Modeling the Thermosphere and Ionosphere

Aaron Ridley

Caveats

- I tend towards the model of "constant improvement"
- This means that I tend to not stress the positive in things
- This may come off as being pretty negative
  - I am not really negative
  - I just play negative on TV
- What does this means for this talk?
  - Models are really, really, really helpful
  - Keep this in mind

Types of Models

- Empirical Models
  - Data-based
  - Simplistically:
    - Gather a bunch of data
    - Process the data in some way
    - Bin it in some way and calculate averages or trends or whatever
    - Fit it to some functional form (spherical harmonics or whatever)
  - Mean is typically correct
  - If the event is outside of the scope of inputs, the results may not be great

Types of Models

- Physics-Based
  - Write out a series of equations
  - Figure out a way to solve those equations in a computer
    - Numerical differentiation and integration
    - Often on a grid of some sort
    - Can be quite complex and time-consuming
  - Missing physics is a big problem!
  - Can do thought experiments:
    - What if CO_2 doubled next year?
    - What if the magnetic field flipped?
  - Often hard to get mean correct, but may work outside of observed drivers (may!)

How to make a physics-based model?

- Switch to other slides!

- You can find these presentations here:
  - http://herot.engin.umich.edu/~ridley/data/CEDAR

Welcome back!

Physics-Based Modeling the Upper Atmosphere

- Neutrals can be described by Navier Stokes (fluid dynamics) equations with extra forcing terms:
  - Chemistry, ion drag, collisional heating with ions
- Ions/electrons are more difficult to model
  - Chemistry (ionization, charge exchange, and recombination), electric fields, magnetic fields, collisional heating, cooling, and momentum transfer with everything (really hard!)

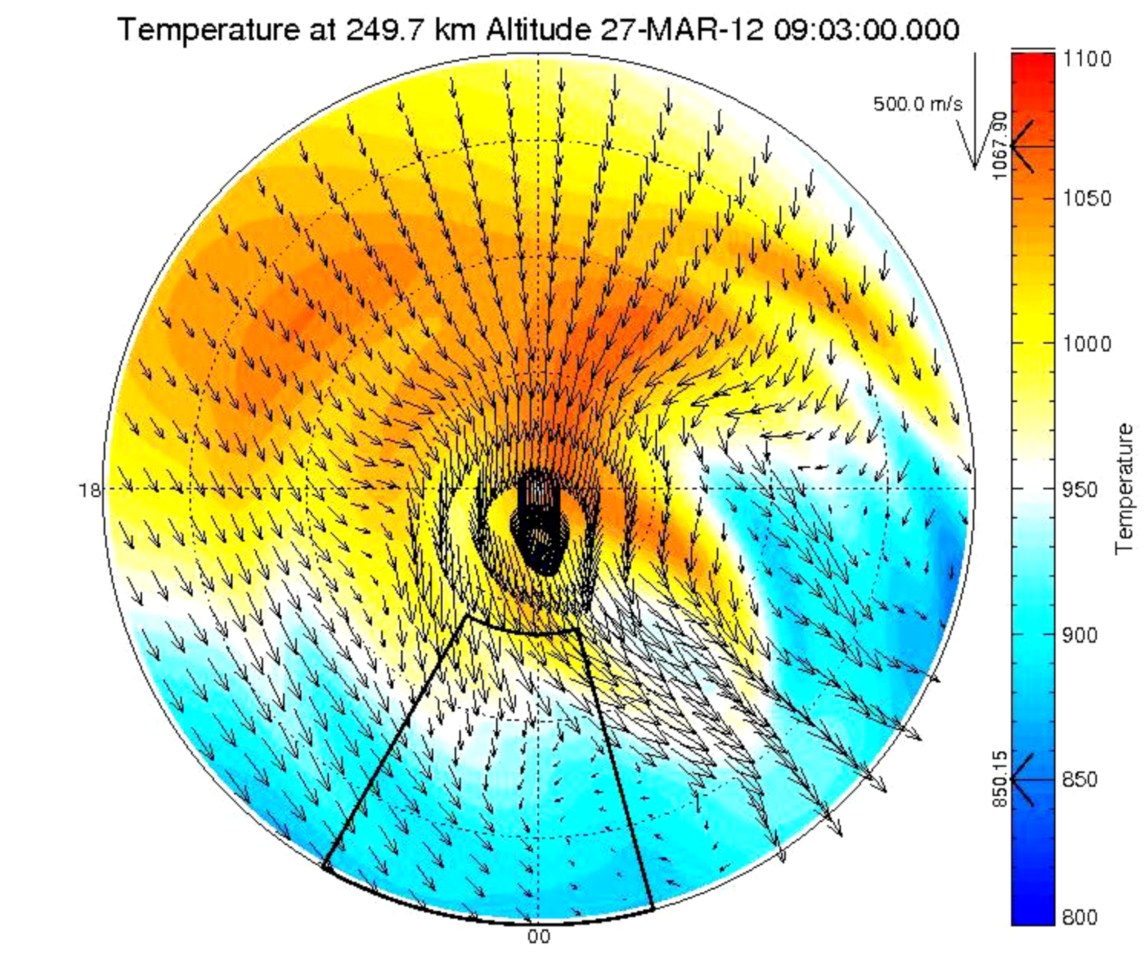
$$\frac{\partial \mathcal{N}_s}{\partial t} + \nabla \cdot \mathbf{u}_s + \mathbf{u}_s \cdot \nabla \mathcal{N}_s = 0.$$

$$\frac{\partial \mathbf{u}_s}{\partial t} + \mathbf{u}_s \cdot \nabla \mathbf{u}_s + \frac{k}{M_s} \nabla T + \frac{k}{M_s} T \nabla \mathcal{N}_s = 0,$$

$$\frac{\partial \mathcal{T}}{\partial t} + u_r \frac{\partial \mathcal{T}}{\partial r} + (\gamma - 1)\mathcal{T}\left(\frac{2u_r}{r} + \frac{\partial u_r}{\partial r}\right) = \frac{k}{c_v \rho \bar{m}_n} \mathcal{Q},$$

$$\mathbf{v} = \frac{\mathbf{A} \cdot \mathbf{b}}{\rho_i \nu_{in}} + \frac{\rho_i \nu_{in} \mathbf{A}_\perp + e N_e \mathbf{A}_\perp \times \mathbf{B}}{\rho_i^2 \nu_{in}^2 + e^2 N_e^2 B^2},$$

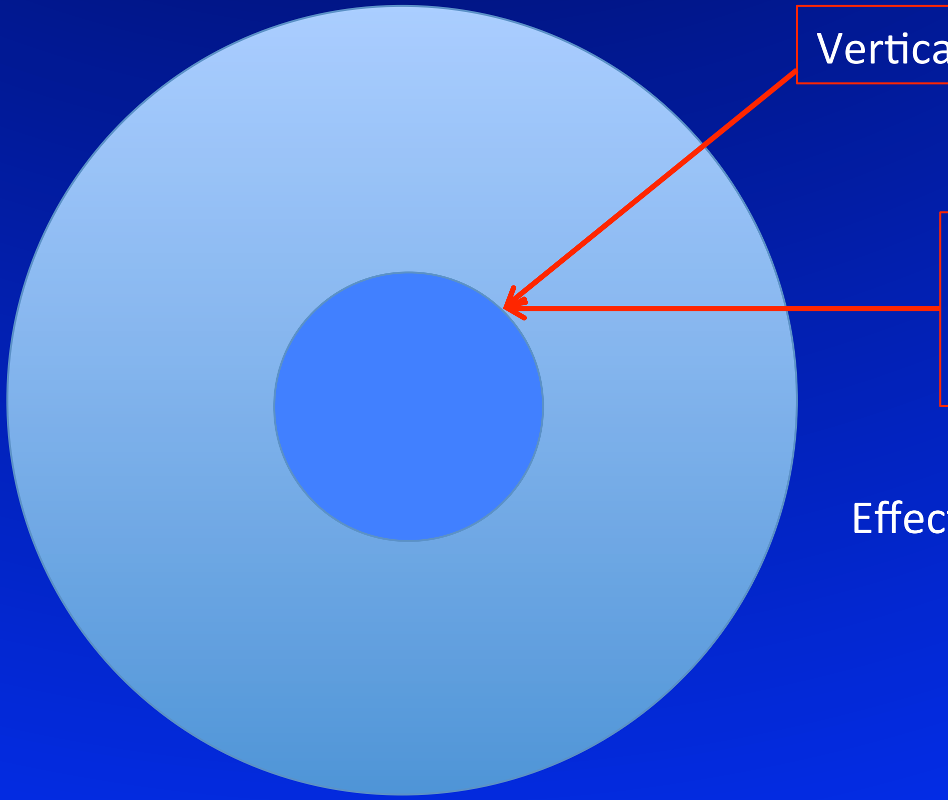
Thermospheric Reaction to a Substorm



Complications

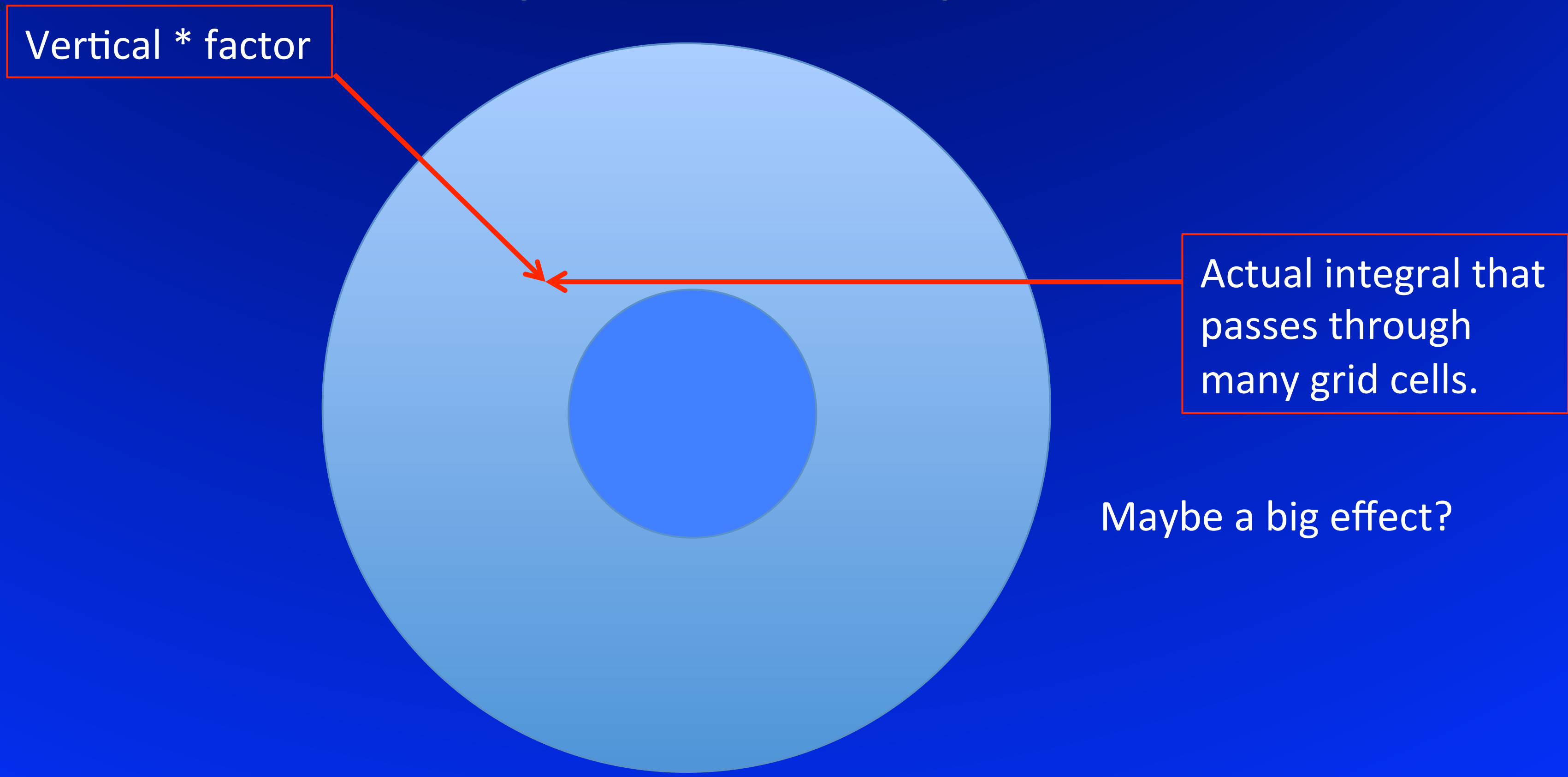
- Missing physics:
  - Navier Stokes Equations are foundation (thermosphere)
  - Add a shiton of source terms
  - What if:
    - The Navier Stokes equation set is not complete enough to fully describe the thermosphere? (heat flux? Collisional heat transfer?)
    - We miss some source terms? (chemistry? small-scale mixing?)
    - The approximations are not correct? Typically can't fully describe the physics completely, since it would take WAY too long
      - Chapman integrals for heating! Fundamental! Approximate!

Chapman Example



Effect? Uh…?

Chapman Example 2



Maybe a big effect?

Parameterizations

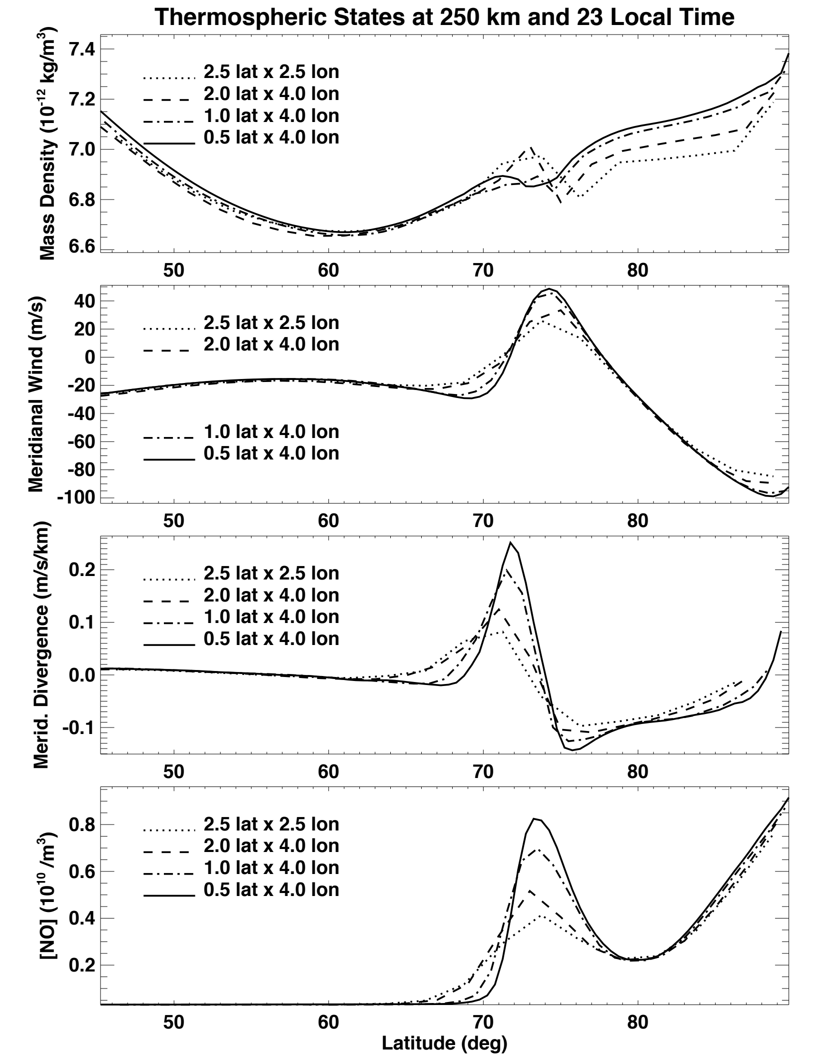
- Simplify physics using parameterizations
  - Thermal conduction
  - Viscosity
  - Eddy diffusion
  - Collisions (neutral-neutral, ion-neutral, ion-electron)
  - Radiative cooling
  - Solar inputs (F10.7 -> EUV spectrum)
  - Aurora and electric fields
  - Tides
- How to tell if parameterizations are correct?
  - This is **REALLY** hard!

Complications

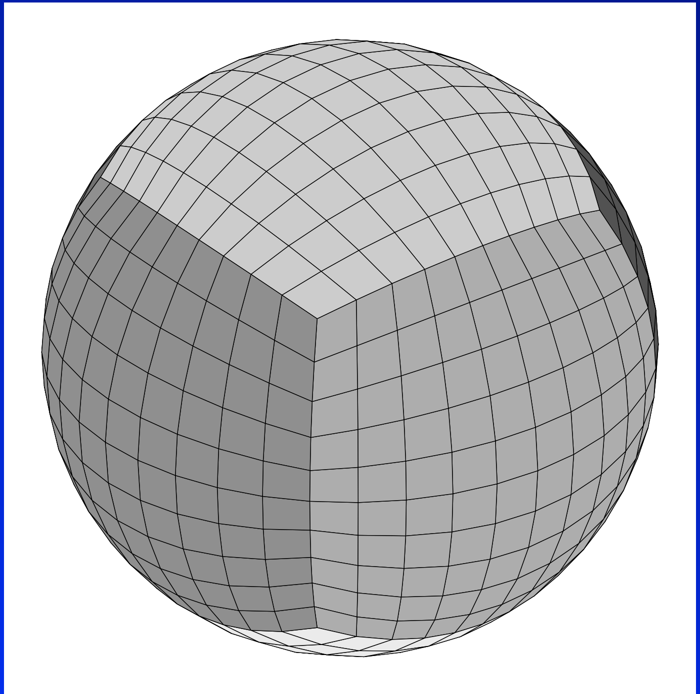
- Numerics:
  - Creating a grid in space and time creates numerical issues
    - Can not capture some features if resolution is too small (electric fields, aurora, storm-enhanced densities, etc.)
    - Low resolution smooths features out
      - Gradients are reduced
      - Forcing terms that are dependent on gradients are reduced
    - Pole problem
      - Longitudinal gradients go to infinity at pole
      - Complicated to solve this
    - How to handle boundary conditions?

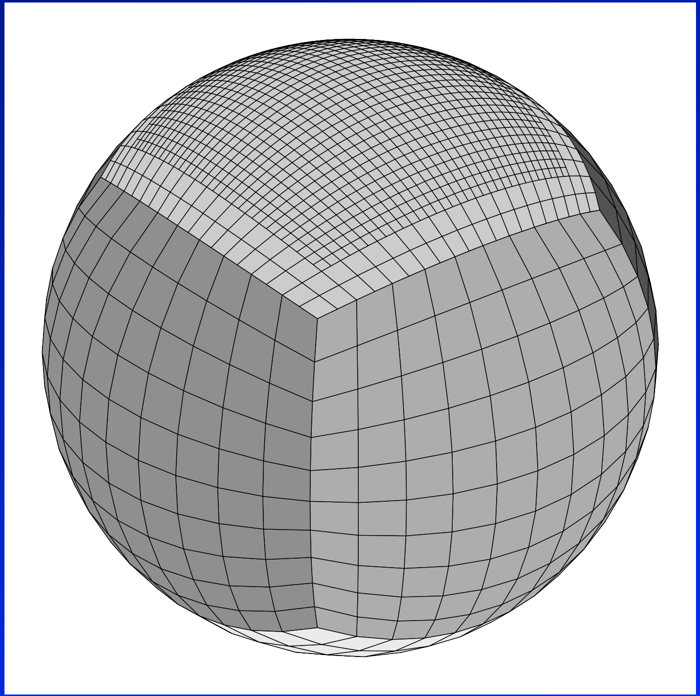
Resolution

- This is a cut through the auroral oval
- Increasing latitudinal resolution from 2.5° to 0.5°
  - Does this cause the heating to increase?
  - Captures E-field and aurora better (not shown)
- Captures:
  - Meridianal wind divergence changes dramatically (cooling!)
  - Captures NO density better (cooling!)
- Net effect is little change in density (a bit higher in the polar cap)
  - Capture physics better, though!



Cubed Sphere?

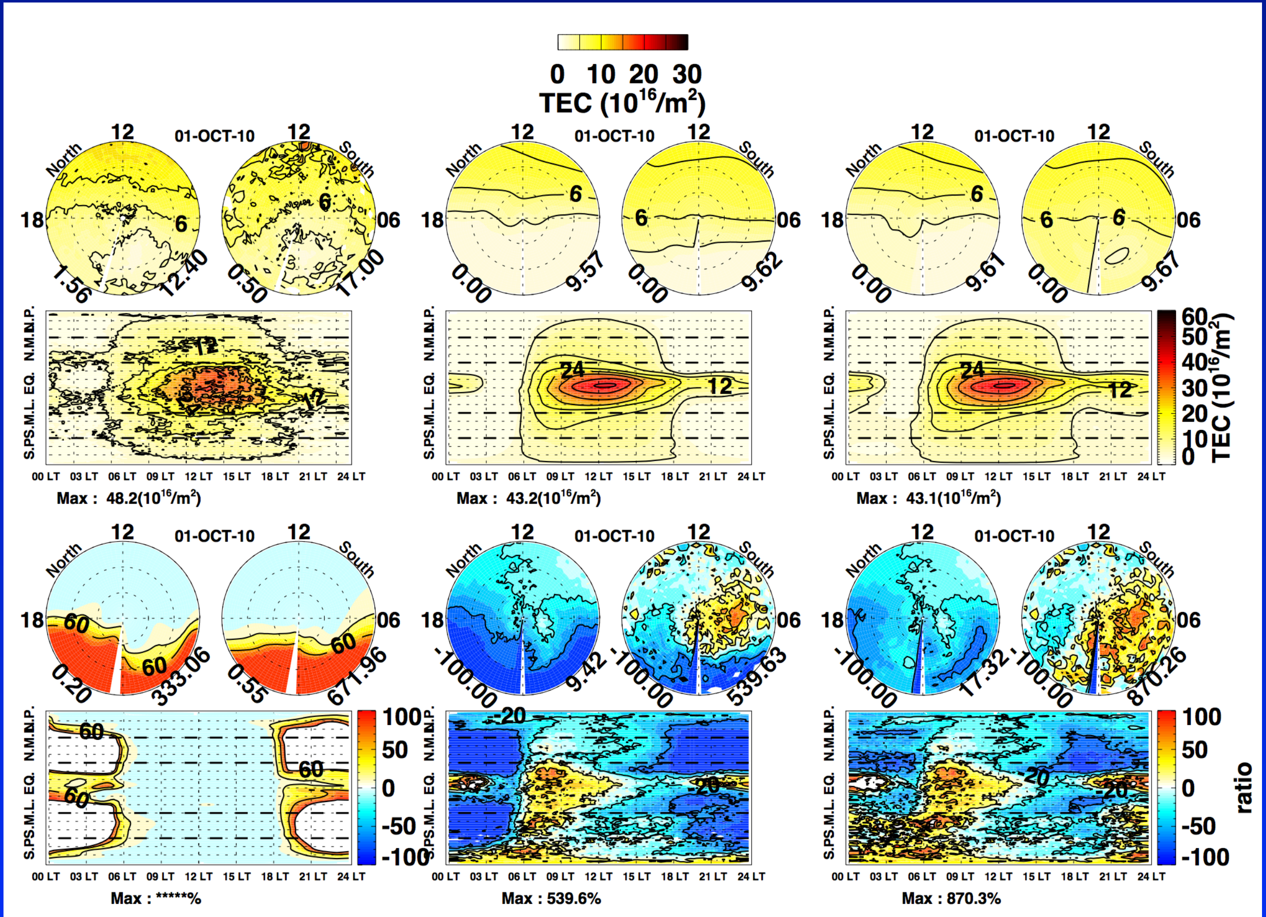




Boundary Conditions

- Seems simple, but really complicated
  - Lower boundary:
    - Ionosphere is simple, since there is *no* ionosphere below some altitude
    - Thermosphere is more difficult:
      - Densities, temperatures, winds
      - Tides? Gravity waves?
  - Upper boundary:
    - Ionosphere is complicated, since magnetic field lines extend out into the magnetosphere
      - Some are open and some are closed
      - If model is altitude limited, how to "cap" the field line? Upflow? Downflow?
    - Thermosphere is maybe a bit easier?
      - Assume some sort of gradient (hydrostatic?)
      - Don't want to reflect waves

Ionospheric Upper Boundary Condition



(Chen Wu!)

Data-Model Comparisons

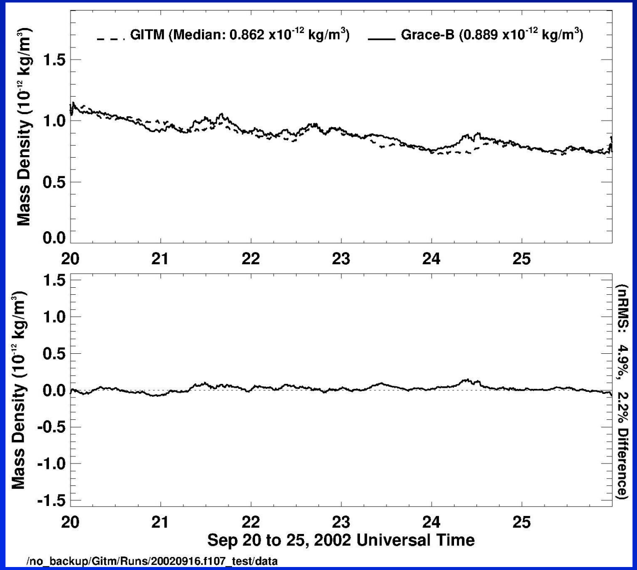
- Validate the Model
  - Reasons to do this:
    - Determine whether the parameters and/or physics is correct
      - Tuning?
    - Determine whether we should trust the model
      - This is really hard to answer
      - It is pretty much an *opinion* and not a scientific quantification
    - Examples?
- Put data into context
  - Small-scale measurements put into a larger-scale model context
  - Can be quite useful, even if model results are not perfect (?)

Problems

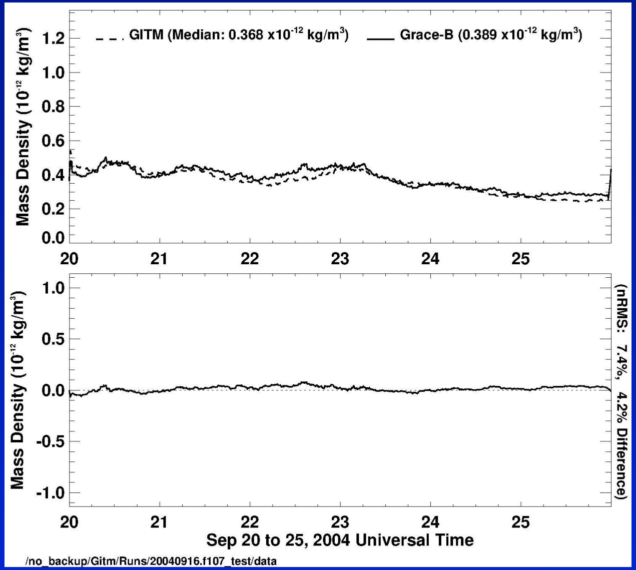
- What to compare to?
  - Local data or global data?
  - Ionosphere or thermosphere
  - Tune the model to one data set and you may detune it for a different data set
    - Tuned GITM to match CHAMP, and totally screwed up electron density! Ugh!
    - Tuned GITM to match CHAMP with larger F10.7 values, and it doesn't work for lower F10.7! Ugh! Why???
- Data is hard!
  - Lots of different formats
  - Lots of different coordinate systems and complications
  - Lots of ways of handling uncertainties
  - Data often doesn't overlap in time or space
- One event is one event
  - If it doesn't match, why?
  - If it does match, what does this mean? The model is perfect?
    - But we know that there are issues with numerics and other things, so should it be perfect?
    - Is it right for the wrong reasons?
- God – what does it all mean???

Tuning to Different Times

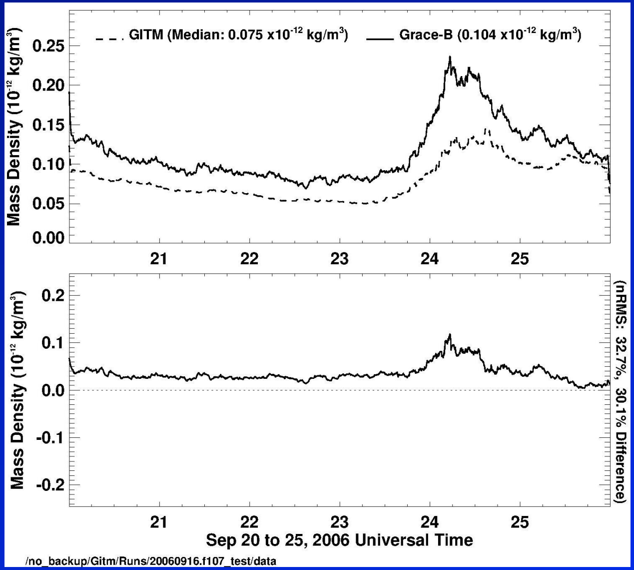
F10.7 Strong



F10.7 Medium

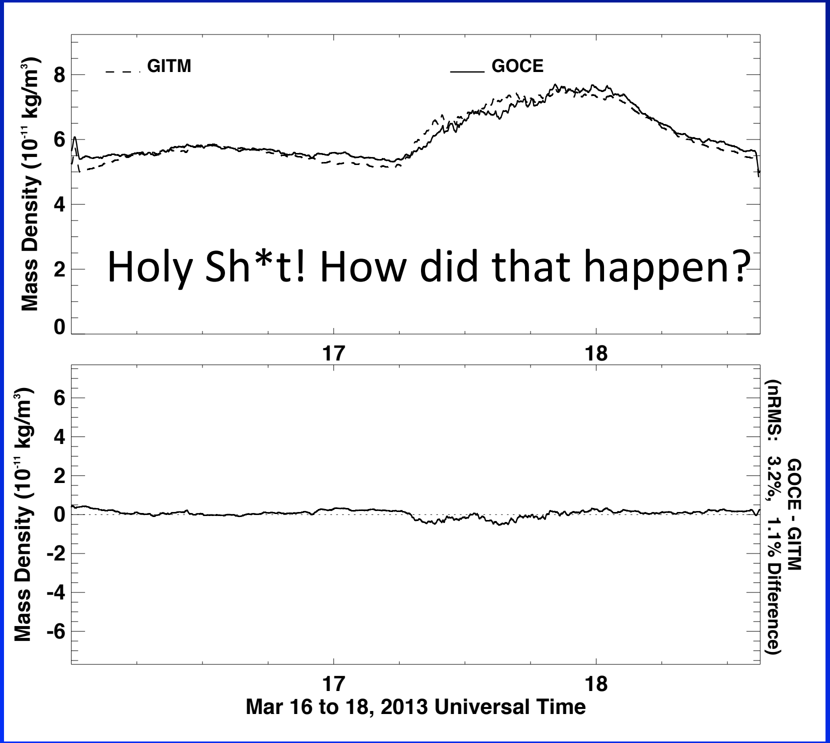


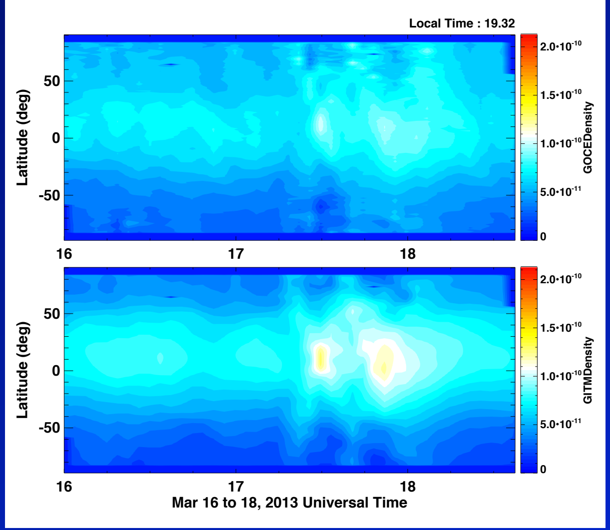
F10.7 Low

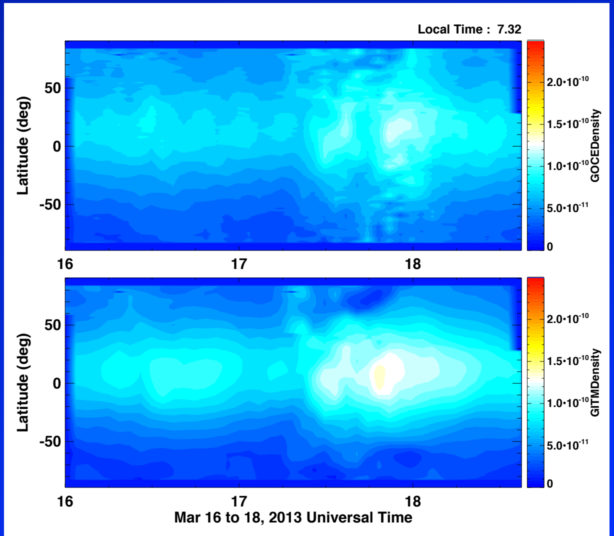


CHAMP neutral mass density data – orbit averages (basically global averages at 400 km)

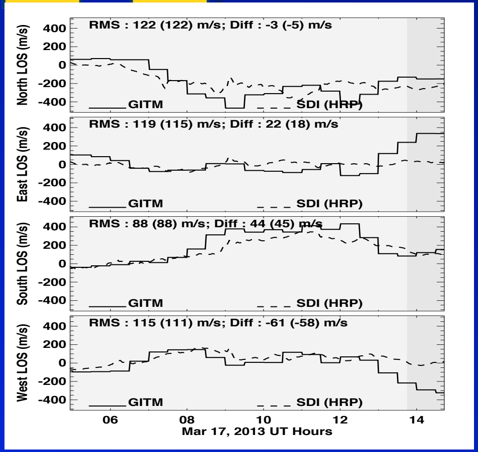
GITM (Weimer + NOAA Run) Compared to GOCE – March 2013

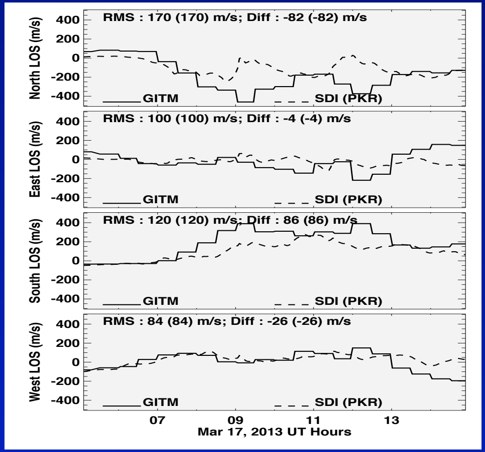


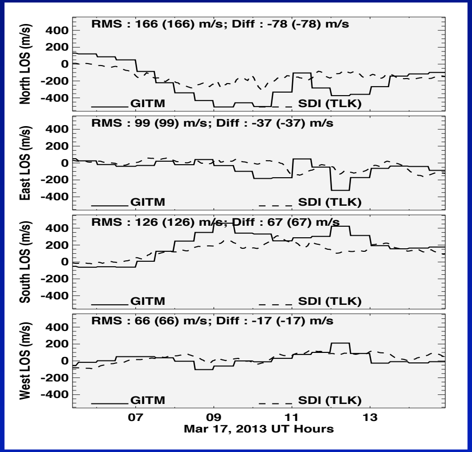


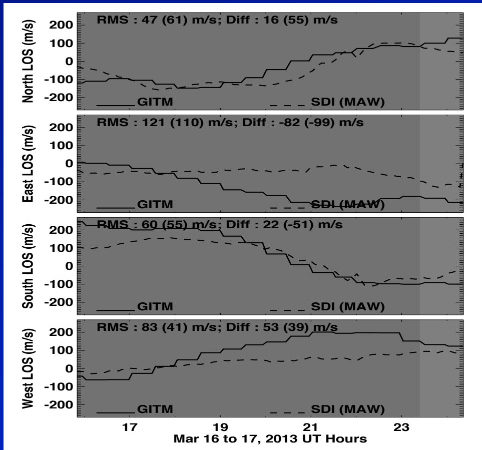


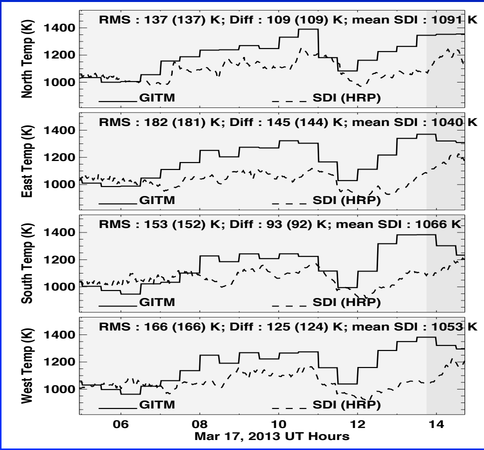
GITM Comparisons to SDI – March 17

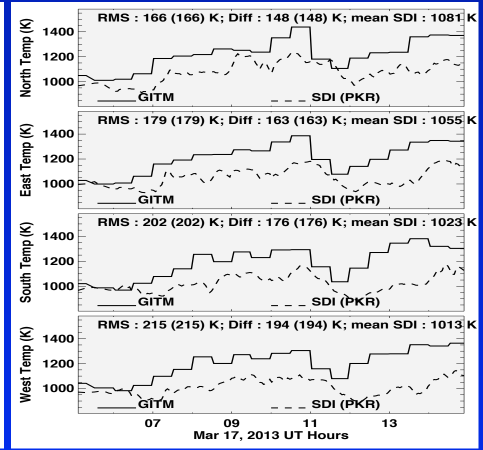


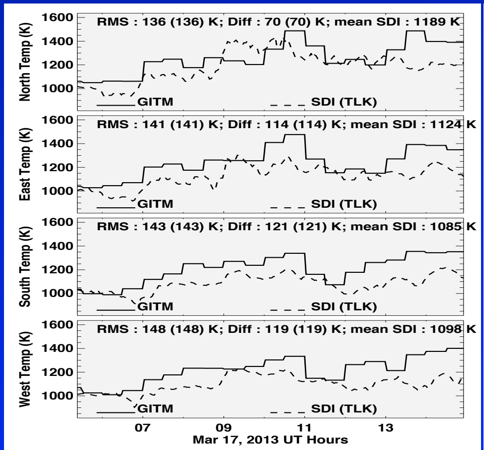


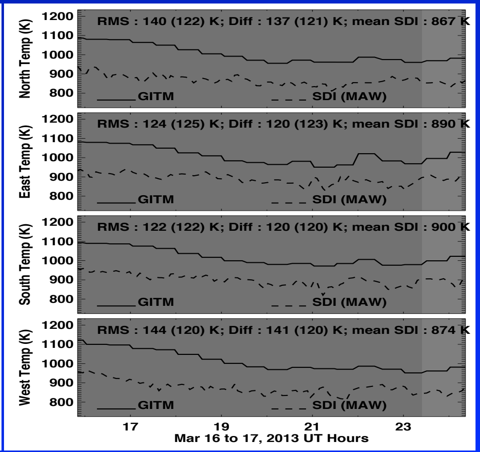




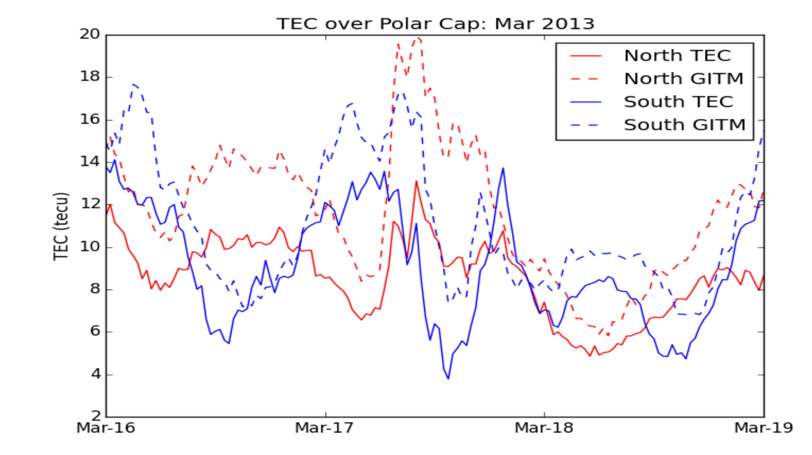








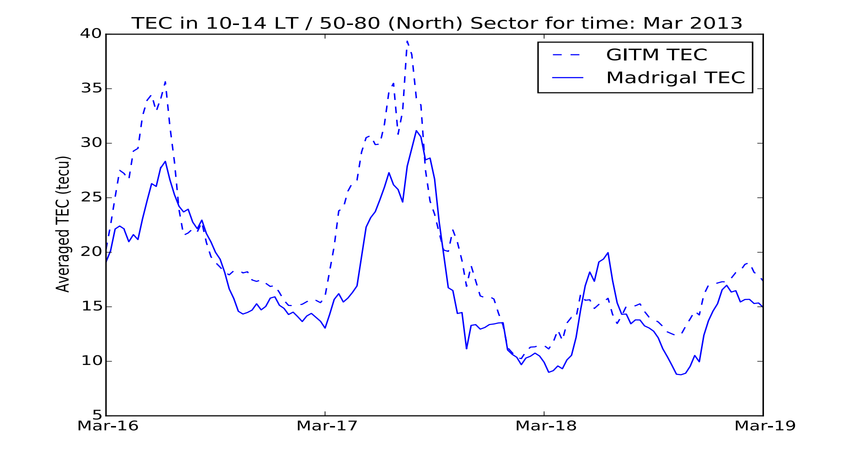
GITM Comparison to TEC

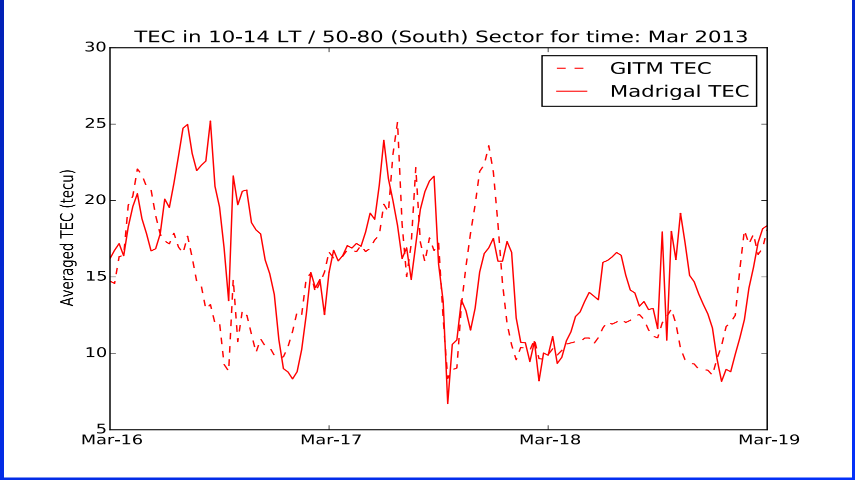


Average TEC over polar regions (+/- 45 deg)

Good? Bad? What does it mean???

Dayside mid-latitude "throat" region





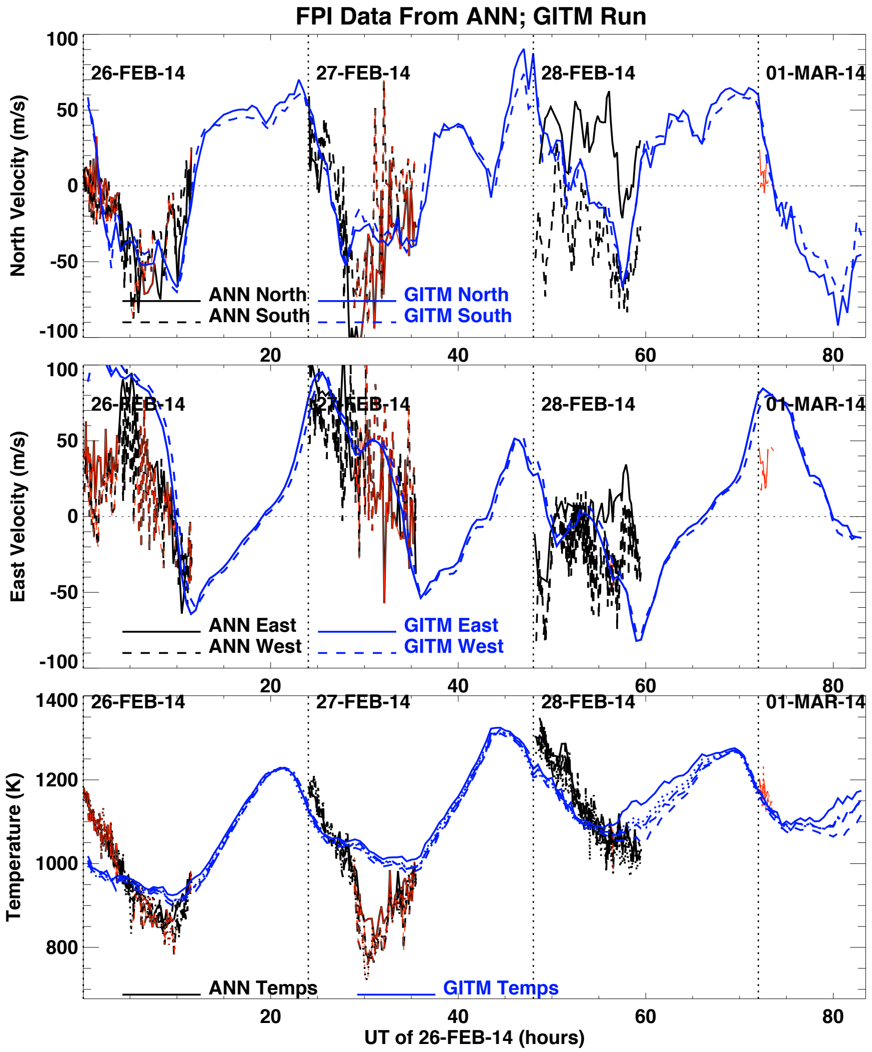
Fabry Perot Interferometer

Neural winds and temperatures above one point on Earth (Ann Arbor)

Is this good? Bad?

What does it mean?

Do you trust the model now?

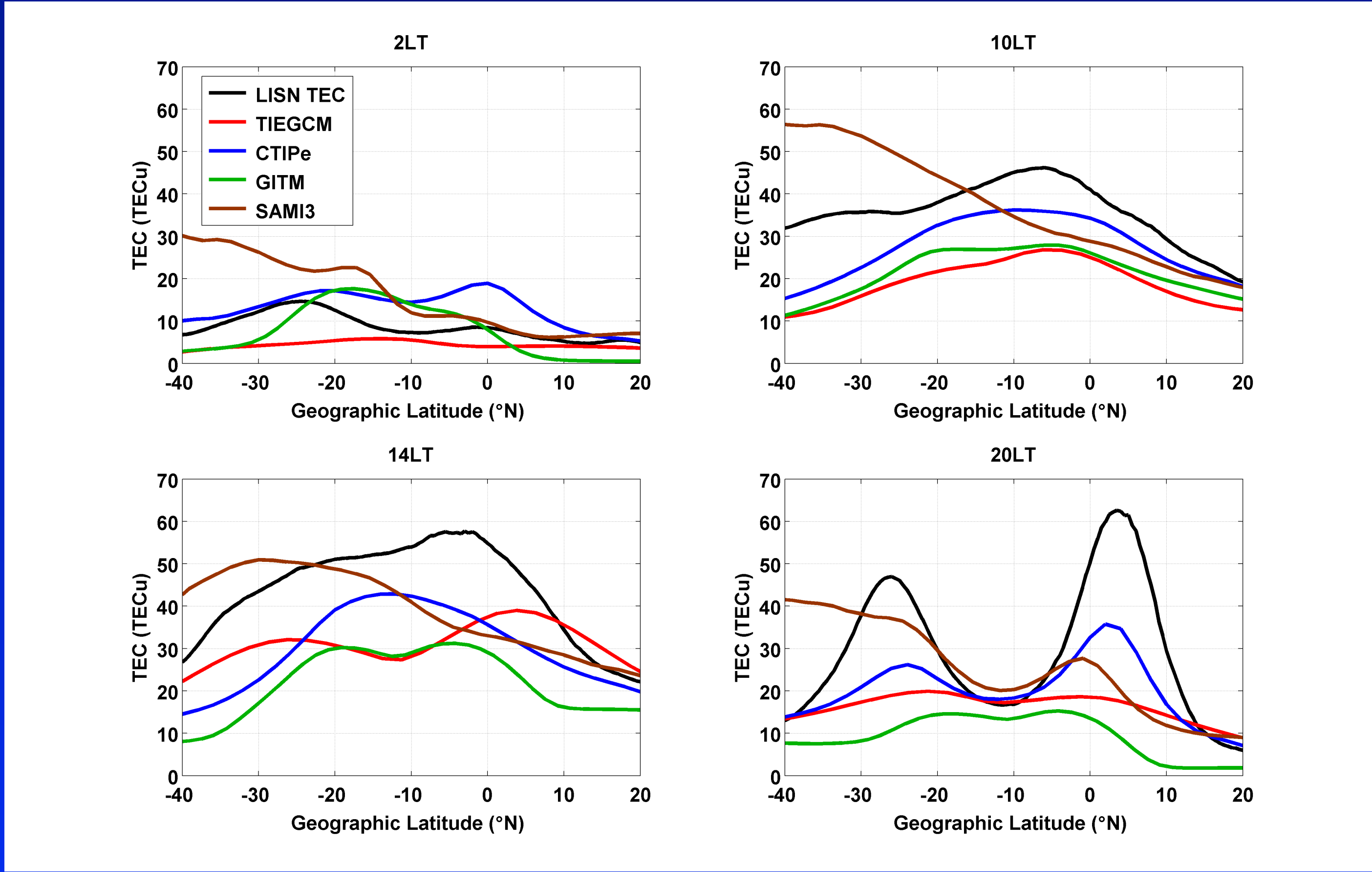


PRIMO – Tzu-Wei Fang, Dave Anderson et al.

Models	Full Names	Participated Modelers
SAMI3	SAMI3 is Also a Model of the Ionosphere	Joe Huba Jonathan Krall (NRL)
TIEGCM	Thermosphere Ionosphere Electrodynamics General Circulation Model	Astrid Maute Art Richmond (NCAR)
GITM	Global Ionosphere-Thermosphere Model	Aaron Ridley Angeline Burrell (University of Michigan)
CTIPe	Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model	Mariangel Fedrizzi Tim Fuller-Rowell Mihail Codrescu (CU/CIRES & NOAA SWPC)

TEC Comparisons (70°W)

November 2012

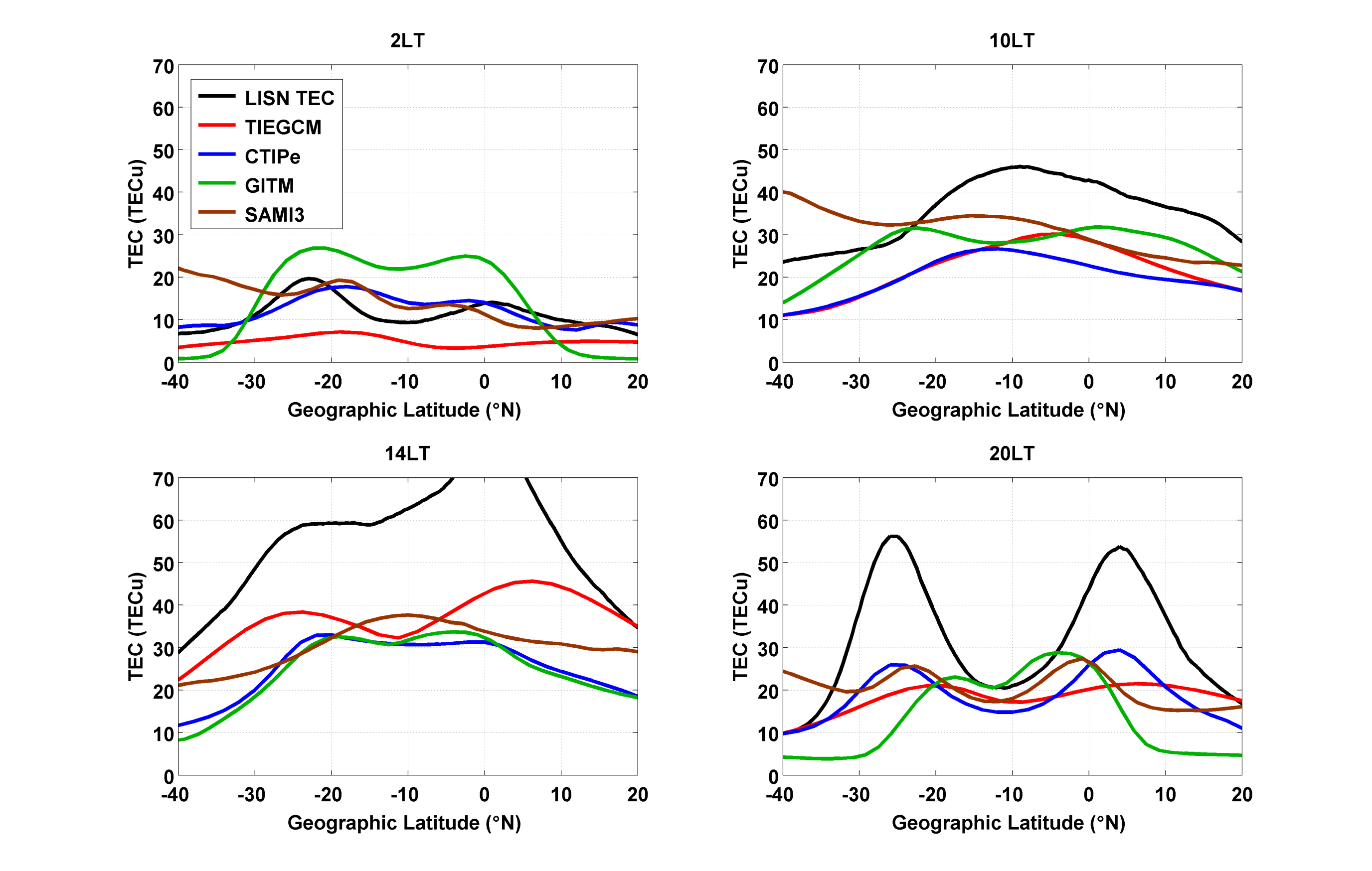


Height for the integration?

LISN data were provided by Cesar Valladares (BC)

TEC Comparisons (70°W)

March 2013



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Summary

- Physics-based models are extremely complicated
  - Physics assumptions, parameterizations, grids, numerics, drivers, boundary conditions, etc.
- Data-Model comparison attempt to give some confidence that the model is doing things right
  - Do they?
- Need to compare to all sorts of different data sets over all sorts of different times
- Really need something like ensemble models to counteract weaknesses (and strengths) of individual models