionospheric models

Millstone Hill Geospace Facility: UHF Ionospheric Radar

Thomson / incoherent scatter
Full ionospheric altitude profiles
Wide field of view across eastern US (steerable)

Ionospheric Changes Over North America During The 2017 Eclipse



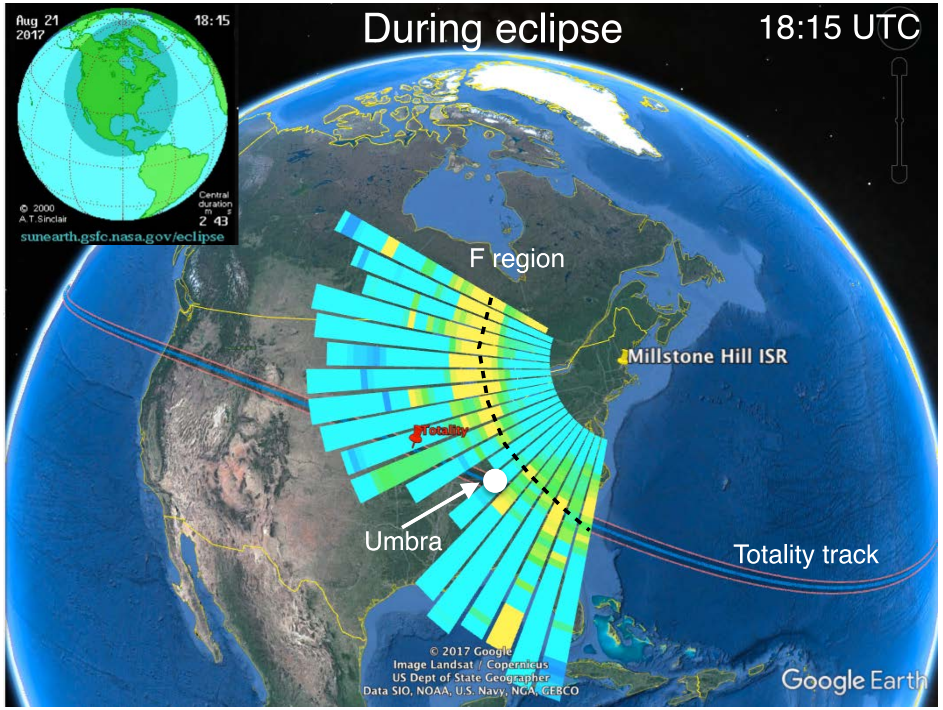


(figure: W. Rideout, MIT Haystack)

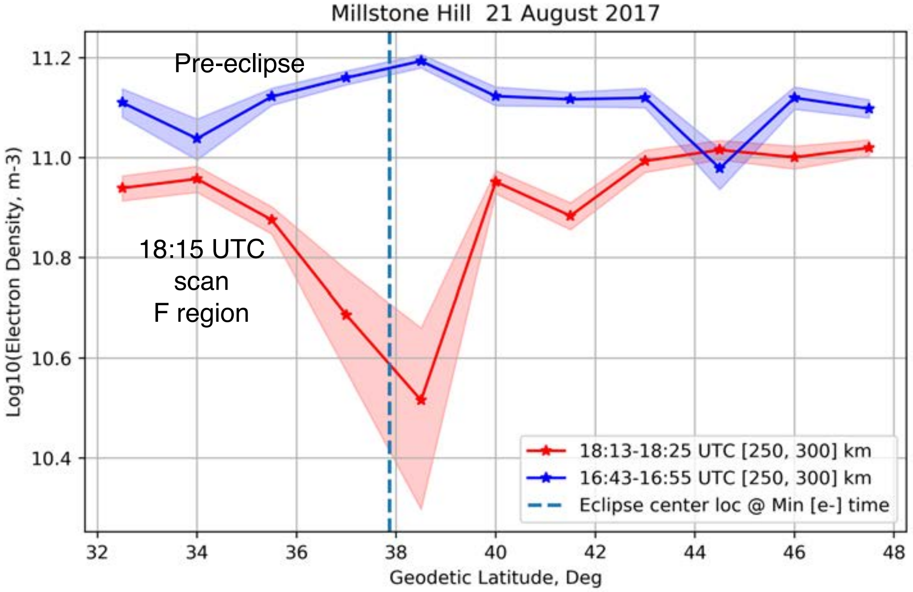
Millstone Hill Geospace Facility
Westford, MA, USA

Decrease in electron density during the eclipse by a factor of ~2

2D Snapshot: F Region Electron Density Decrease During The 2017 Eclipse



- 35-40% maximum [e-] density decrease
- Electron density dip is asymmetric:
  - ~ 4 deg equatorward of minimum
  - ~ 1 deg poleward of minimum
- Minimum [e-] within 1 deg latitude of totality umbra's latitude



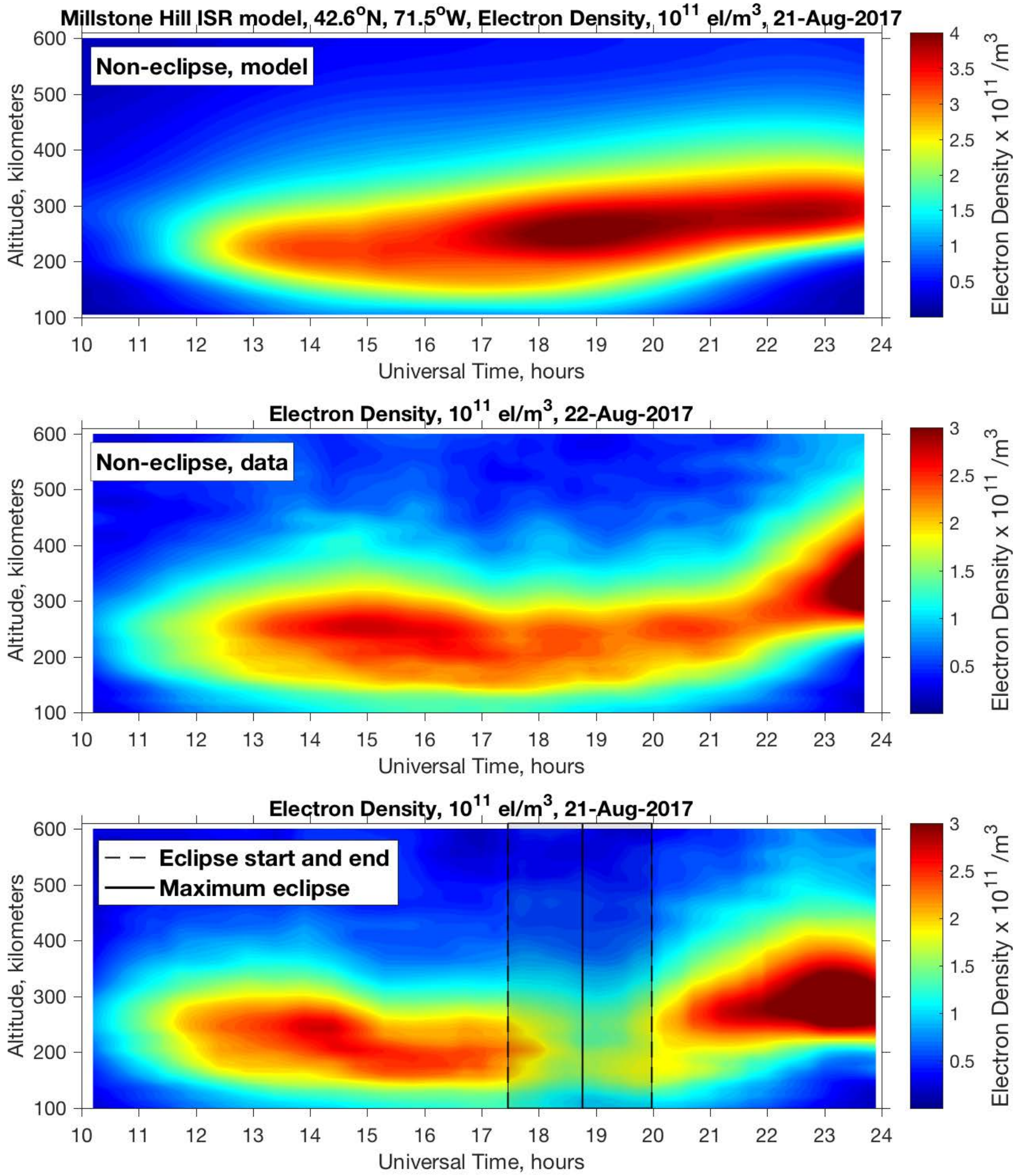
Millstone Hill Geospace Facility Westford, MA, USA

Support: NSF AGS-1242204, NASA NNX17AH71G

HAYSTACK OBSERVATORY

Ionospheric Changes Over Massachusetts During The 2017 Eclipse (>1000 km away from totality)

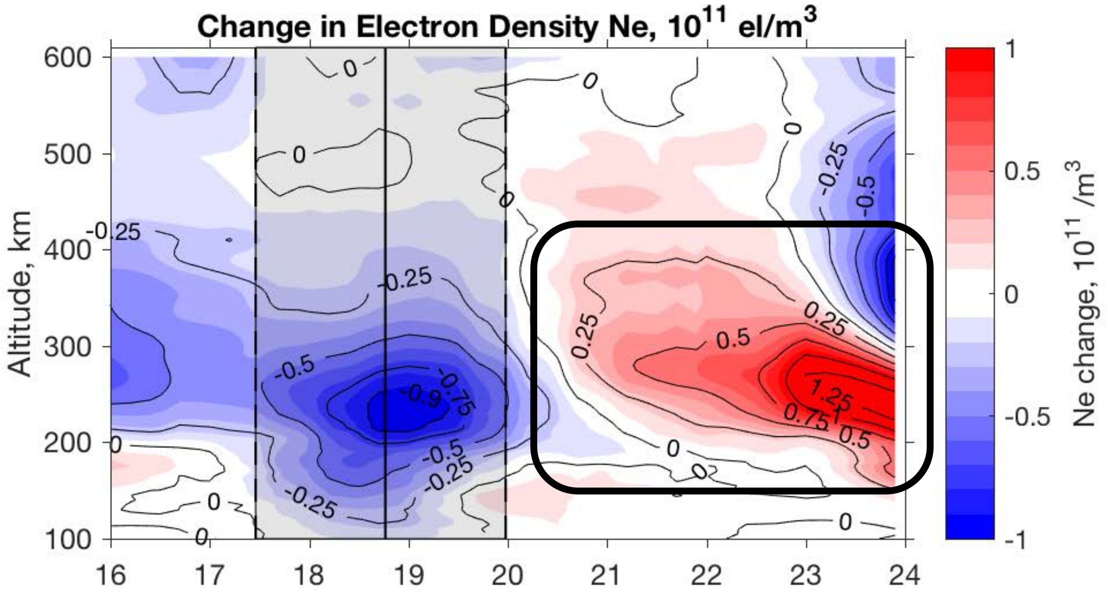
- Gradual decrease in electron density 100-600 km at eclipse start, more than 1000 km away from umbral shadow
- Quick recovery after eclipse
- Lower altitudes recovered faster than higher altitudes
- Natural space weather variations occurred even on non-eclipse day

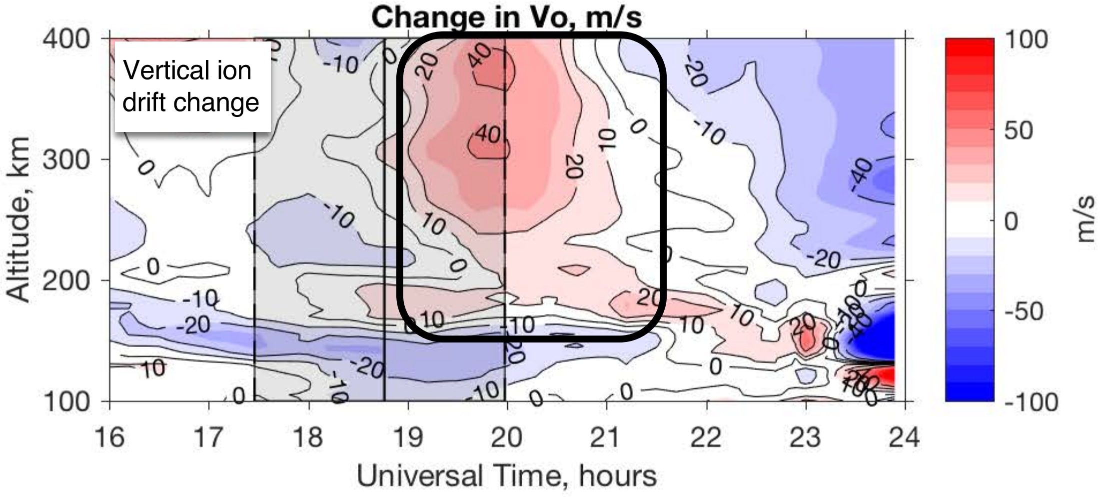


Goncharenko et al, subm. to GRL, 2018

Vertical Ionospheric Perturbations at Mid-Latitudes Seen With Incoherent Scatter Radar

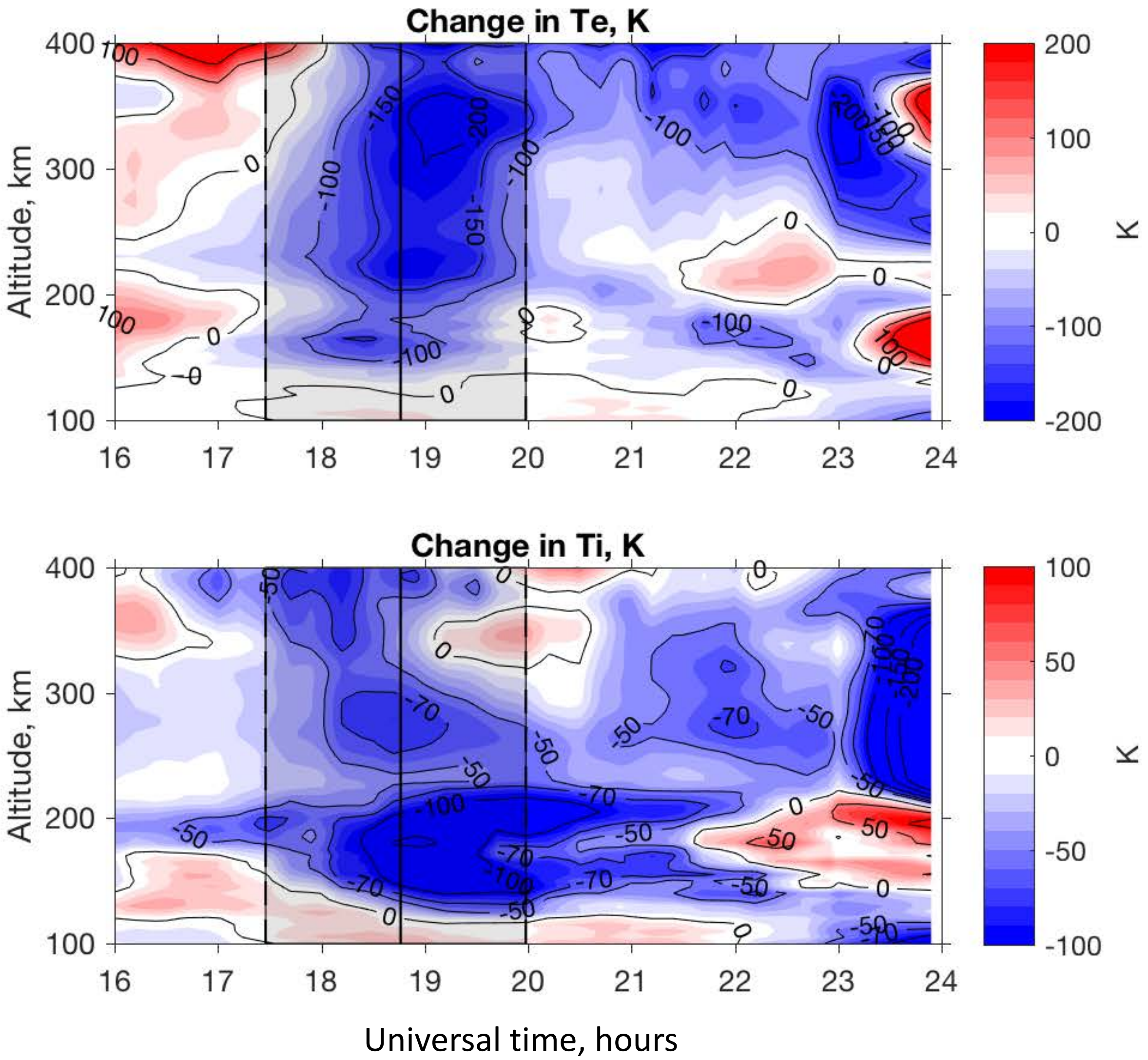
- **Expected** electron density decrease during the eclipse; peak decrease of 40% at ~230 km – why not F1-region?
- **Unexpected** very large F region electron density increase 21-24 UTC; delayed eclipse effect [plasmasphere supply]?
- **Unexpected** very strong upward 40+ m/s F region ion drift after eclipse maximum
- Reminiscent of local sunrise, but much larger amplitude; potentially due to enhanced thermospheric heating and/or enhanced wind





Goncharenko et al, subm. to GRL, 2018

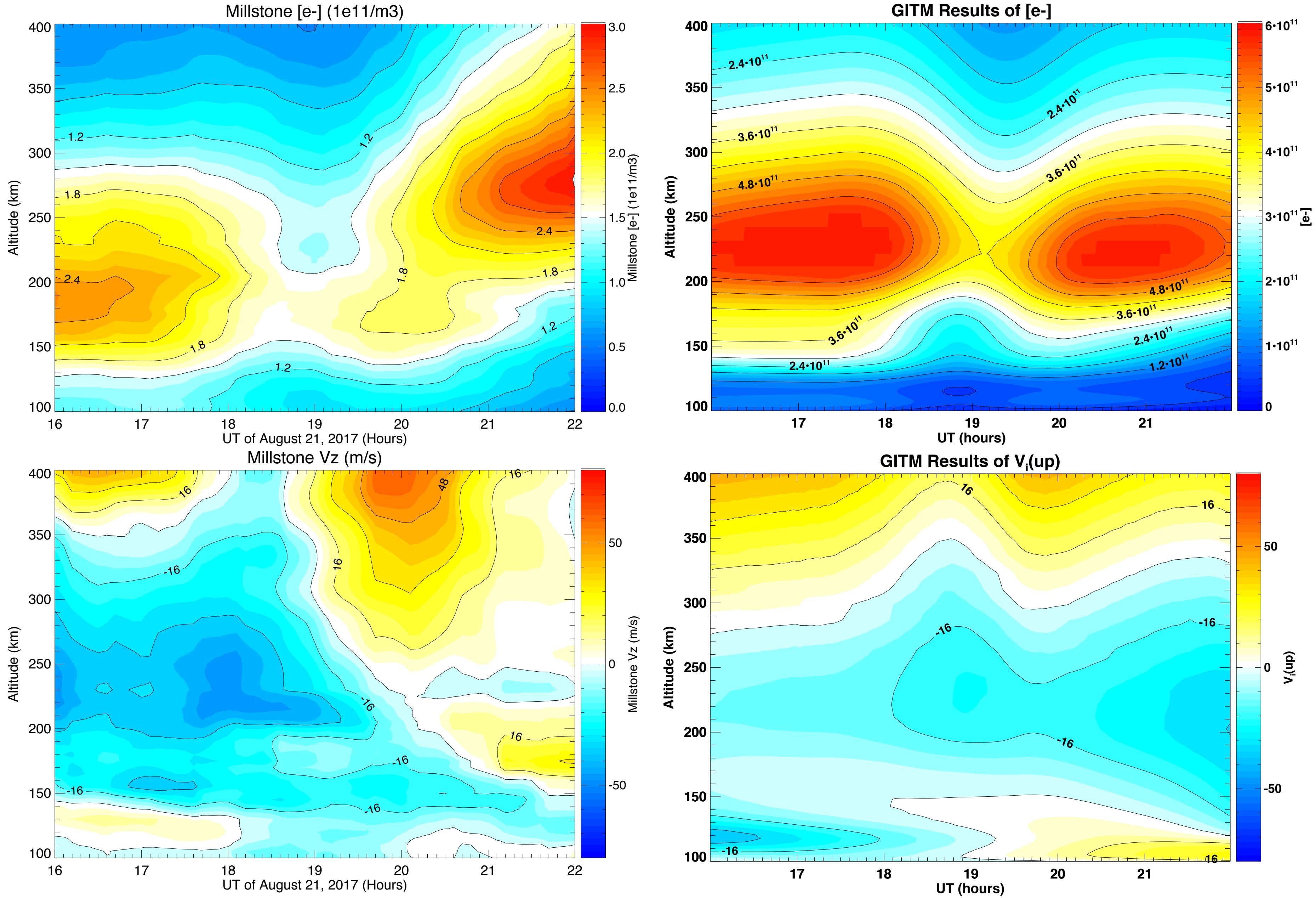
Plasma temperature changes, Millstone Hill ISR



- There is a chill in the air during the eclipse; 150-200 K cooling of electron temperature
- Lower than 500-600 K cooling observed in other eclipse cases – why?
- Cooling is delayed; longer delay at higher altitudes
- Cooling of ion temperature is 70-100 K; symmetric around eclipse max above F-region peak, longer delay below 200 km

Goncharenko et al, subm. to GRL, 2018

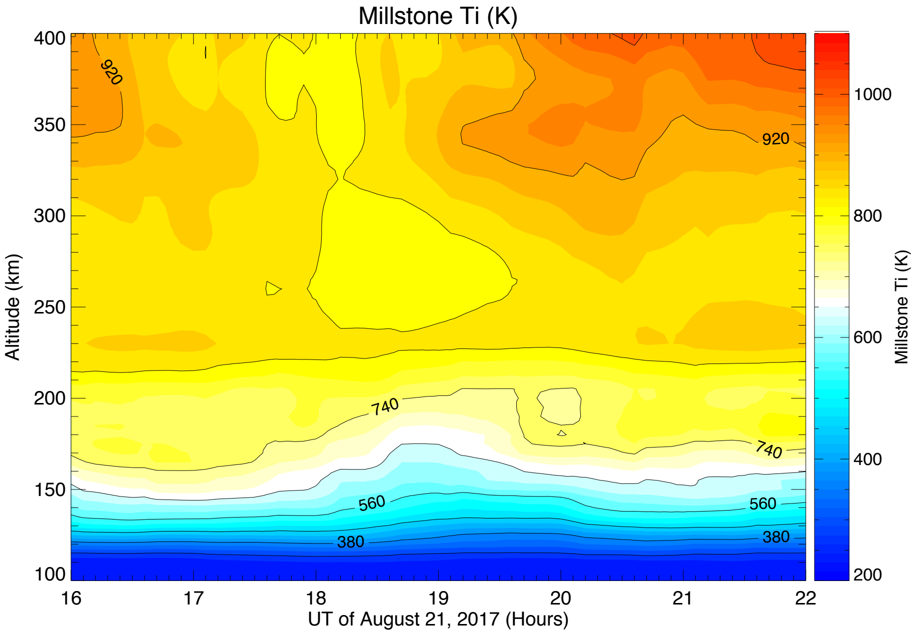
Millstone Hill ISR and GITM model: Ne and Vi

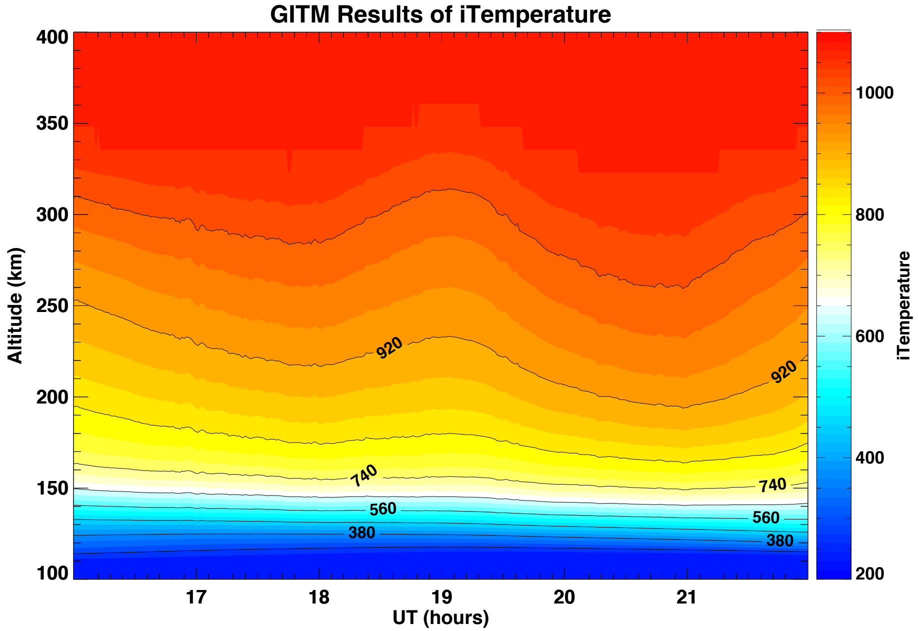


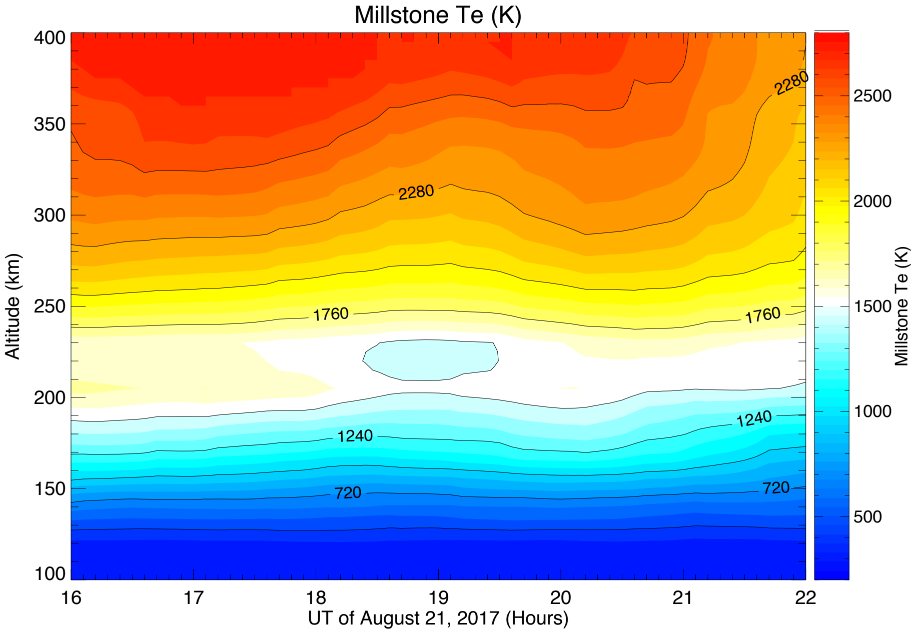
- Initial state: GITM electron density is higher ~ factor of 2
- Model captures well eclipse effects due to change in ionization (Ne decrease)
- Effects related to dynamics are more challenging to simulate (differences in Vi, height of F2 region post-eclipse)

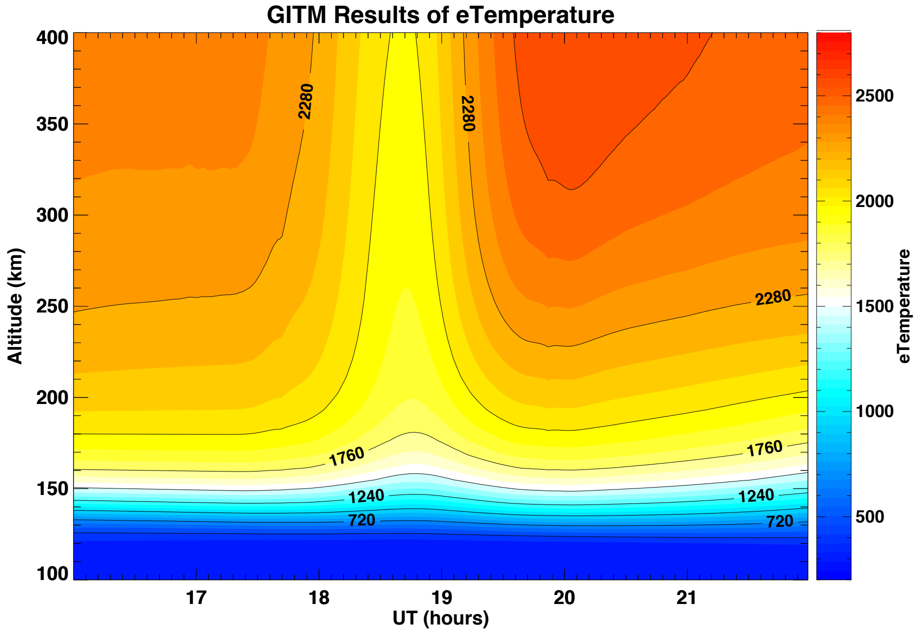
GITM simulations: Aaron Ridley and Chen Wu, Wu et al., manuscript in preparation

Millstone Hill ISR and GITM model: Ti and Te









- Differences in the initial state: observed Ti is colder than predicted, but Te is higher
- Eclipse-induced cooling in Te is lower than predicted – why?

GITM simulations: Aaron Ridley and Chen Wu, Wu et al., manuscript in preparation

Summary

- Large volume of high-quality experimental data on different aspects of ionospheric response to the eclipse of Aug 21, 2017
- Some ionospheric features are expected, some are not
- Significant difference in ionospheric response to eclipse in both latitude and longitude
- Theoretical models capture well ionospheric variations related to changes in ionization; simulation of dynamics is more challenging
- Large differences in eclipse response in different models