A Few Highly-Specific Examples of Modeling in Aeronomy

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CEDAR 2014 Workshop, Seattle WA


PRESENTING AT AN INSTRUMENTATION WORKSHOP
AS A MODELER

Myth:

Modeling is a (superior/inferior) substitute for Experiments, Observations, and Theory.

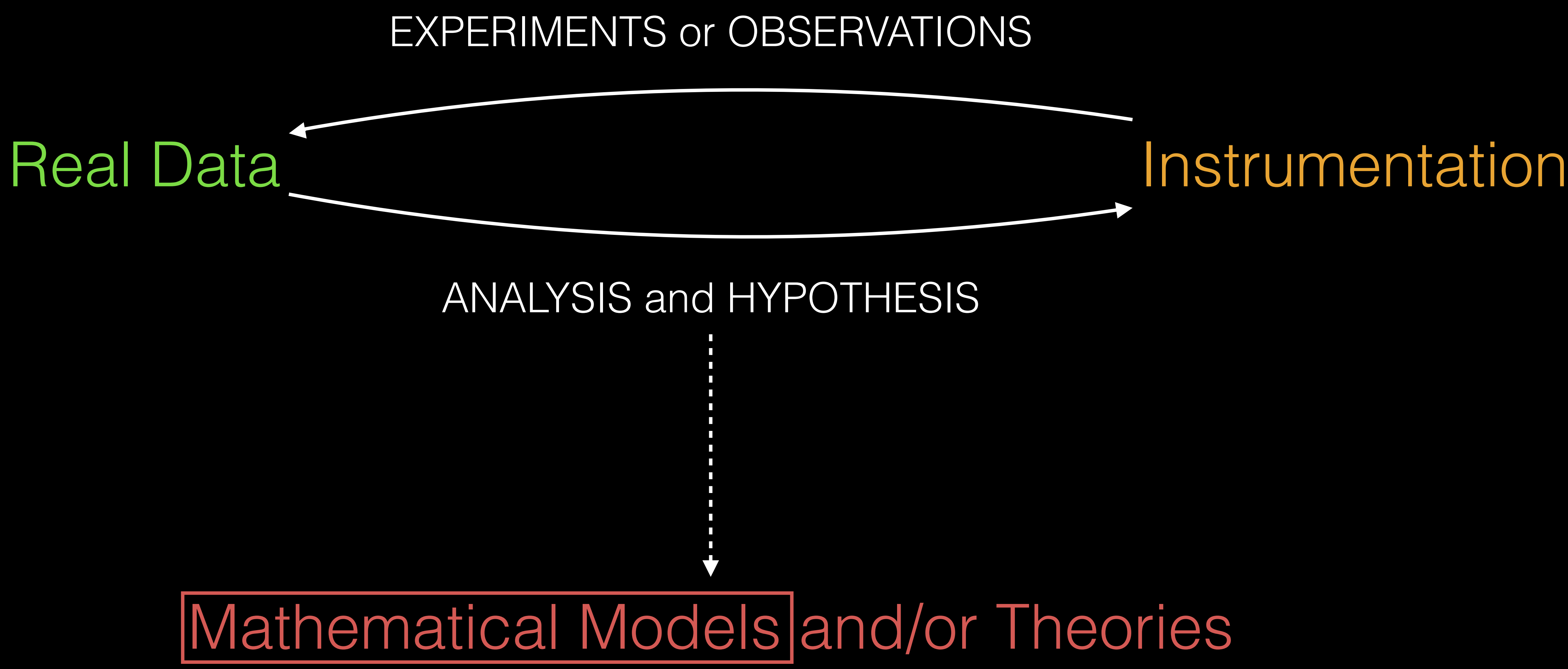
Reality:

Modeling is complementary with Experiments, Observations, and Theory.

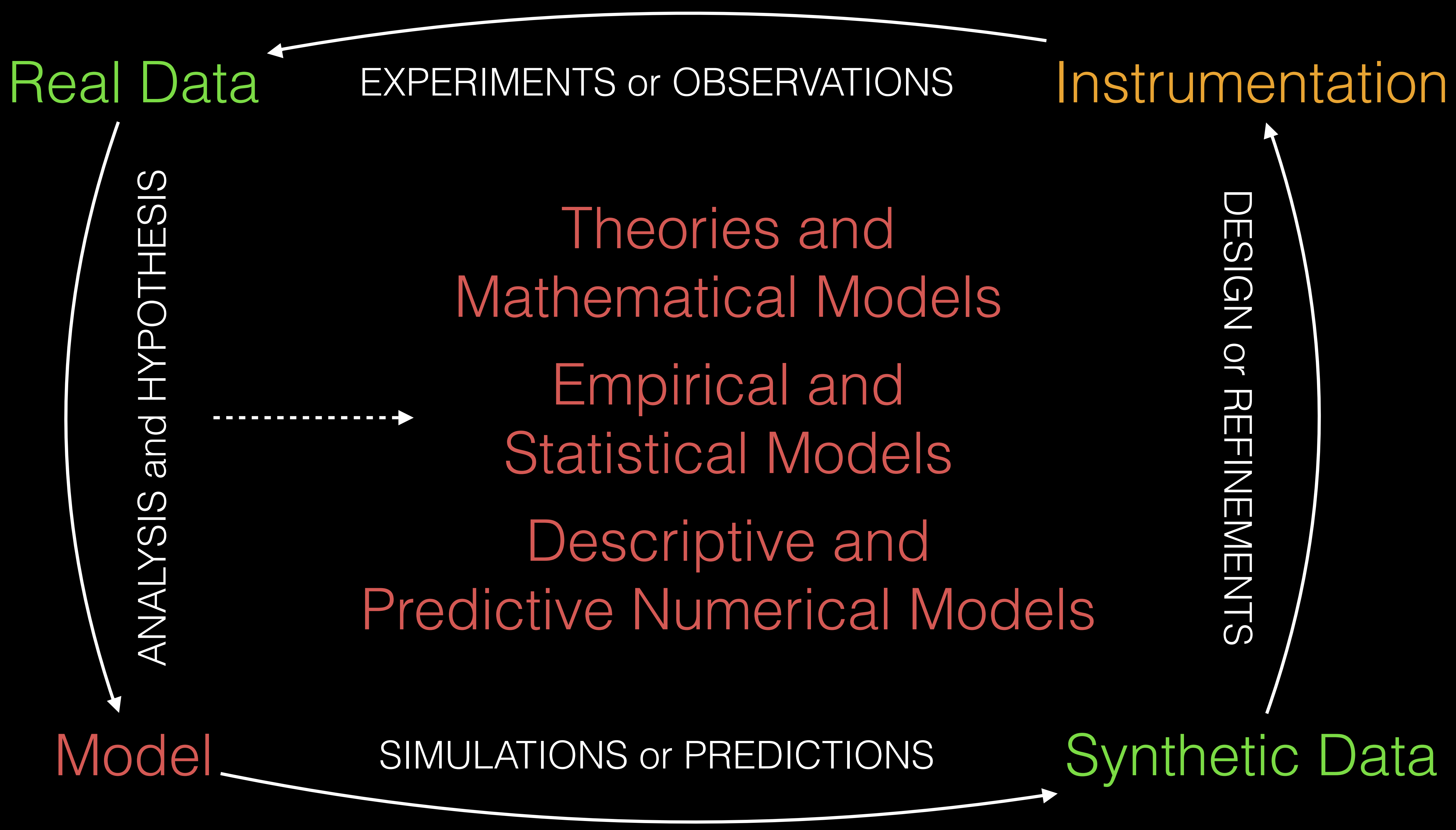
Contents

- **What is Modeling (in the context of this talk)**
- Models in Aeronomy
- Modeling Case Studies
- Examples of Modeling to Elucidate Observations

Experimental Science



"Models" can be intermediate products to Theories
OR useful mathematical descriptions or relationships.



As science evolves, the models can become part of the “loop”!

As an Experimentalist,

… often use Theory and Modeling to develop and validate new instruments and data analysis methods.

As a Modeler,

… often combine Theory with Experimental data to develop, validate, and utilize new Models.

As a Theoretician,

… often use insight from Experiments, and use Models when general solutions become impossible, tedious, or nonlinear.

Working <u>together</u> (Collaboratively*), we can more efficiently advance science, to *observe*, *explain*, and *describe* complex natural systems and phenomena.

*More feasible than doing all at once

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- **Models in Aeronomy**
- Modeling Case Studies
- Examples of Modeling to Elucidate Data

Some Models in Aeronomy

- Theoretical Models
- Empirical / Statistical Models
- Physics-Based Numerical Models
- Hybrid Physics / Assimilative Models

Some Models in Aeronomy

	May be:
• Theoretical Models	**Derived from First Principles or Continued Experiments**
• Empirical / Statistical Models	**Fit to Experimental Data**
• Physics-Based Numerical Models	**Numerical Solutions of Theoretical / Mathematical Models**
• Hybrid Physics / Assimilative Models	**Numerical Solutions of Theoretical / Mathematical Models With Input From Experimental Data**

Some Models in Aeronomy

Examples:

- Theoretical Models
  - Navier-Stokes' Equations of Fluid/Gas
  - Maxwell's Equations of Electromagnetics
- Empirical / Statistical Models
  - Model of Species Densities and Temperatures
  - Model of Mean Winds
- Physics-Based Numerical Models
  - Solution for Atmospheric Equations of Motion
  - Solution for Ionospheric MHD
- Hybrid Physics / Assimilative Models
  - Ionospheric TEC Forecast Model
  - Operational Weather Prediction Model

Some Models in Aeronomy

Examples:

- Theoretical Models
  - Navier-Stokes' Equations of Fluid/Gas
  - Maxwell's Equations of Electromagnetics
- Empirical / Statistical Models
  - MSISE-90 / NRLMSISE-00
  - HWM-93 / HWM-07 IRI CIRA
- Physics-Based Numerical Models
  - WACCM CMAM SWMF / GITM
  - TGCM / TIE- / TIME-GCM SAMI 2/3
  - MM5 WRF NOGAPS-ALPHA
- Hybrid Physics / Assimilative Models
  - USU-GAIM ECMWF / IFS / EULAG
  - NOGAPS-ALPHA w/NAVDAS
  - WRF / WRFDA CMAM-DAS

Flashback!

2013 Student Workshop Focus: **Modeling**
(Next pages are linked to presentations!)

The Basics of Modeling the Thermosphere and Ionosphere

Now Available in 1D!

Aaron Ridley[1]

[1]Department of Atmospheric, Oceanic and Space Sciences
University of Michigan

CEDAR Student Workshop, 2013

Data Assimilation Models

L. Scherliess

Center for Atmospheric & Space Sciences
Utah State University

Logan, Utah 84322

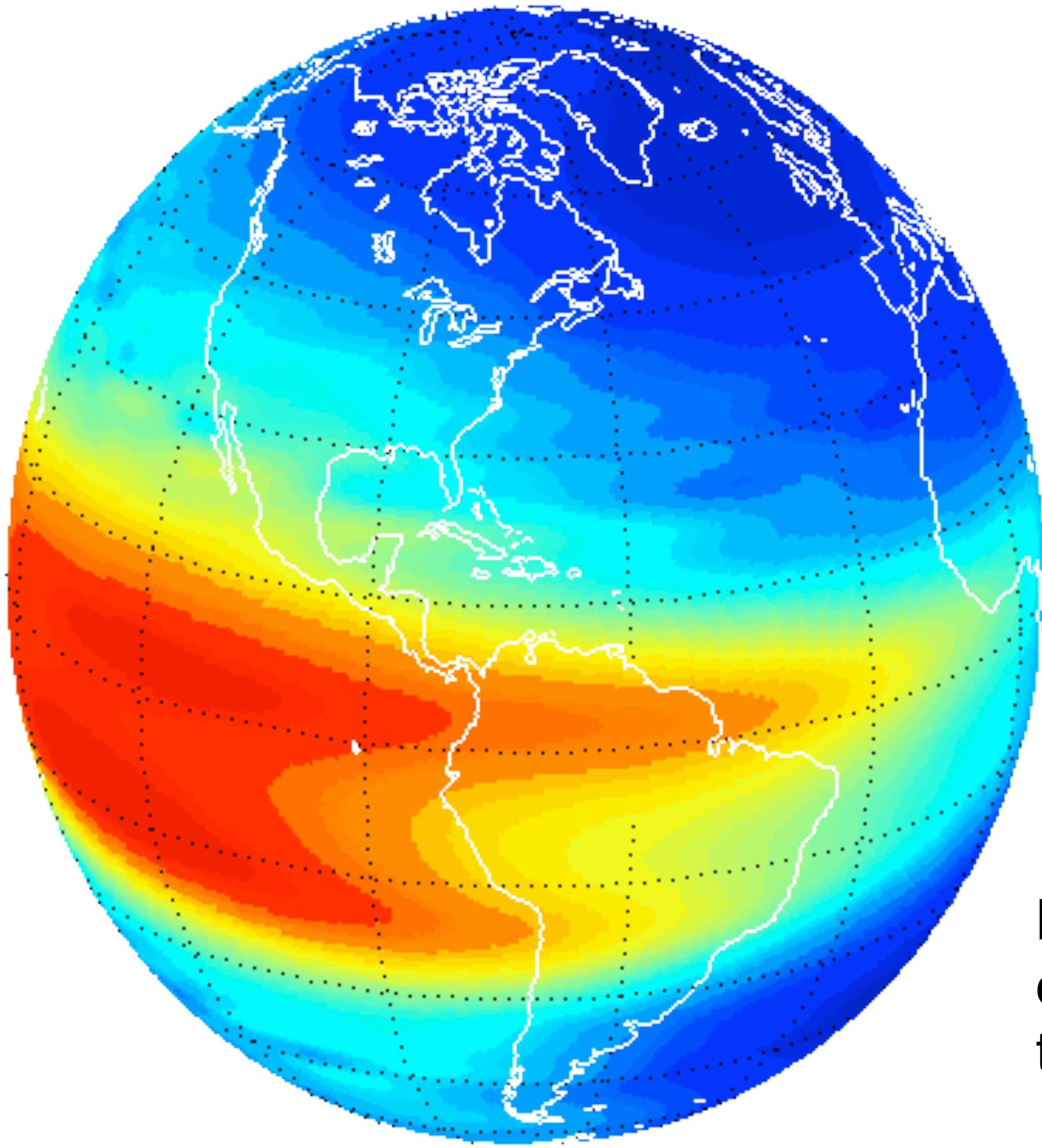
CEDAR Workshop
Santa Fe
June, 2013

G A I M
"Bringing The Pieces Together"

Utah State University

Ionospheric Data Assimilation:

Techniques and Performance



Anthony Mannucci, JPL

Xiaoqing Pi, JPL
Attila Komjathy, JPL
Mark Butala, JPL
Chunming Wang, USC
Vardan Akopian, JPL
Brian Wilson, JPL

Based on material originally developed by Brian Wilson (JPL) for the URSI General Assembly 2008

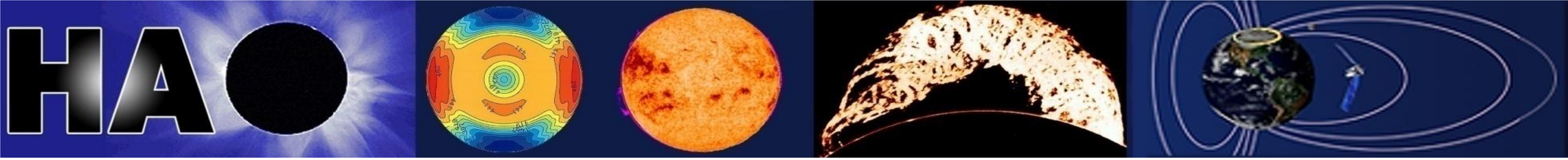
MODELING THE EARTH'S IONOSPHERE (WITH SAMI2)

J.D. Huba
Plasma Physics Division
Naval Research Laboratory
Washington, DC

CEDAR Workshop
Boulder, CO

23 June 2013

Acknowledge: G. Joyce and M. Swisdak



What can I do with the TIEGCM?

Astrid Maute and lots of people at HAO, and the community

High Altitude Observatory

NCAR

NCAR

High Altitude Observatory (HAO) – National Center for Atmospheric Research (NCAR)

The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation. An Equal Opportunity/Affirmative Action Employer.

June 2013

Models in Aeronomy

- Theoretical / Mathematical Models
- Empirical / Statistical Models
- Physics-Based Numerical Models → **Modeling Case Studies**
- Hybrid Physics / Assimilative Models

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Chicken or Egg?

Which comes first: Model or Experiment?

It depends…

¿🐣?

Usually, experiments inspire model development and “simulations”; other times, models predict new observable phenomena.

Why Perform a Modeling Study?

A few reasons (among others):

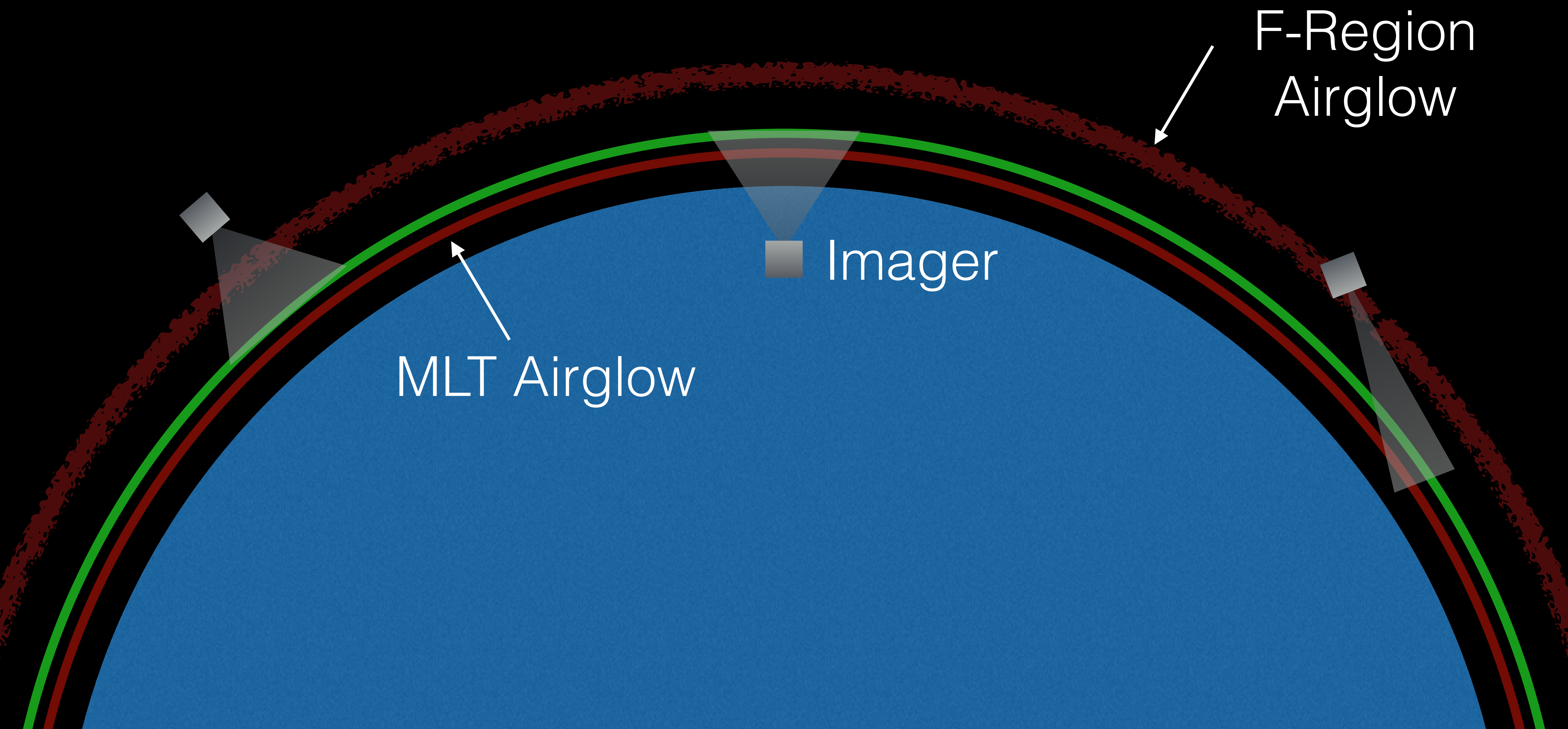
1. **Explanatory**: To simulate systems or observed scenarios, to interpret or extend experimental data.

2. **Explorative/Predictive**: To predict outcomes or to produce "synthetic data" to guide experiment design.

3. **Theoretical**: To investigate complex systems or scenarios under controlled, reproducible conditions.

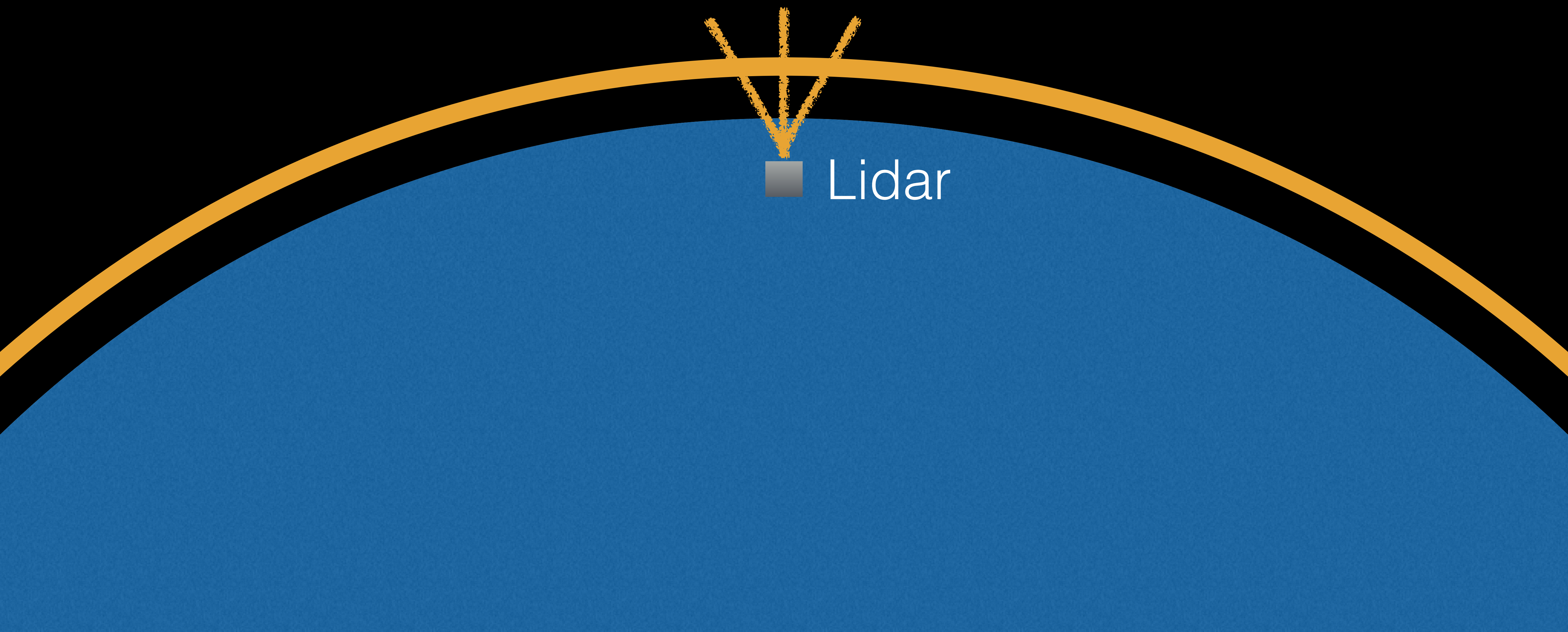
Example: Imaged/Integrated Airglow Intensity and Temperature Data

A Small Caveat: Observable systems are layers of finite thickness!



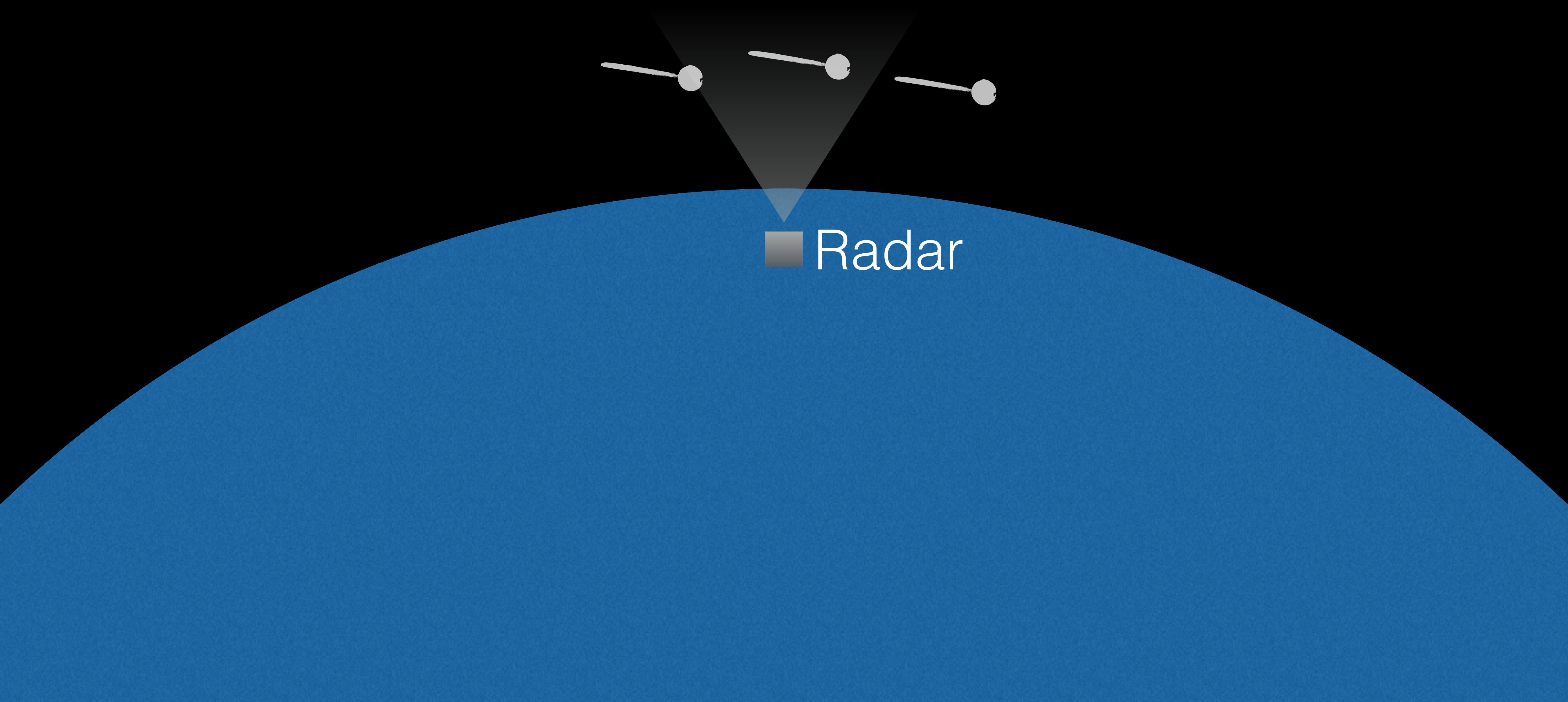
Example: Resonance or Rayleigh Lidar Temperature/Density Data

A **Small Caveat:** Observations usually restricted to profiles!



Example: Meteor Wind Radar Data

A Small Caveat: Quality of observations determined by meteor trails, which also occur over a narrow range of altitudes.



Limitations of Observed Data

(that Models can help to circumvent!)

- Altitude span (~80-100km, ~250km)
- Resolution (Time/Space)
- Geographic constraint (Excellent data over your favorite observatory / under your satellite)
- Time (Day/Night/Uptime/Season)
- Observed System Biases (Noise, Nonlinearity)

Example Case Study:

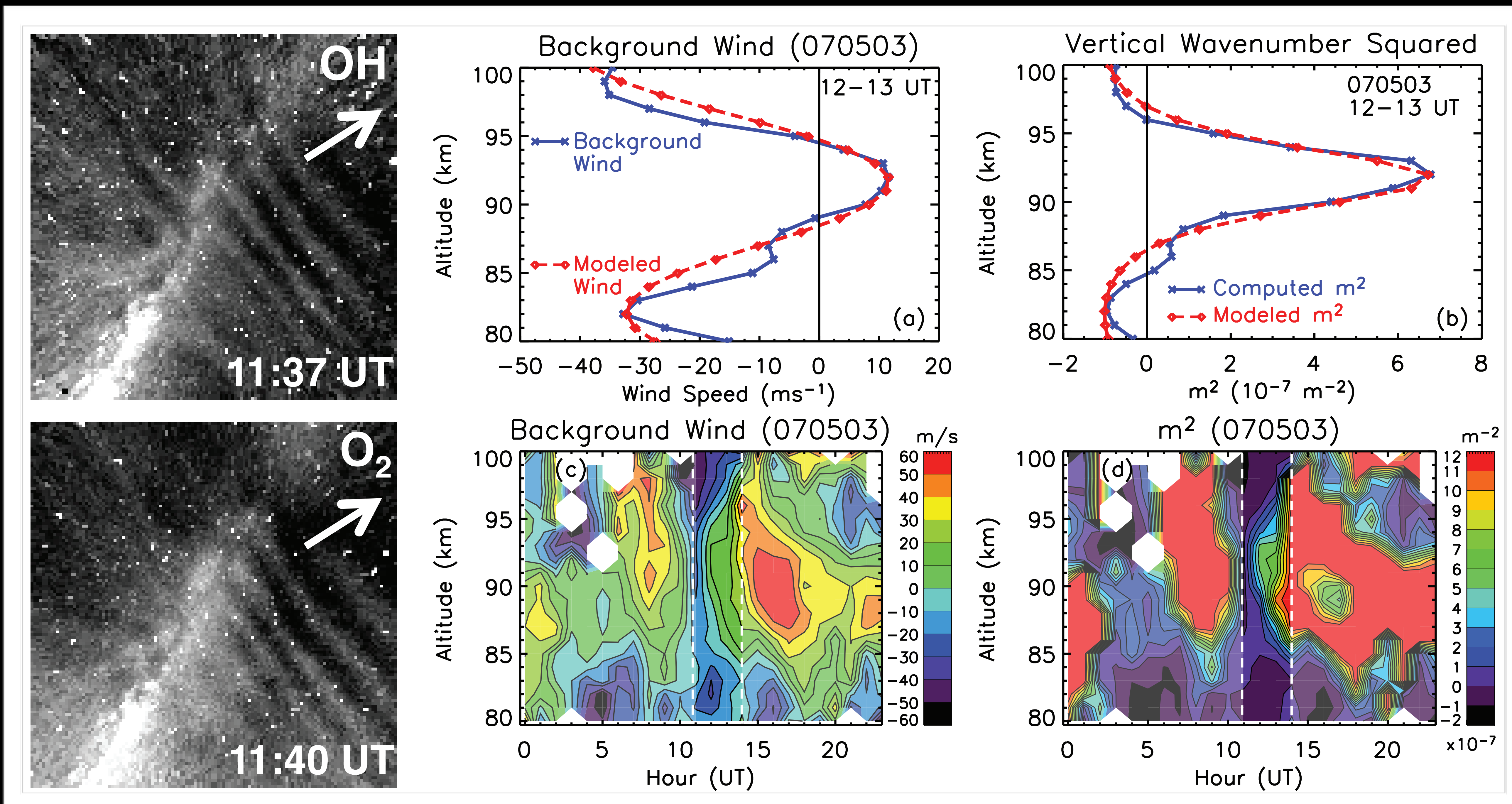
Simulating short-period gravity wave propagation to elucidate wave dynamics near the airglow layers.

[e.g., *Simkhada et al.*, ANGEO, 27, 2009]

Short-Period Wave Propagation:

Weak Trapping in Mesospheric Wind Fields

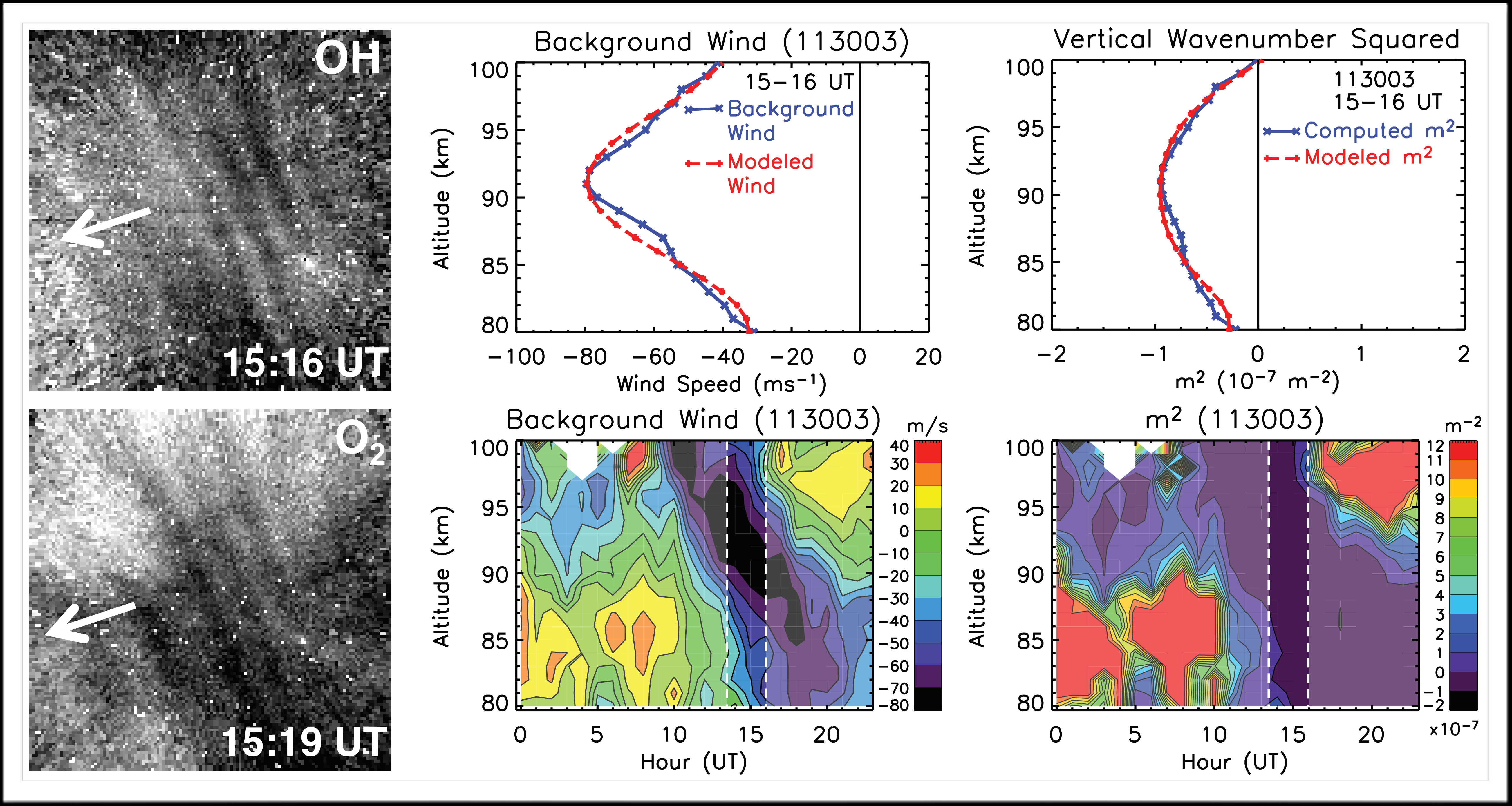
[*Simkhada et al.*, 2009] - 6.75 minute period, 15 km wavelength



Short-Period Wave Propagation:

Evanescence in Mesospheric Wind Fields

[*Simkhada et al.*, 2009] - 11.38 minute period, 17 km wavelength.



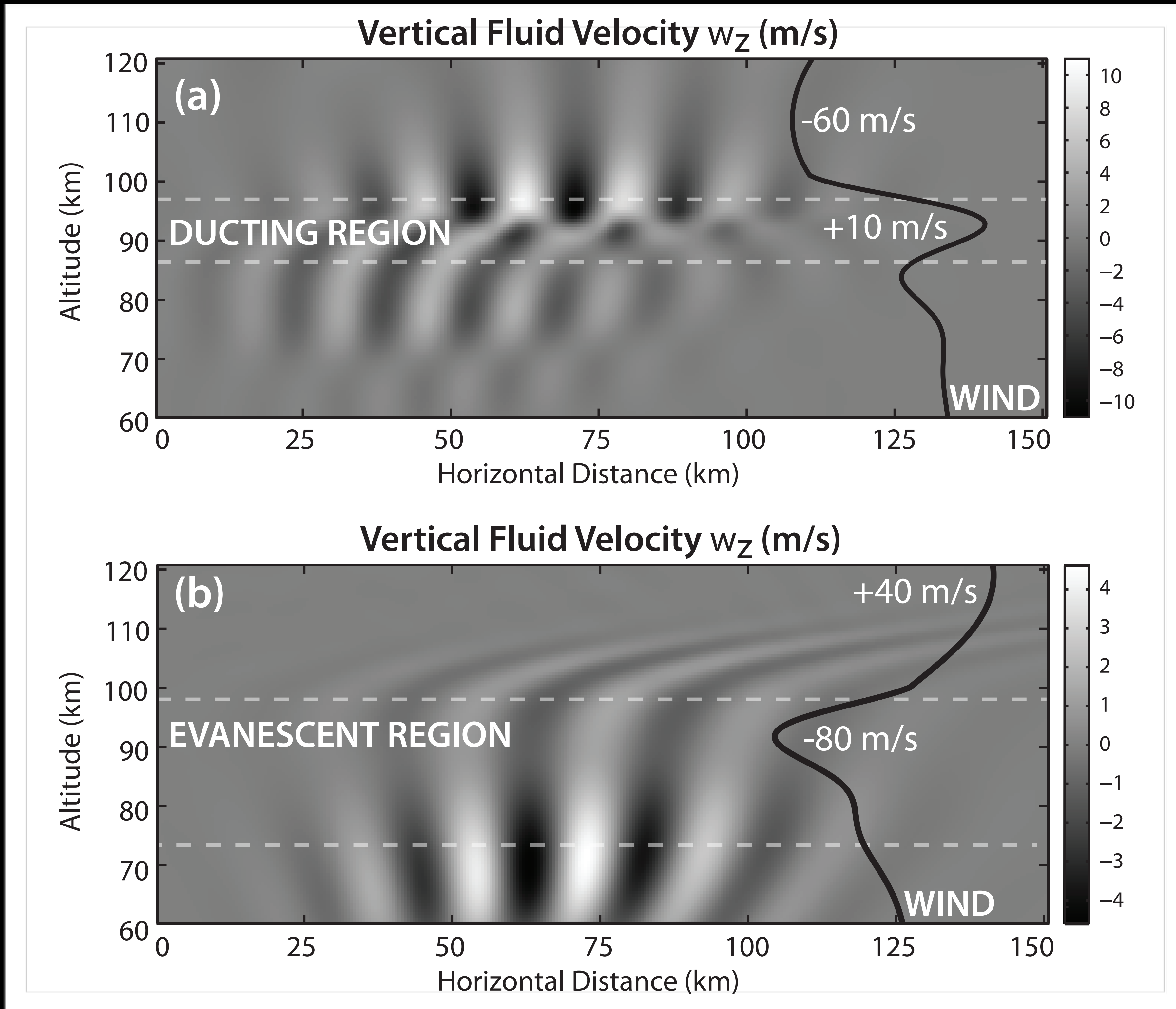
Short-Period Wave Propagation:

Numerical Model Configuration

[*Simkhada et al.*, 2009].

- **Model Equations:** Time-dependent compressible 2D Euler equations with gravity and viscosity.
- **Ambient Model Profiles:** Meteor radar winds (80-100km); MSISE-90 temperature and densities.
- **Wave Source Parameters:** Oscillators with frequencies and wavelengths of the observed waves.

Short-Period Wave Propagation:
Evanescence and Trapping in Mesospheric Wind Fields



Assumptions:

Due to the observations:

- Wind profile spanning only ~80-100 km; temperatures based on empirical model averages, not measured.
- Wave field known only at 2 altitudes via airglow layers separated by only a few kilometers.

Due to the model(er) / computer:

- Two versus three dimensions.
- Limited resolution, domain scale, and timespan of run.
- Time-independent, horizontally-homogeneous background states.

Minimum Standards?

The impossible fantasy of modeling is to simulate all features of an observed system, without assumptions.

The reality of modeling is to simulate the most important features of an observed system, using only reasonable assumptions, while *adding value* beyond observations and experiment.

Why Perform a Modeling Study?

A few reasons (among others):

1. **Explanatory**: To simulate systems or observed scenarios to interpret or extend experimental data.

2. **Explorative/Predictive**: To predict outcomes or produce "synthetic data" to guide experiment design.

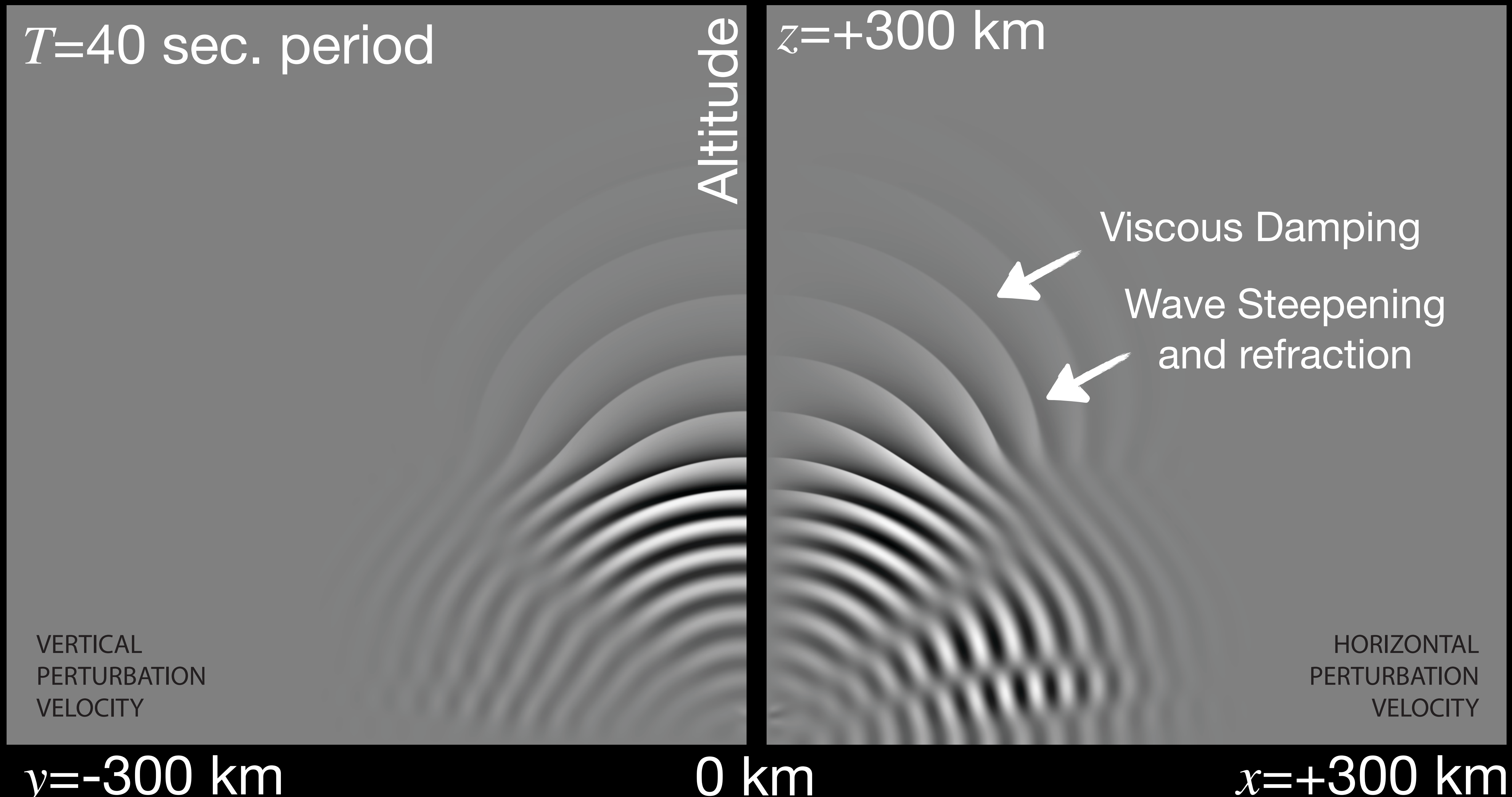
3. **Theoretical**: To investigate complex systems or scenarios under controlled, reproducible conditions.

Example Case Study:

Simulating acoustic waves generated by tropospheric sources to investigate their observable signatures in the Mesosphere, Lower-Thermosphere, and Ionosphere.

[e.g., *Snively*, GRL, 40, 2013;
Zettergren and Snively, GRL, 40, 2013;
Marshall and Snively, JGR, 119, 2014]

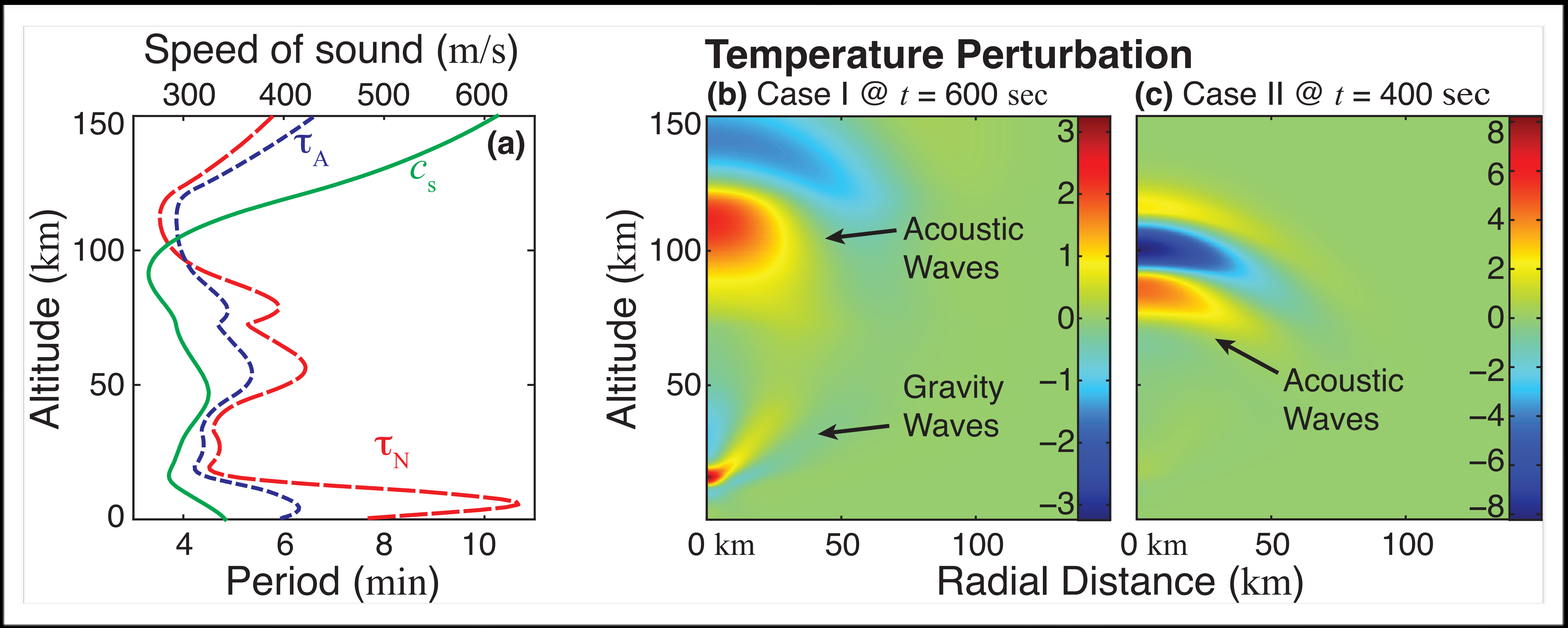
In 2011, I needed a new door sign: I decided to create an axisymmetric model for MLT-region acoustic waves.



Then, I wondered... Are these readily observable?

Ambient Atmosphere and Wave Sources:

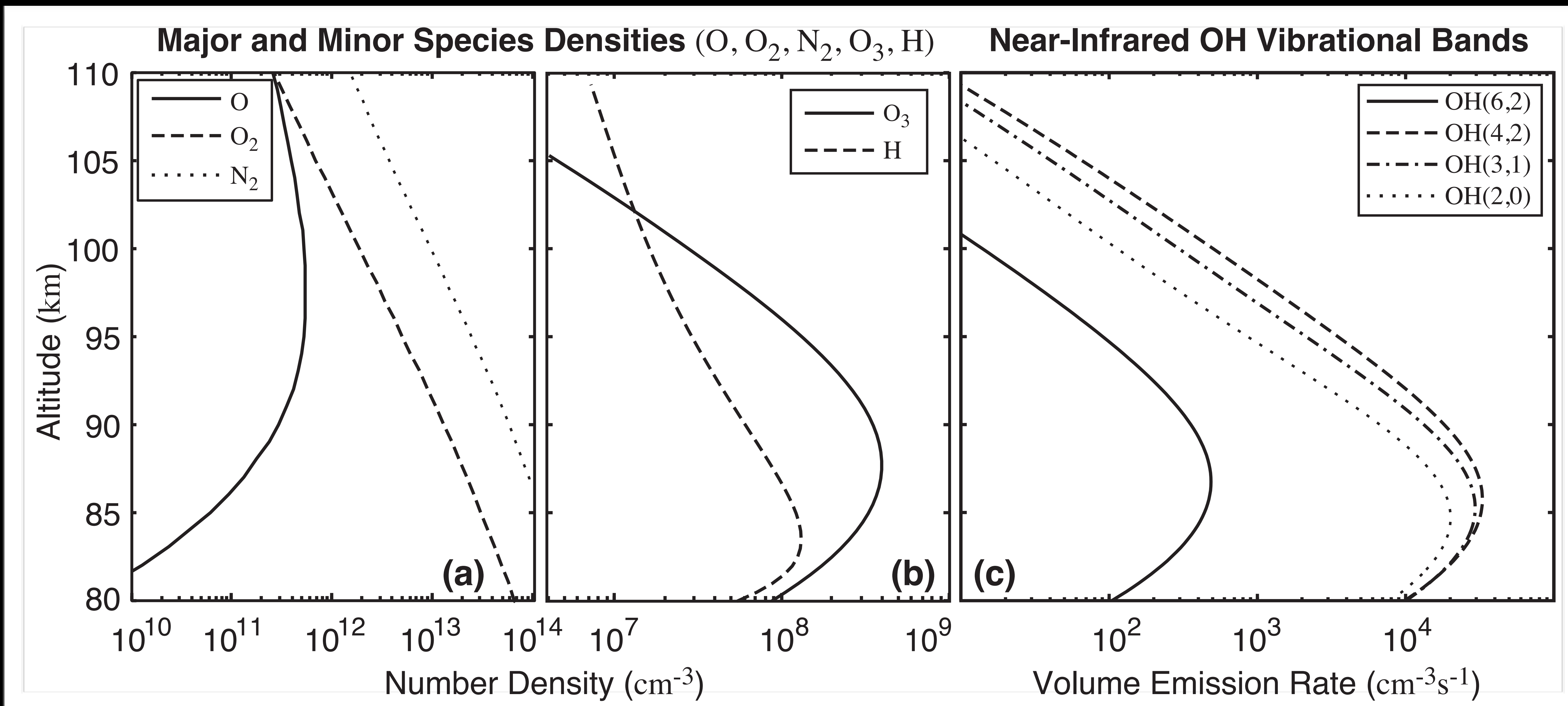
Updraft sources are specified in the troposphere of a "typical" atmosphere, using a cylindrically-axisymmetric nonlinear gas dynamics model.



Case 1 Source: ~2.35 minute updraft

Case 2 Source: ~50 second updraft

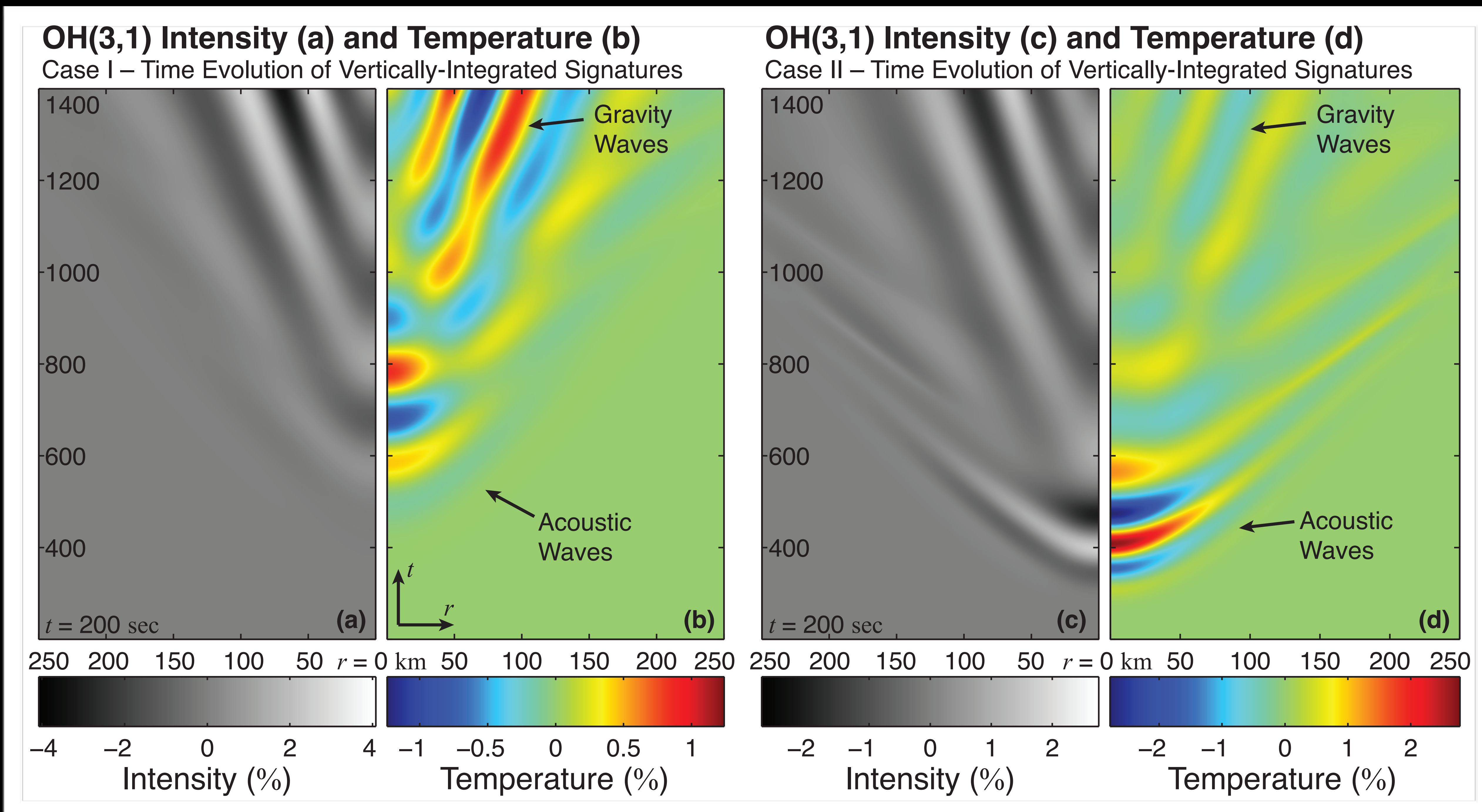
Airglow Photochemical Models:



OH (v) airglow model: Solution for H, O, and O_3 continuity equations, along with OH(v) and resulting band emission intensities [e.g., *Adler-Golden*, 1997; *Snively et al.*, 2010; *Snively*, 2013].

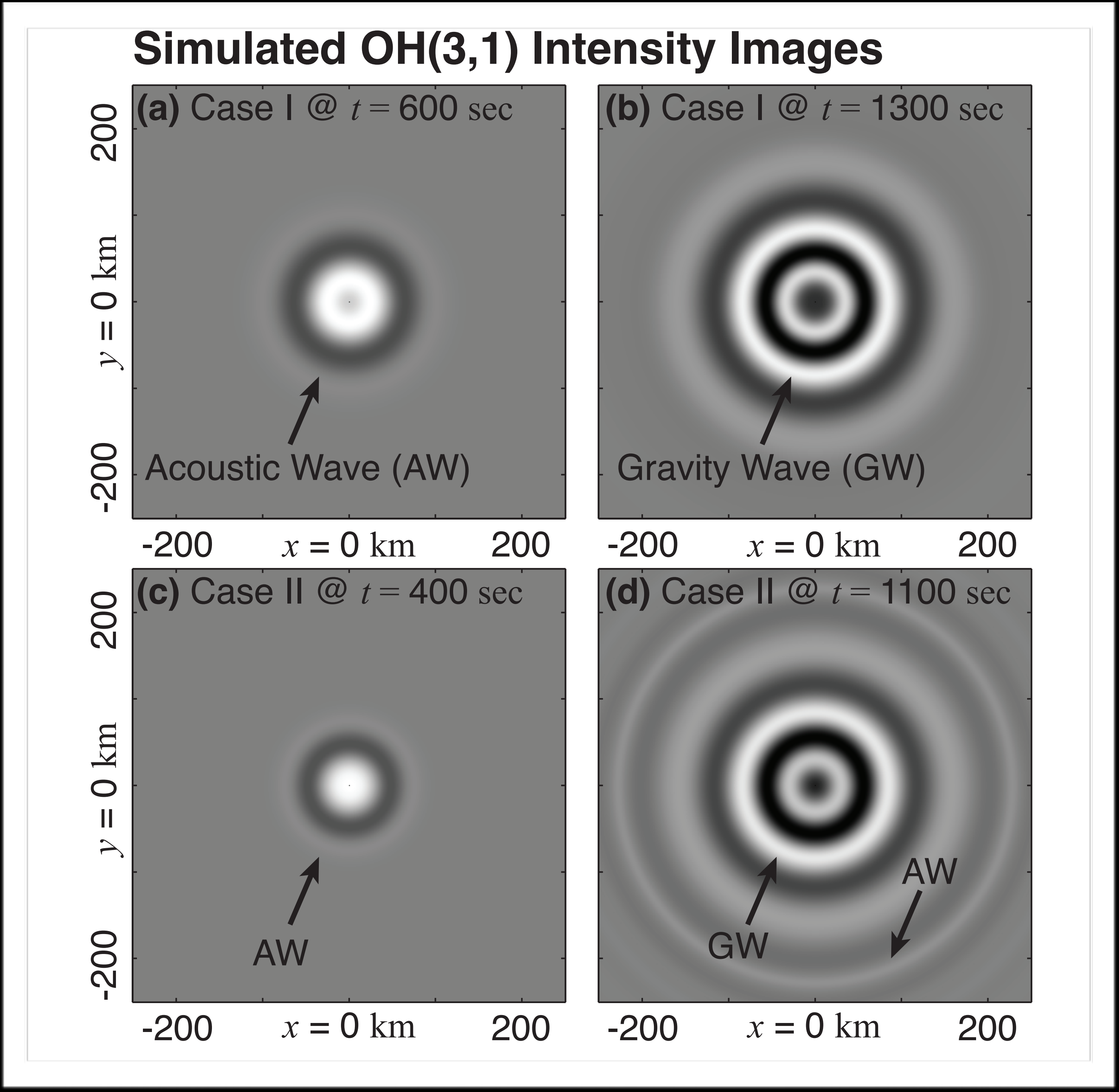
Modeled Airglow Response:

Acoustic waves appear as precursors to gravity waves in the hydroxyl layer, resulting in oscillations above the source prior to GW arrival.



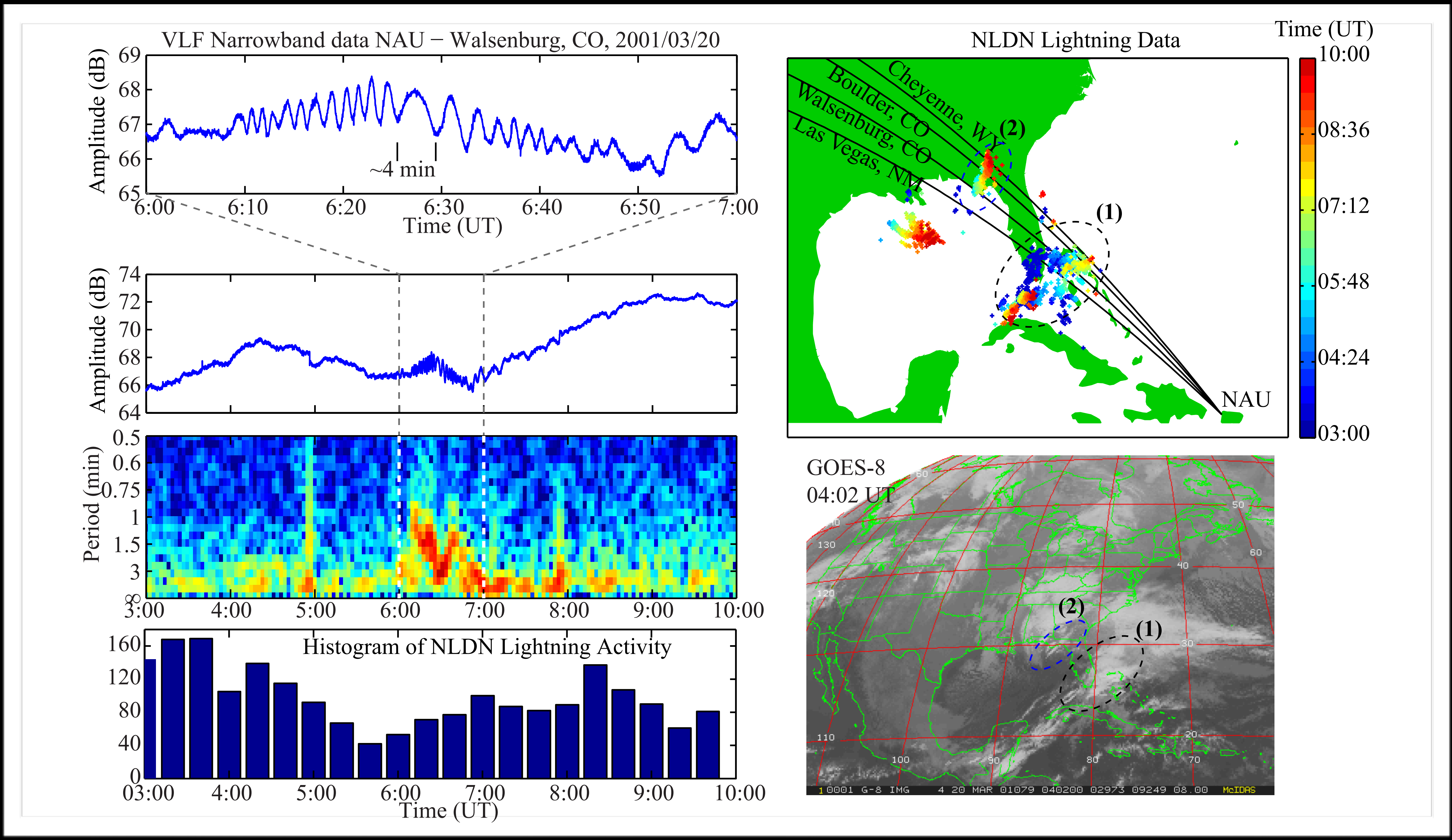
Simulated Airglow Intensity Images

Convectively-generated Acoustic and Gravity Waves may be detectable, but not easily distinguishable within a single event in airglow - need good luck/weather! (The Gravity Waves are more persistent and observable)



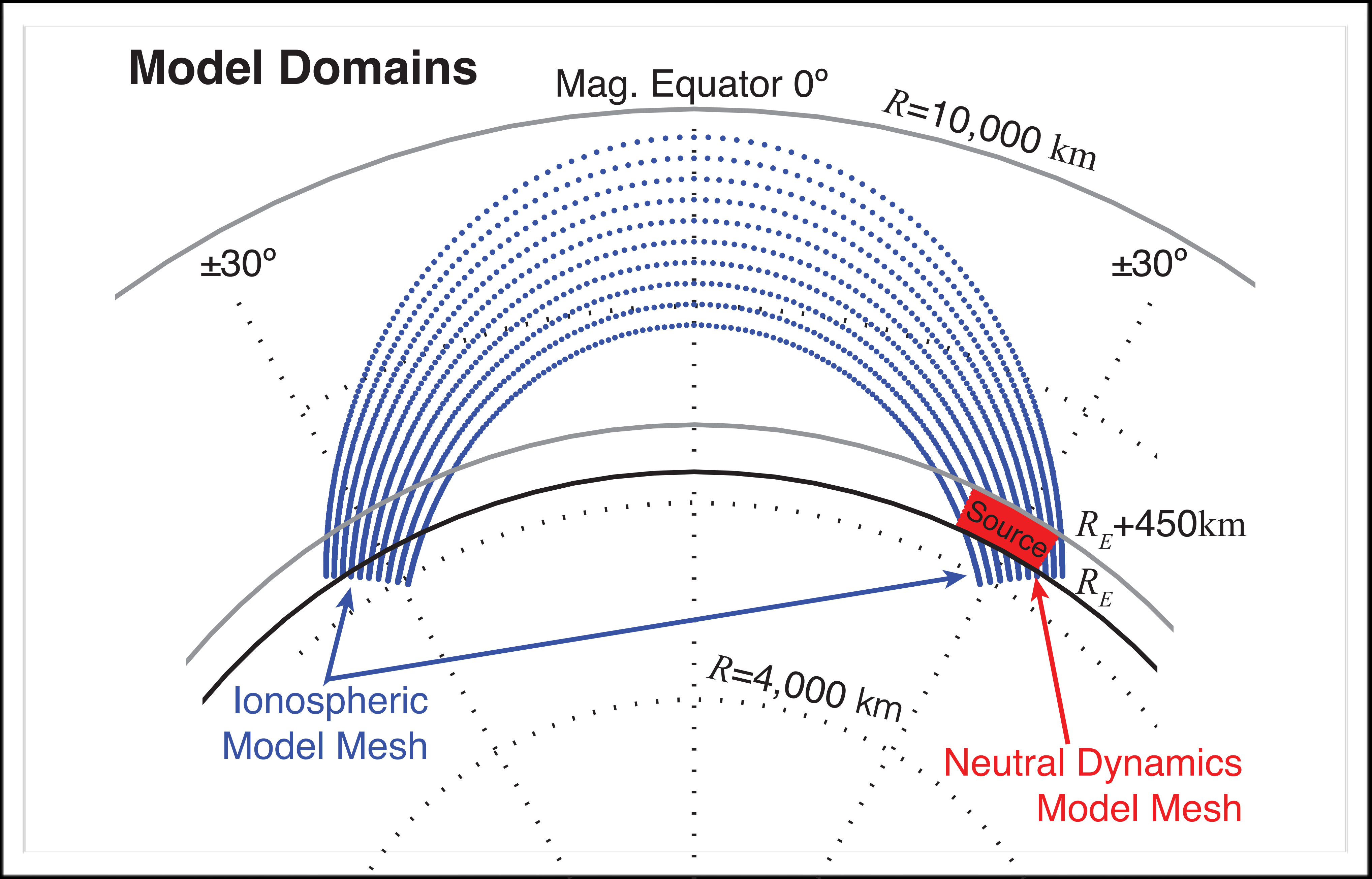
Observed D-Region Responses

Marshall and Snively, 2014, report 1-4 minute period oscillations in VLF data, with model simulations suggesting possible acoustic waves over convection (at sufficient amplitudes to be observable in airglow, too).



Neutral+Ion Model Configuration

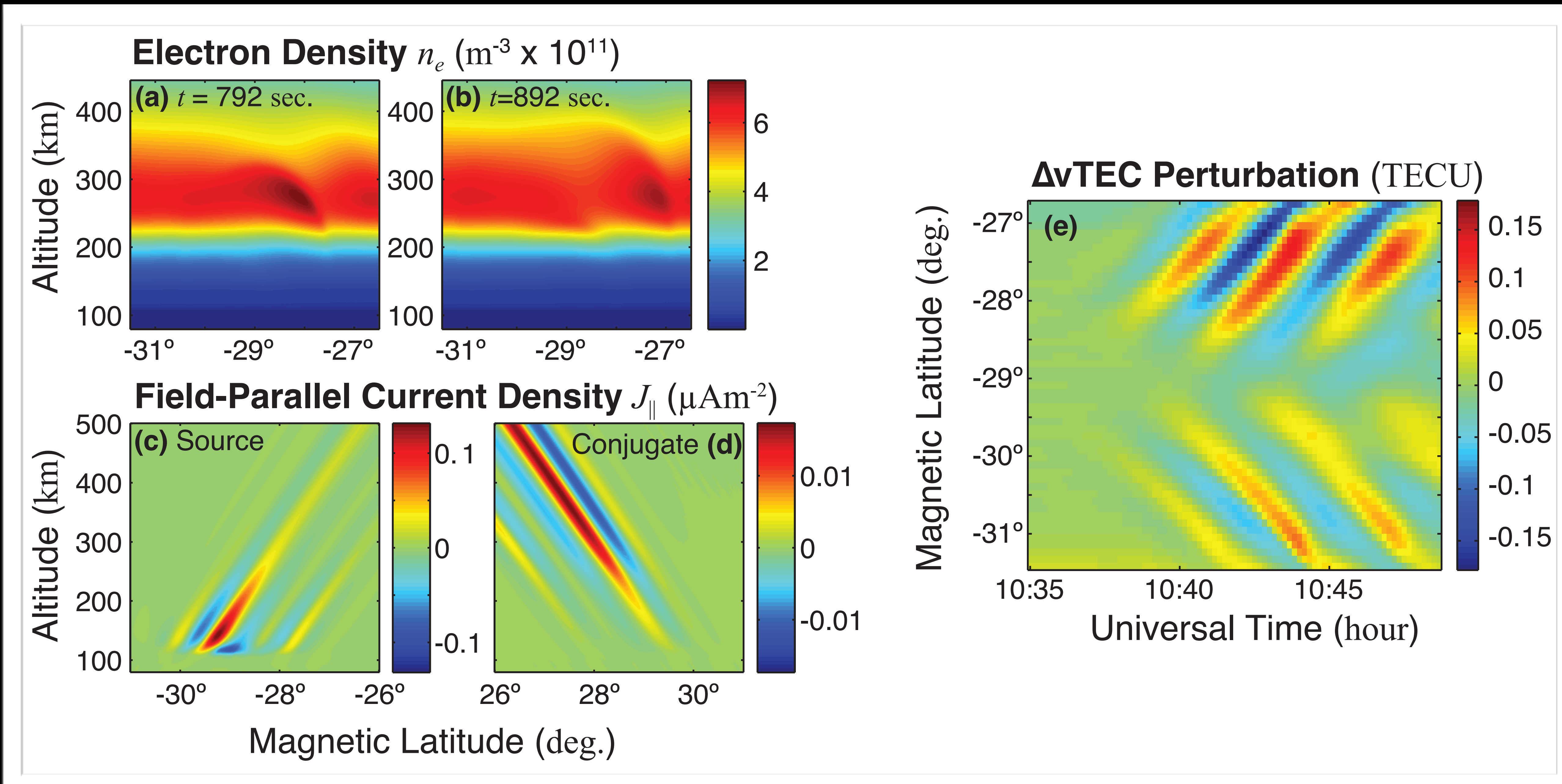
The acoustic wave perturbations to the ionosphere can be calculated by driving an ionospheric model with the time-dependent neutral dynamics.



[*Zettergren and Snively*, 2013]

Simulated Ionospheric Response

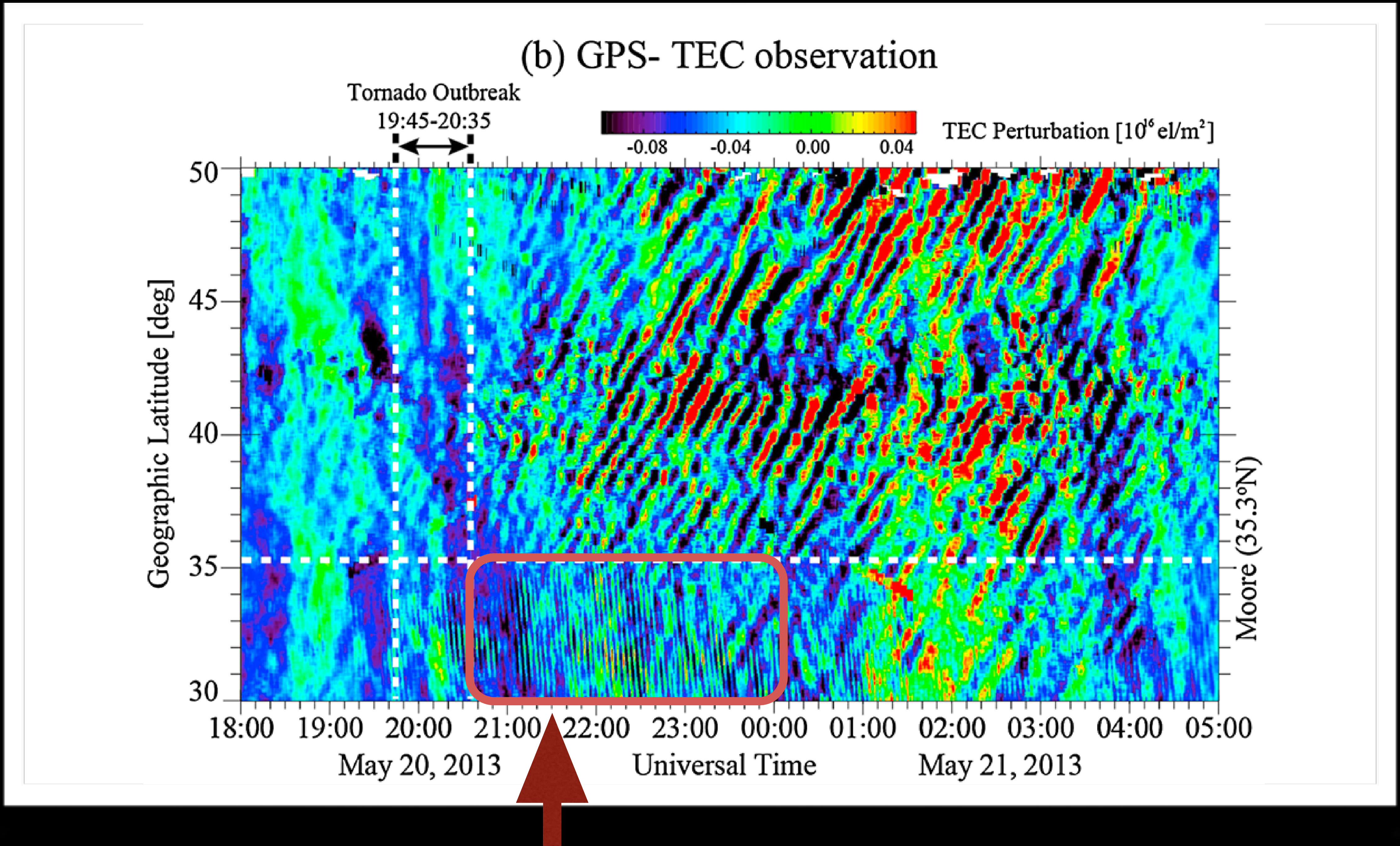
Anticipate that ~3-4 minute period acoustic waves are quite readily detectable in the f-region ionosphere and vertically-integrated TEC.



Dominant equator-ward electron signature ~0.05-0.15 TECU

Observed F-Region Responses

Nishioka et al., 2013, report simultaneously (and independently) in GRL that similar-scale ~3.5-4 minute (likely acoustic) waves were detected in TEC data above an EF5 Tornado-producing storm.



Dominant equator-ward electron signature ~0.05 TECU

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mesosphere lower thermosphere modeling

About 15,800 results (**0.05** sec)

Extension of the MSIS **thermosphere model** into the middle and **lower** atmosphere
AE Hedin - Journal of Geophysical Research: Space Physics (…, 1991 - Wiley Online Library
… **model**, along with rocket and incoherent scatter data in the upper **mesosphere** and **lower** …
particularly near the solstices, apparently because of errors in either the **lower** end of … is that
pressures or densities calculated by integration from below and above the **mesopause**, with the …
Cited by 1929 Related articles All 9 versions Web of Science: 1453 Cite Save

A **thermosphere**-ionosphere-**mesosphere**-electrodynamics general circulation **model** (TIME-GCM): Equinox solar cycle minimum simulations (30–500 km)
RG Roble, EC Ridley - Geophysical Research Letters, 1994 - Wiley Online Library
… many of the critical arge-scale problems that exist in the upper **meso- sphere** and **lower** … Liu, SC
and TM Donahue, **Mesospheric** hydrogen related to ex0spheric escape mechanism, J. Atrnos …
role of atomic oxygen in the dynamics and energy budget of the **mesosphere** and **lower** …
Cited by 363 Related articles All 8 versions Web of Science: 305 Cite Save

A **model** estimate of cooling in the **mesosphere** and **lower thermosphere** due to the CO2 increase over the last 3–4 decades
RA Akmaev, VI Fomichev - Geophysical research letters, 2000 - Wiley Online Library
Abstract. Long-term observations indicate a substantial cooling in the **mesosphere** and
lower thermosphere (MLT) over the last 3-4 decaxles. Available **model** studies have
primarily considered the effects of CO2 doubling expected to occur in the future. We …
Cited by 73 Related articles All 8 versions Web of Science: 56 Cite Save

How will changes in carbon dioxide and methane modify the mean structure of the **mesosphere** and **thermosphere**?
RG Roble, RE Dickinson - Geophysical Research Letters, 1989 - Wiley Online Library
… Radiative transfer from the underlying stratosphere determines in part the **mesospheric**
temperature structure. … on the global mean thermal and compositional structure of the **meso- sphere**
and **thermosphere**. … on gravity wave induced eddy diffu- sion in the **mesosphere** and **lower** …
Cited by 398 Related articles All 7 versions Web of Science: 305 Cite Save More

The effect of breaking gravity waves on the dynamics and chemical composition of the **mesosphere** and **lower thermosphere**
RR Garcia, S Solomon - Journal of Geophysical Research: …, 1985 - Wiley Online Library
… budget if a meridional flow of the order of 1 m s- x existed in the **meso- sphere**. … is specified at the
lower boundary, the waves in the **model** break at **mesospheric** altitudes, as … the **model**, and the
model summer **mesopause** is slightly colder and the winter **mesosphere** warmer thah …
Cited by 630 Related articles All 8 versions Web of Science: 559 Cite Save

A **model** calculation of the diurnal variation in minor neutral constituents in the **mesosphere** and **lower thermosphere** including transport effects
T Shimazaki, AR Laird - Journal of Geophysical Research, 1970 - Wiley Online Library
The nonequilibrium calculation for various neutral constituents in the **mesosphere** and **lower**
thermosphere (Hunt, 1966) was extended by including the effects of molecular and eddy
diffusion. Nitrogen and its oxides were added, and more recent laboratory data for …
Cited by 156 Related articles All 5 versions Web of Science: 148 Cite Save

ionosphere model

About 148,000 results (**0.06** sec)

A coupled thermosphere/**ionosphere** general circulation **model**
RG Roble, EC Ridley, AD Richmond… - Geophysical …, 1988 - Wiley Online Library
Abstract. The NCAR thermospheric general circula-tion **model** (TGCM) is extended to include a self-consistent aeronomic scheme of the thermosphere and **ionosphere**. The **model** now calculates total temperature, instead of pertur-bation temperature about some **...**
Cited by 440 Related articles All 5 versions Web of Science: 326 Cite Save

[CITATION] A coupled thermosphere-**ionosphere model** (CTIM)
TJ Fuller-Rowell, D Rees, S Quegan, RJ Moffett… - STEP Report, 1996
Cited by 161 Related articles Cite Save

Sami2 is Another **Model** of the **Ionosphere** (SAMI2): A new low-latitude **ionosphere model**
JD Huba, G Joyce, JA Fedder - Journal of Geophysical …, 2000 - Wiley Online Library
Abstract. A new low-latitude ionospheric **model** has been developed at the Naval Research Laboratory: Sami2 is Another **Model** of the **Ionosphere** (SAMI2). SAMI2 treats the dynamic plasma and chemical evolution of seven ion species
Cited by 235 Related articles All 9 versions Web of Science: 161 Cite Save

The Sheffield University plasmasphere **ionosphere model**—A review
GJ Bailey, N Balan, YZ Su - Journal of Atmospheric and Solar-Terrestrial …, 1997 - Elsevier
A brief description of the Sheffield University plasmasphere **ionosphere model** (SUPIM) is presented. In the **model**, time-dependent equations of continuity, momentum, and energy balance are solved along eccentric-dipole magnetic field lines for the densities, field- **...**
Cited by 111 Related articles All 6 versions Web of Science: 82 Cite Save

A cometary **ionosphere model** for Io
PA Cloutier, RE Daniell Jr, AJ Dessler… - Astrophysics and Space …, 1978 - Springer
Abstract The **ionosphere** of Jupiter's satellite Io, discovered by the Pioneer 10 radio-occultation experiment, cannot easily be understood in terms of a **model** of a gravitationally bound, Earth-like **ionosphere**. Io's gravitational field is so weak that a gravitationally bound **...**
Cited by 79 Related articles All 8 versions Web of Science: 70 Cite Save

[HTML] Titan's **ionosphere**: **Model** comparisons with Cassini Ta data
TE Cravens, IP Robertson, J Clark… - Geophysical …, 2005 - Wiley Online Library
[2] Voyager 1 remotely measured an electron density profile in Titan's **ionosphere** in 1980 using the radio occultation technique [Bird et al., 1997]. Many models of Titan's **ionosphere** have been constructed over the past decade or so [eg, Keller et al., 1992; Banaskiewicz et **...**
Cited by 67 Related articles All 15 versions Web of Science: 55 Cite Save

Geomagnetic storm simulation with a coupled magnetosphere-**ionosphere**-thermosphere **model**
J Raeder, Y Wang, TJ Fuller-Rowell - Space Weather, 2001 - Wiley Online Library
We present the first global, self-consistent, fully electrically coupled magnetosphere-**ionosphere**-thermosphere **model**, based on the UCLA magnetosphereionosphere **model** and the NOAA Coupled Thermosphere **Ionosphere Model** (CTTM). Initial results from this **...**
Cited by 54 Related articles All 7 versions Cite Save

Note that citations in the following pages are linked!

Oxygen and Ozone Airglow from Model vs. Satellite Data

Model Confirmation of GW effects on summer/winter mesopause temperature.

[Garcia and Solomon, JGR, 90, 1985]

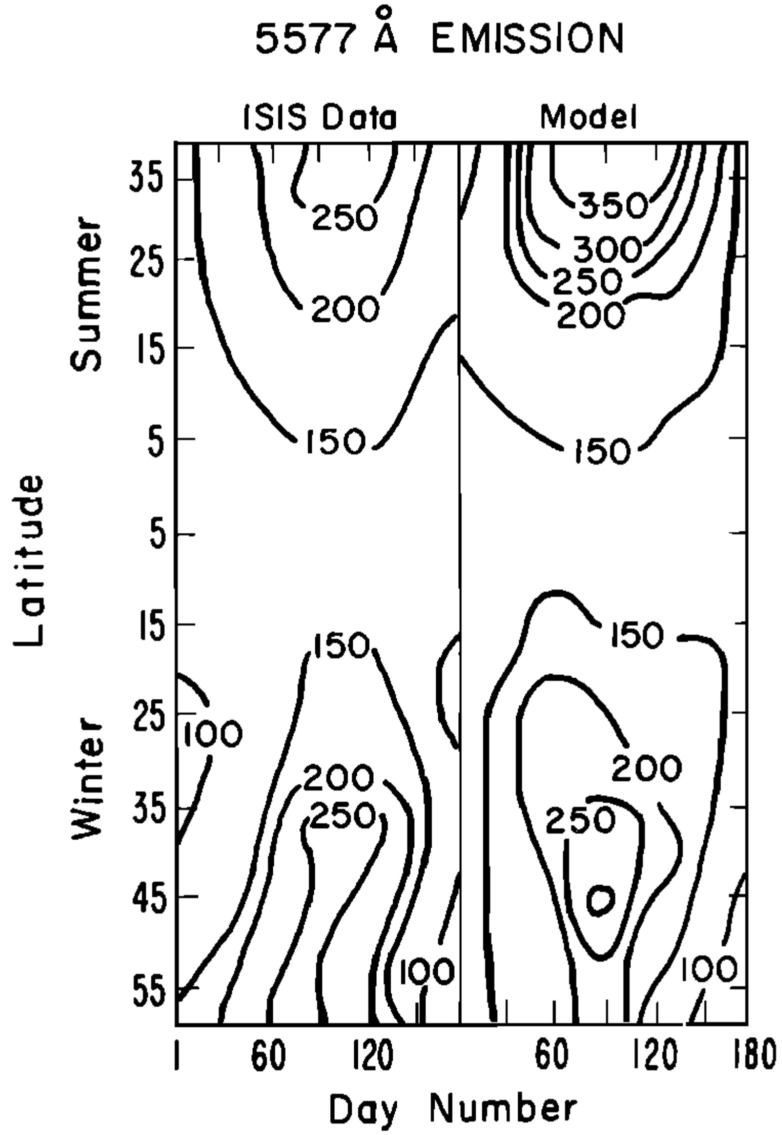


Fig. 15. Seasonal and latitudinal variations of atomic oxygen O green line emission intensities as observed by the ISIS satellite [*Cogger et al.*, 1981] and calculated in the model. Data and model results labeled "summer" ("winter") encompass the spring (fall) maximum. See Cogger et al. for details.

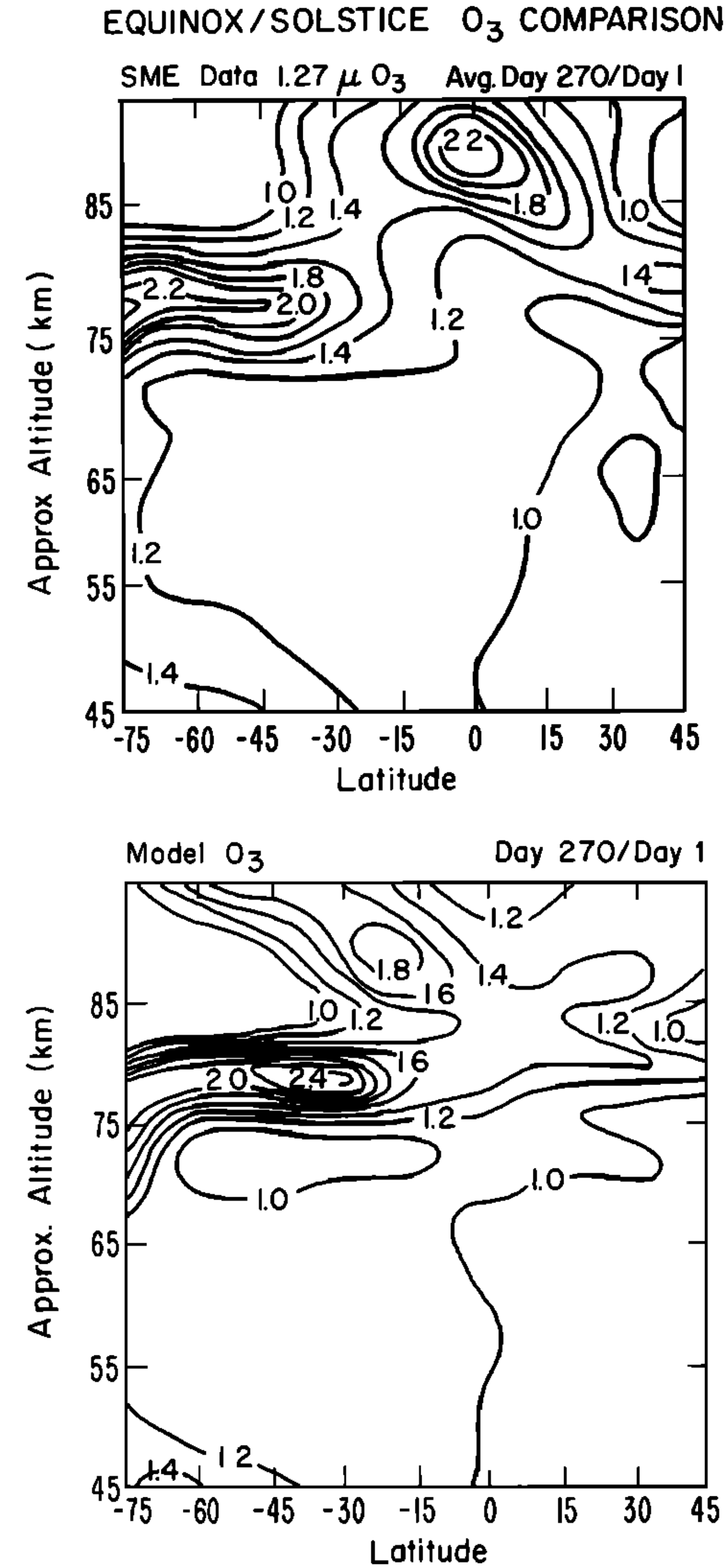


Fig. 18. (Top) Ratio of O_3 observations by the Solar Mesosphere Explorer satellite [*Thomas et al.*, 1984] for 1-week averages about day 270 to day 1 (southern hemisphere spring/summer; northern hemisphere fall/winter). (Bottom) Same, as computed by the model.

Wave-Driven Instabilities in Noctilucent Clouds

[Fritts et al., GRL, 20, 1993]

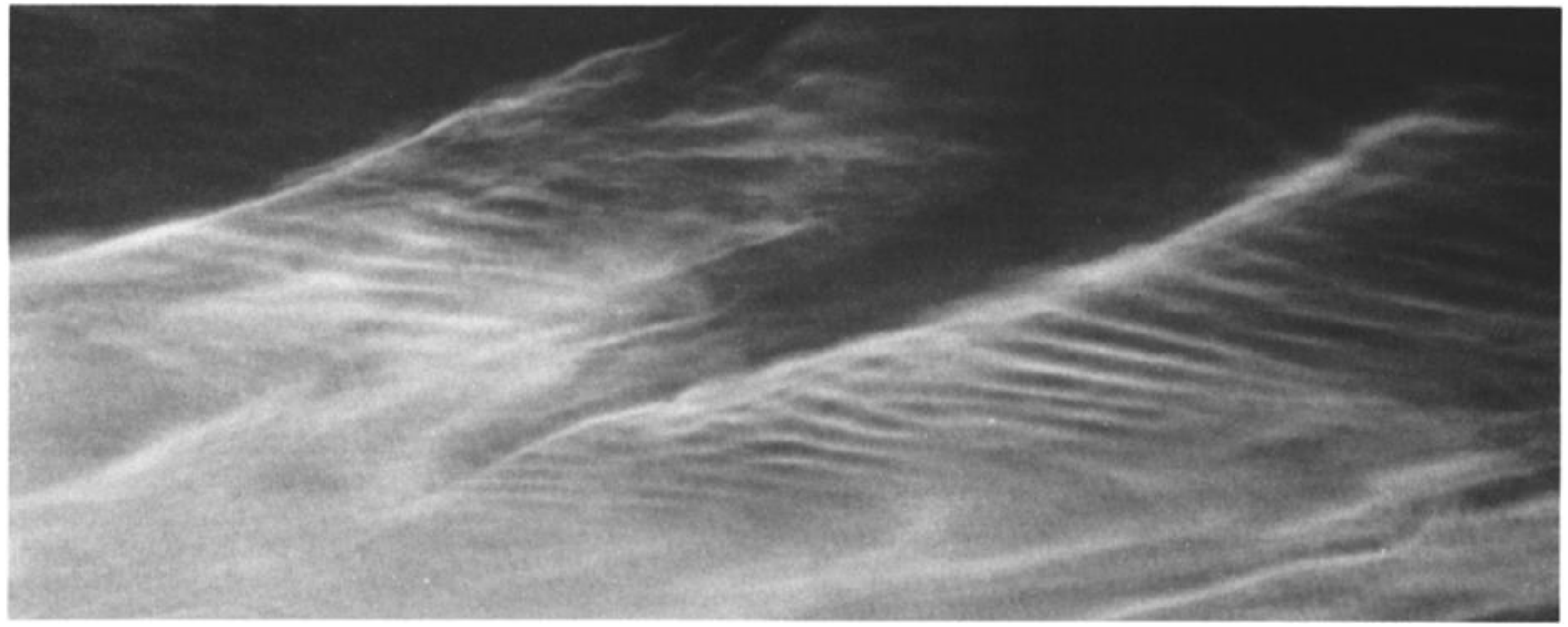


Figure 1. View of NLC display from Kustavi, Finland (61°N, 21°E) on 22 July 1989 showing characteristic band and streak structures. In this case, bands are separated by ~ 50 km and streaks by ~ 3 to 5 km (photo by Pekka Parviainen).

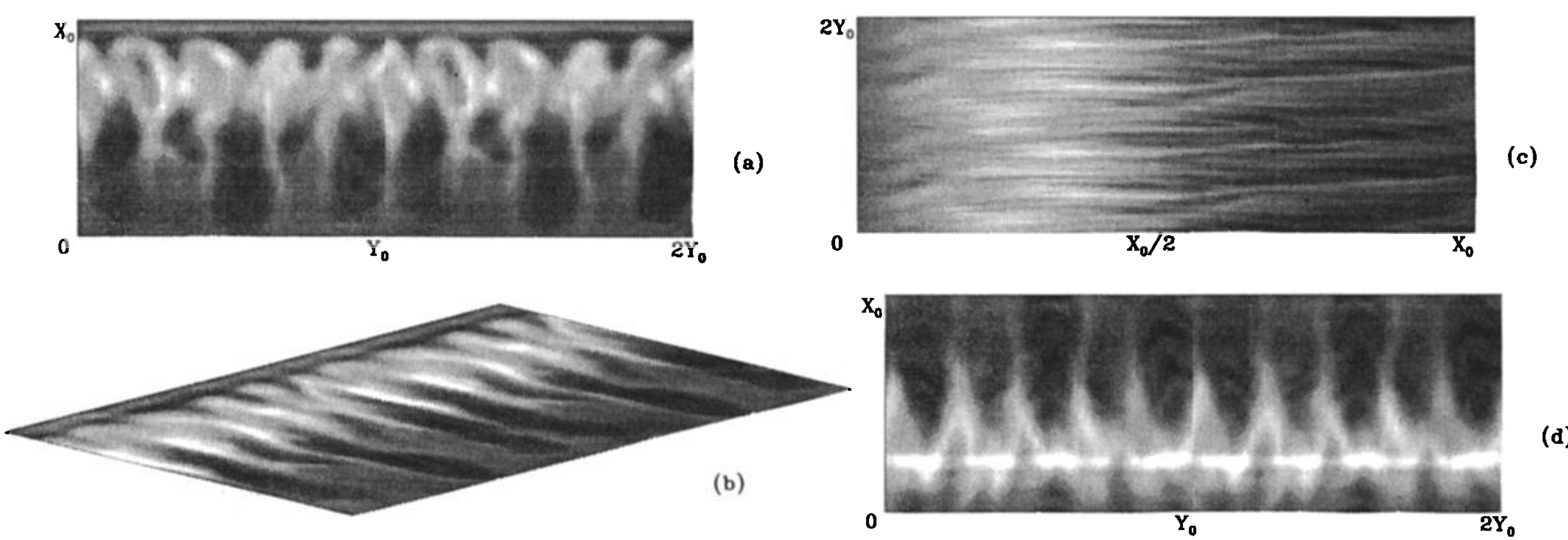


Figure 2. Simulated NLC brightness at the time of maximum instability amplitude at an elevation of 18° and azimuths of 180° (a), 135° (b), 90° (c), and 0° (d). These images represent projections of an area with $x_0 = 2y_0 = 4H$.

Weather Research Model-Data Comparison (Katrina)

[Skamarock and Klemp, JCP, 227, 2008]

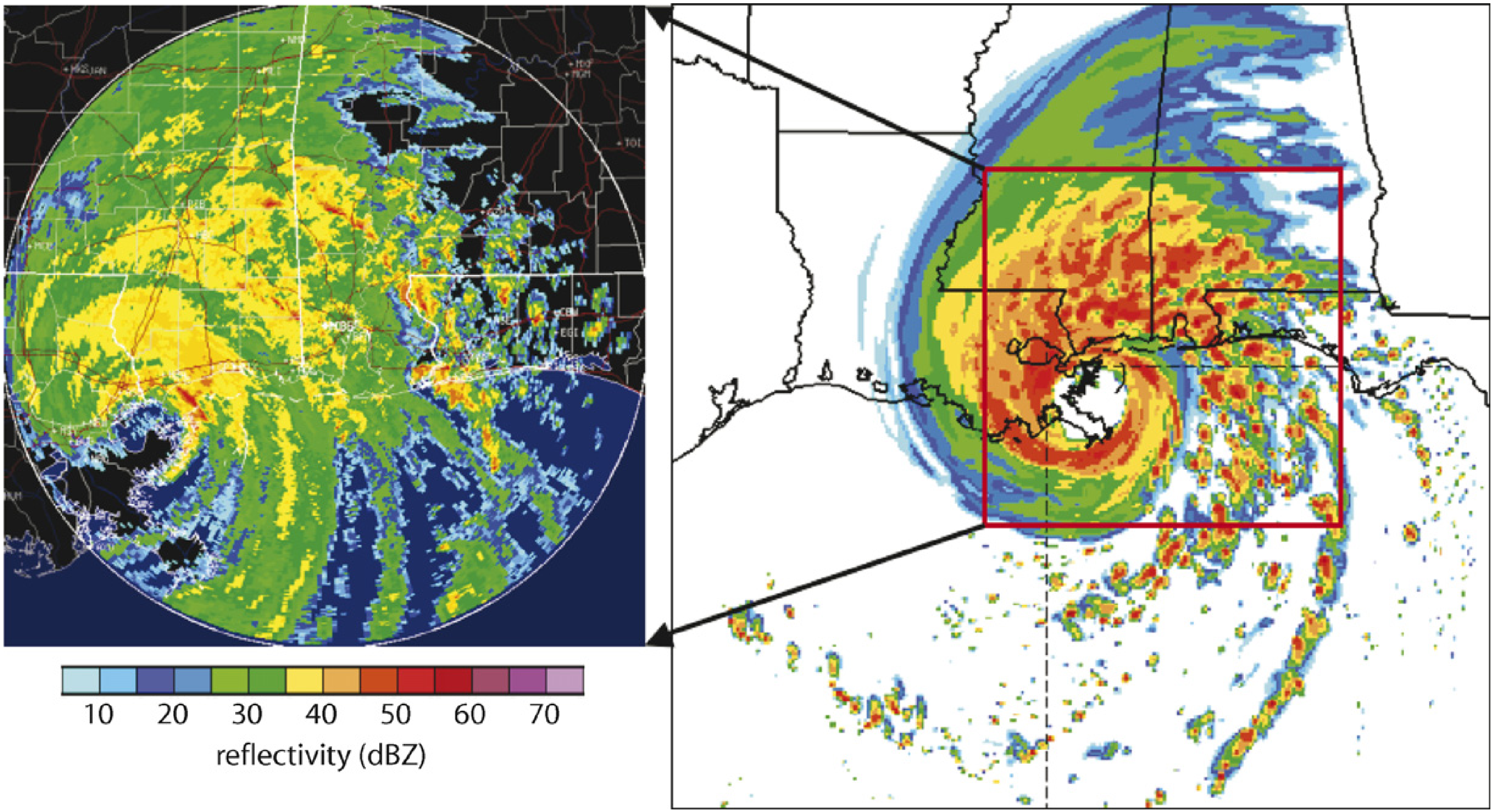
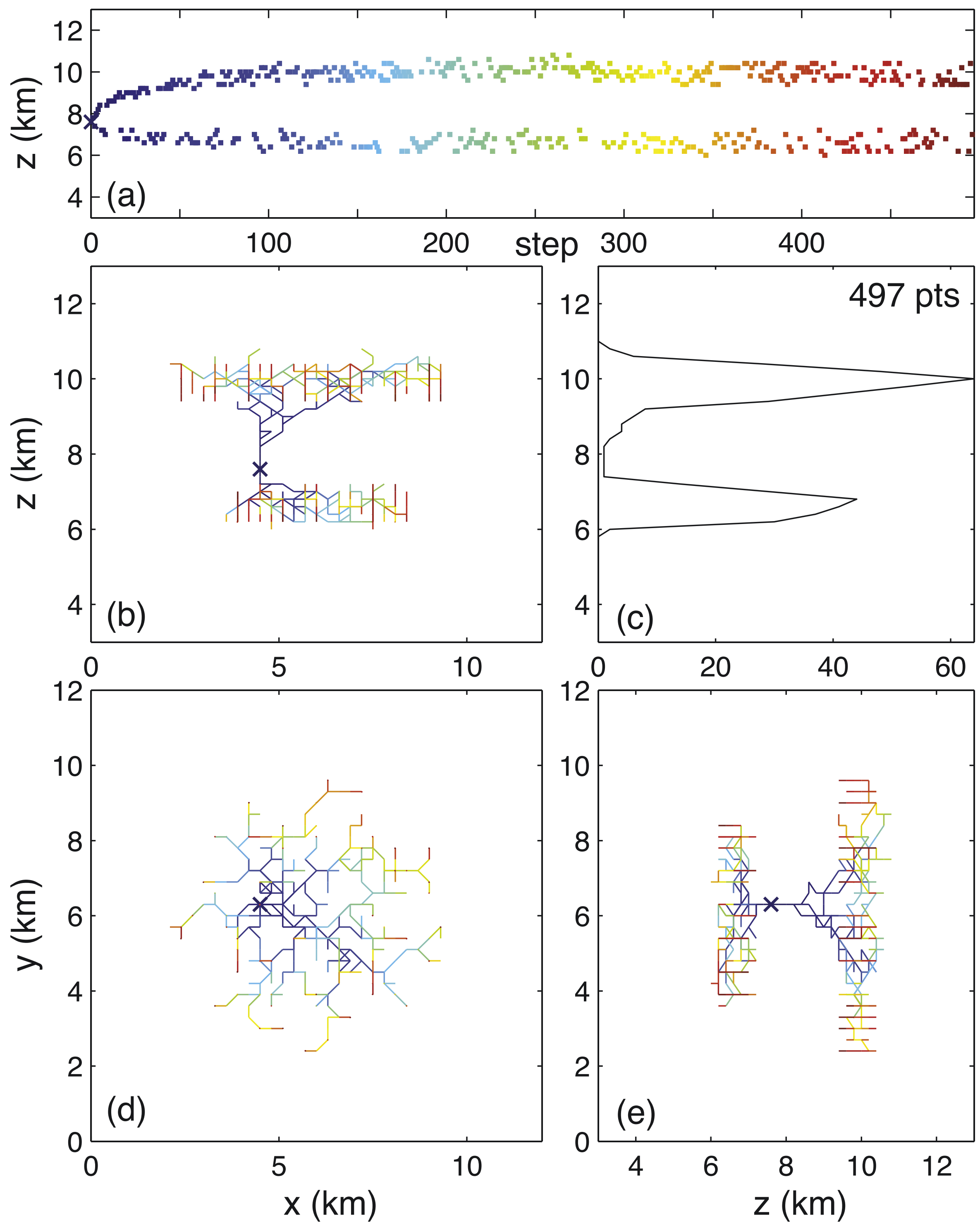
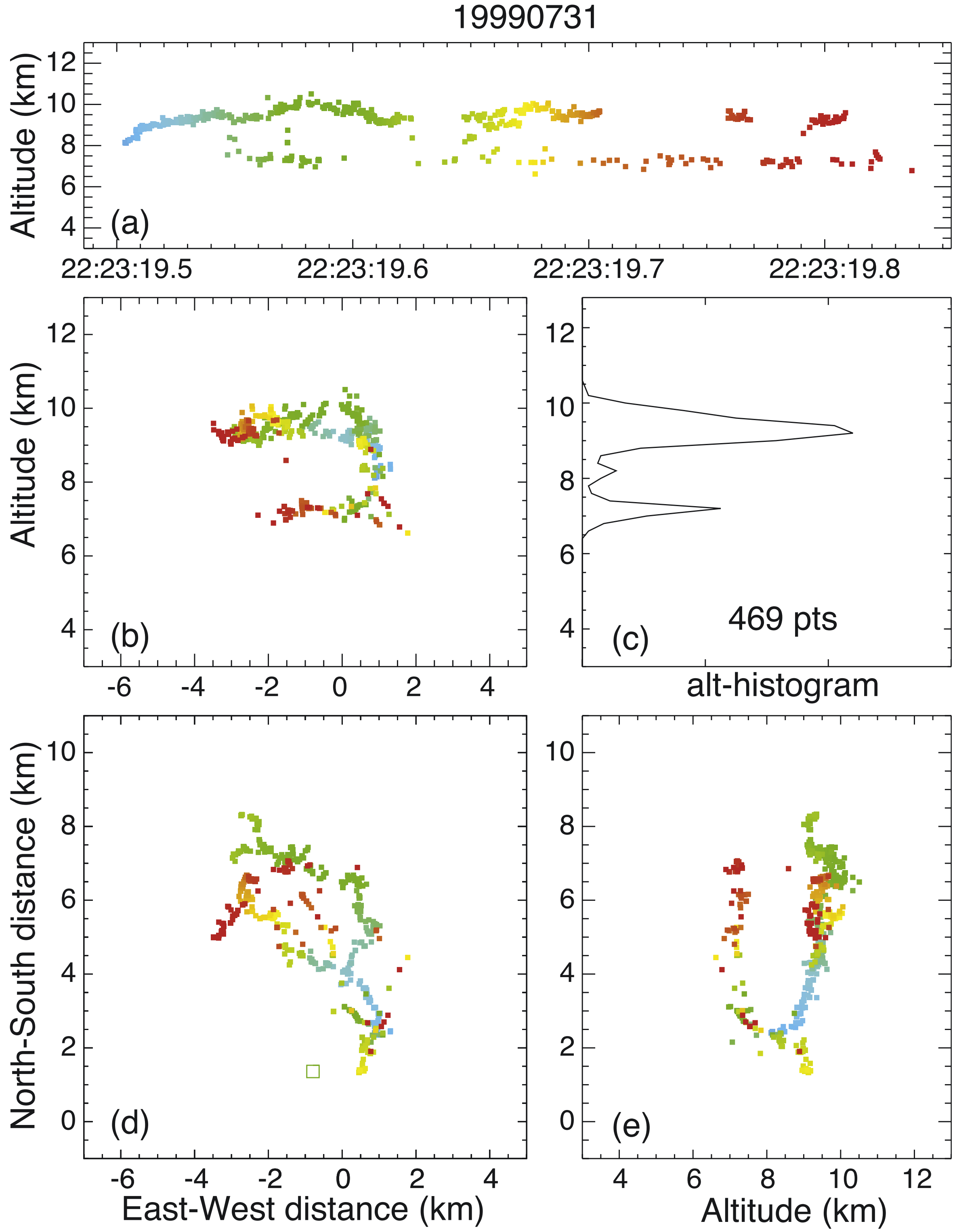


Fig. 7. Observed radar reflectivity (left) from the Mobile Alabama radar for Hurricane Katrina making landfall at 14 UTC 29 August 2005. A 62 h ARW reflectivity forecast valid at that time using $\Delta x = 4$ km.

Simulated Fractal Model vs. Lightning Mapper Array Data for Intracloud Lightning Discharge

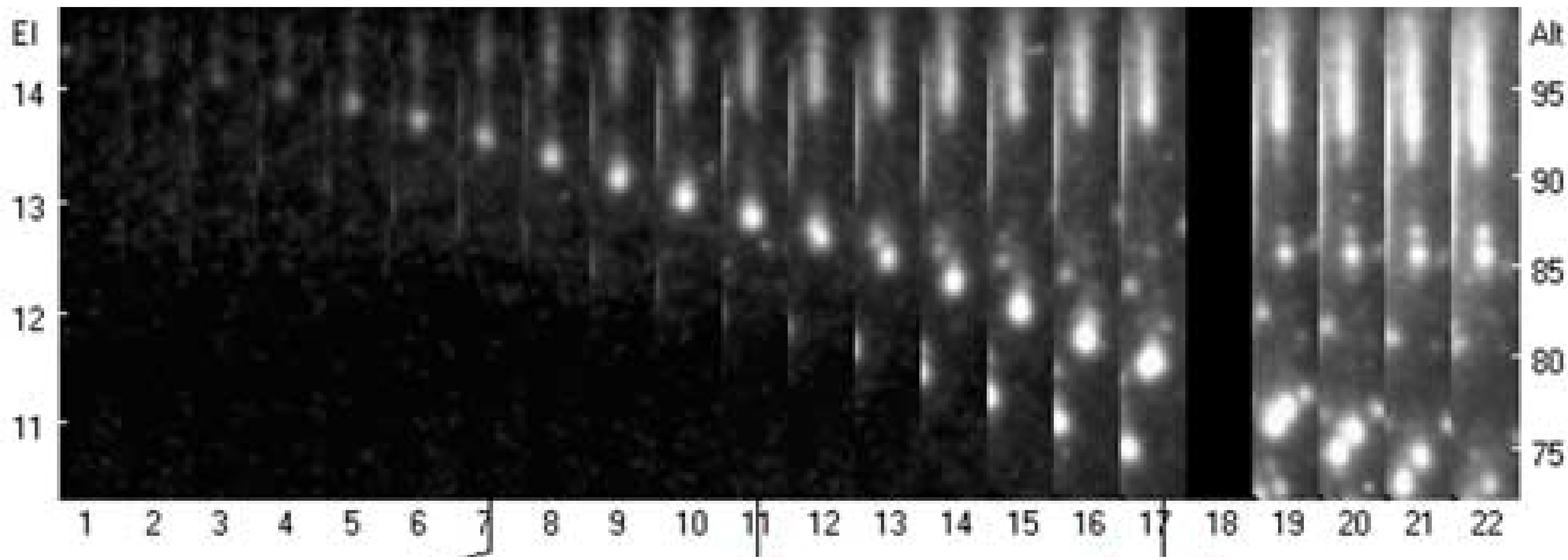
[Riousset et al., JGR, 112, 2007]



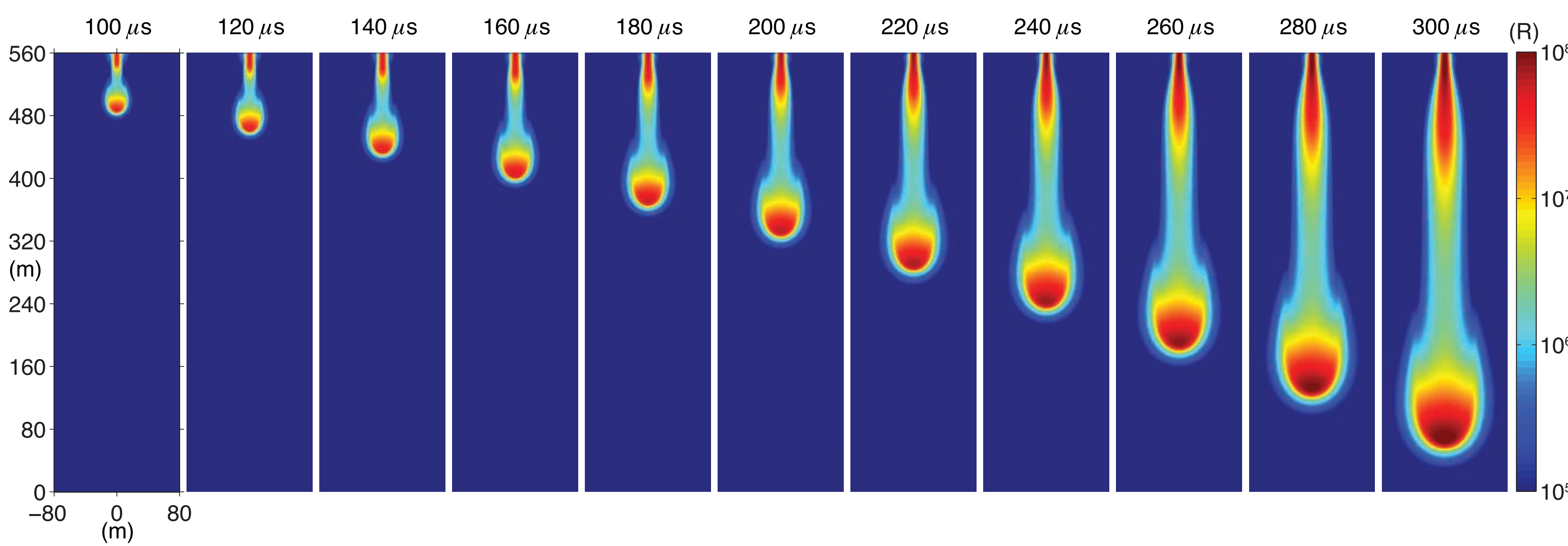


Sprite Streamer Observations and Modeling:

[Stenbaeck-Nielsen et al., GRL, 34, 2007]



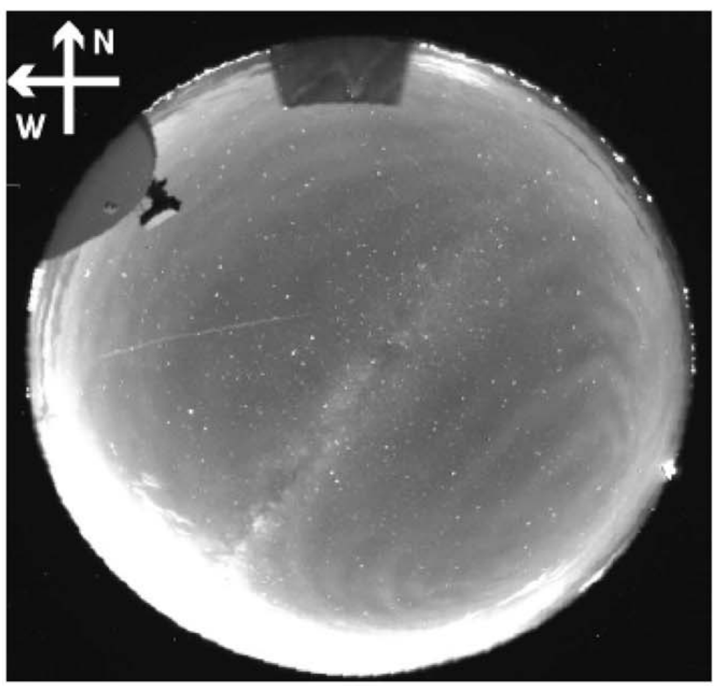
[Liu et al., JGR, 114, 2009]



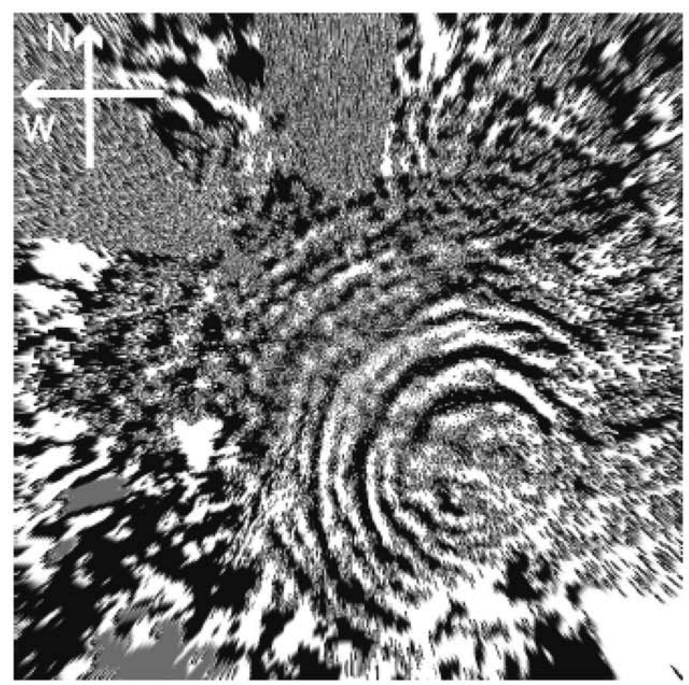
Concentric Gravity Waves Above a Convective System

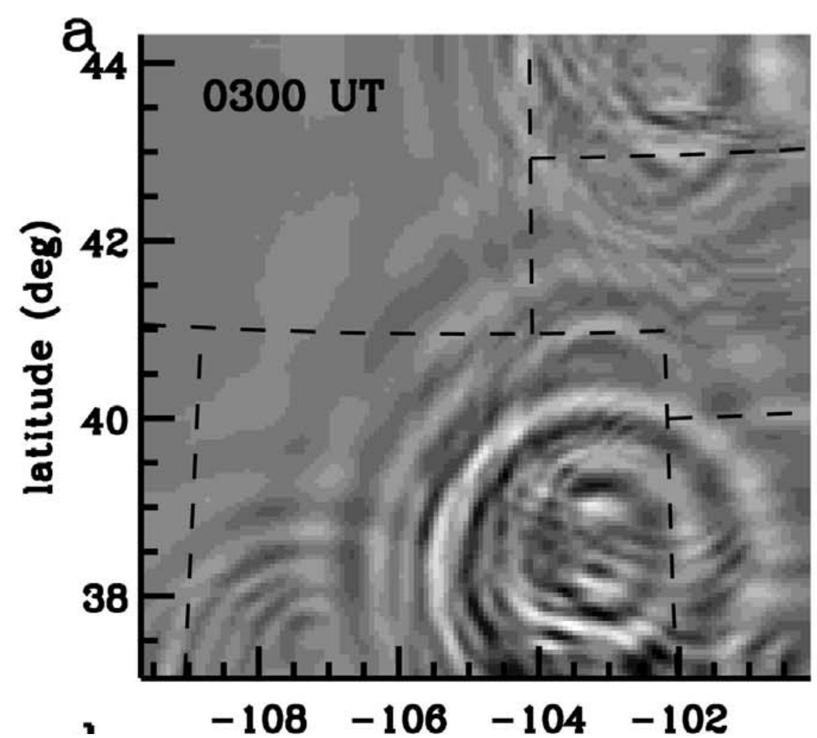
[Vadas et al., JGR, 117, 2012]

OH AIRGLOW RAW IMAGE



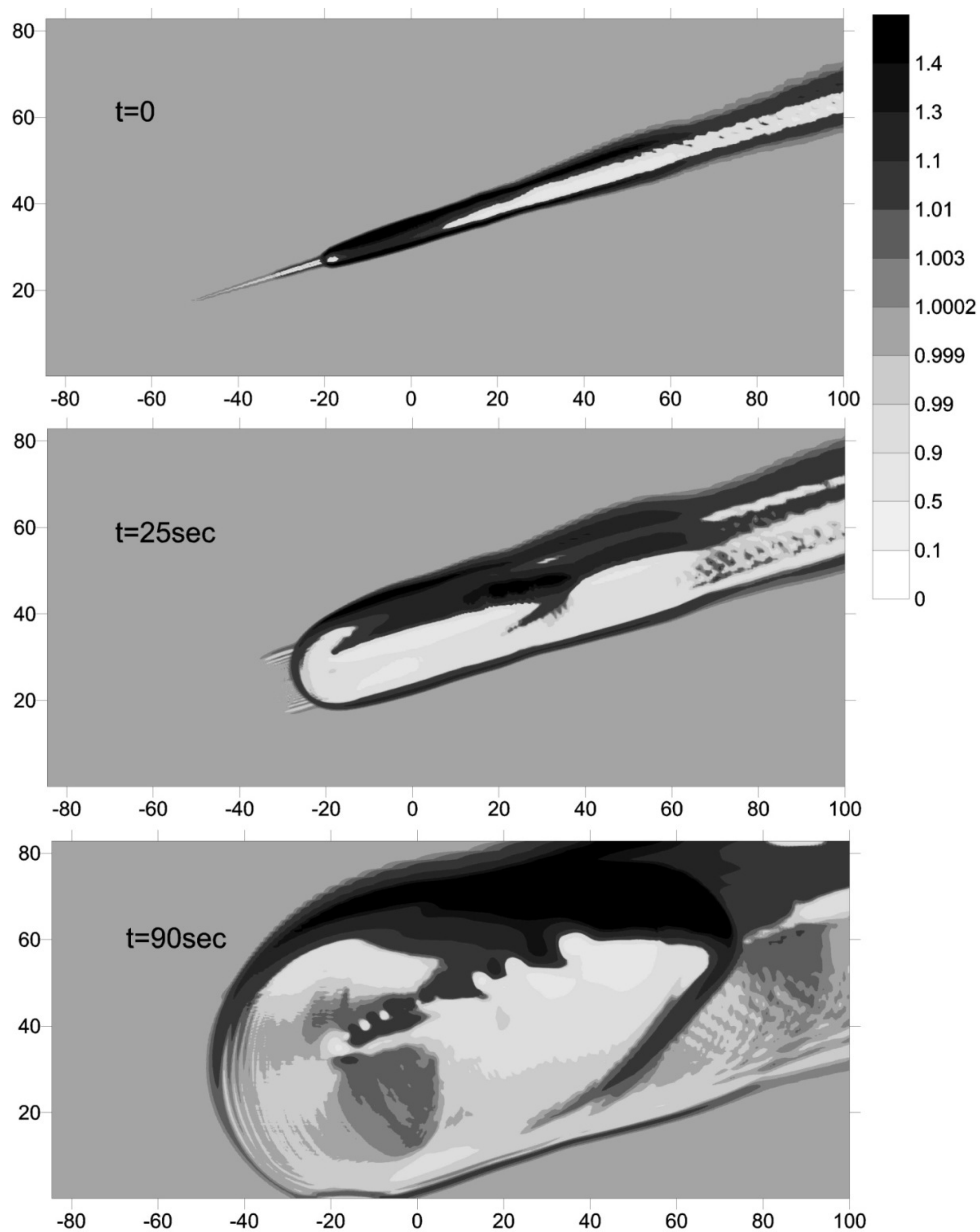
OH AIRGLOW ON FLAT FIELD





Modeled Pressure Perturbation and Glass Damage Following the Chelyabinsk Meteor Event

[Popova et al., Science, 342, 2013]



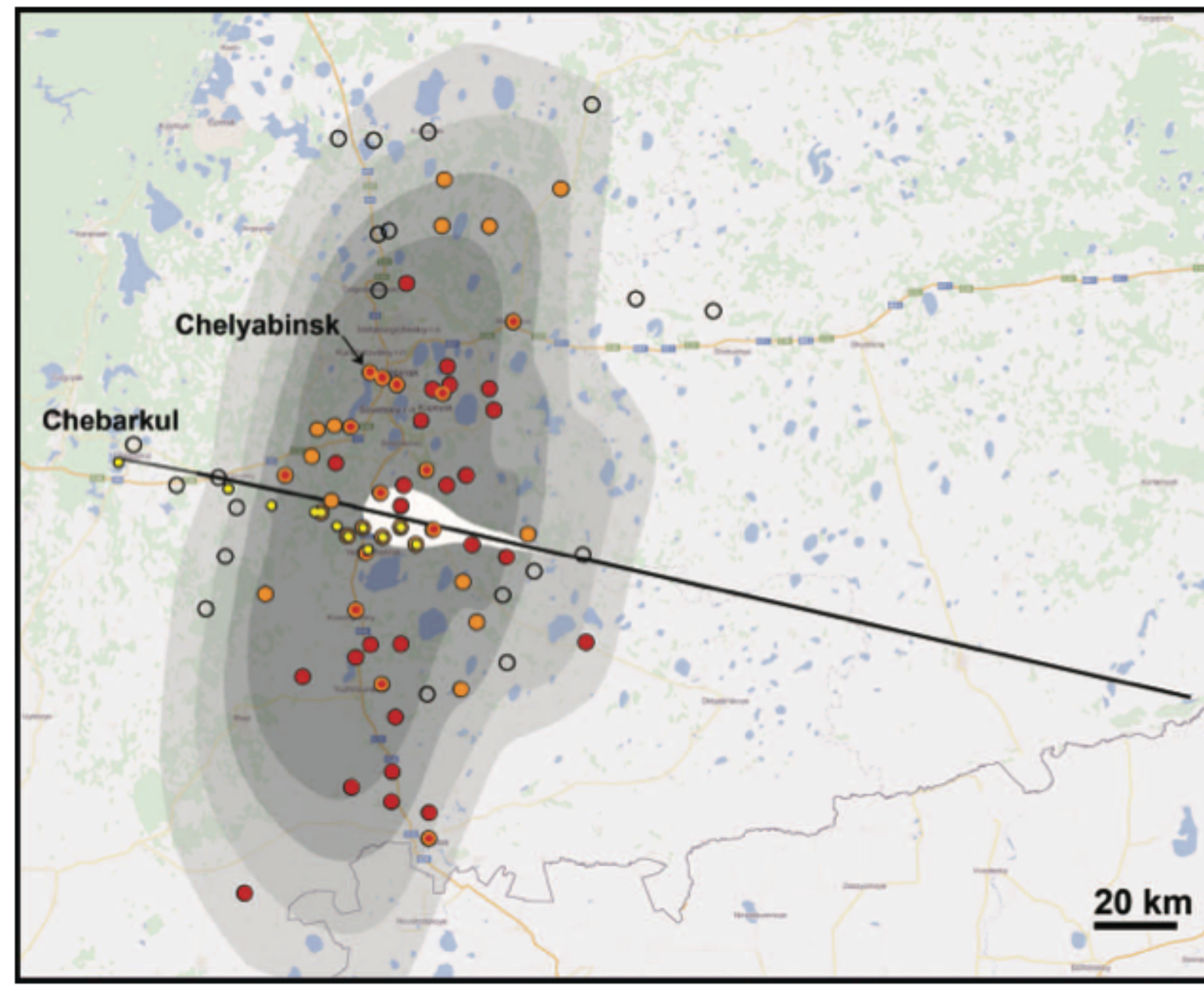


Fig. 3. Map of glass damage on the ground with models of overpressure. Field survey data are shown in solid orange circles for reported damage and open black circles for no damage; solid red circles show the most damaged villages in each district, as reported by the government. Each point, irrespective of population density, represents one of many villages or city districts scattered throughout the area. Model contours (with progressive gray scale) represent kinetic energies and overpressures from inside out: 300 kT $\Delta p > 1000$ Pa, 520 kT $\Delta p > 1000$ Pa, 300 kT $\Delta p > 500$ Pa, and 520 kT $\Delta p > 500$ Pa, respectively. Also shown are the locations of meteorite finds (yellow points) and the ground-projected fireball trajectory (black line), moving from 97-km altitude on the right to 14-km altitude on the left. White shows the fireball brightness on a linear scale.

These are just a few examples of combined modeling and observational/experimental studies – *many* other diverse and excellent case studies exist in the literature!

Summary / Conclusions

- Modeling is too diverse to capture in any one talk (as also demonstrated by last year's Student Workshop).
- Models are never perfect, but are frequently useful.
- When used appropriately and creatively, modeling is an important and complementary methodology to experiment, observation, and theory.
- *Collaboration is encouraged!*