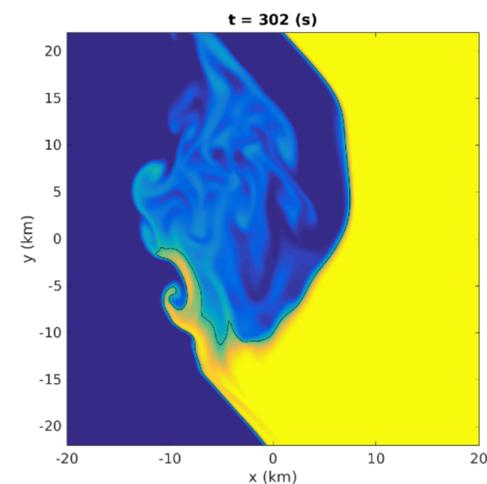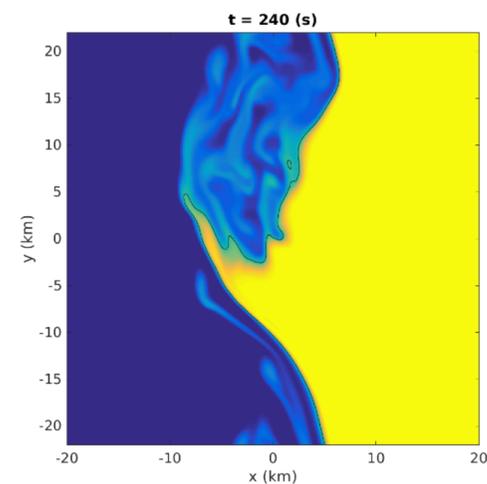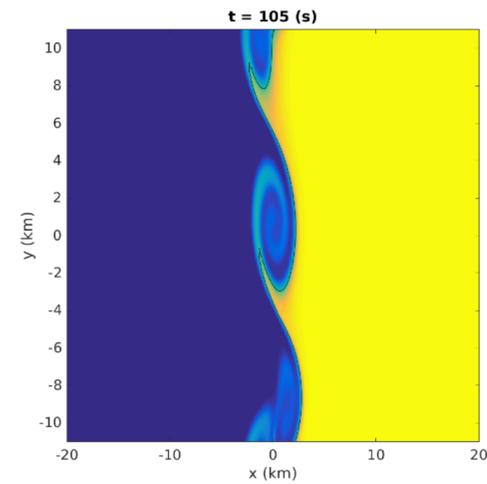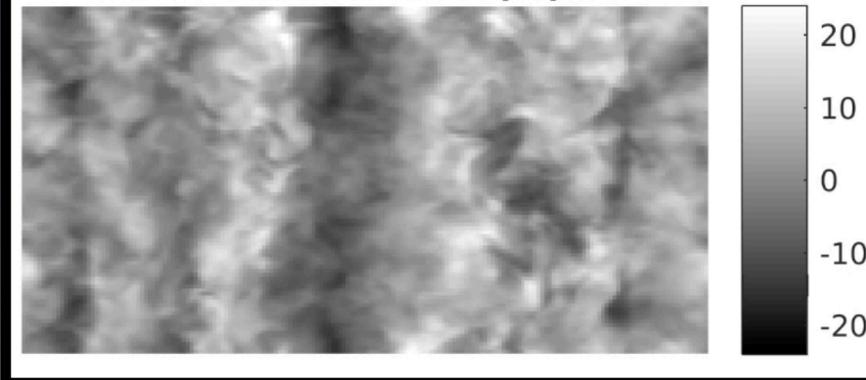# Multi-scale modeling:
advances and future needs

M. D. Zettergren, T. Nishimura, A. Ridley, Y. Deng, R. McGranaghan
and the rest of our GC workshop contributors

with contributions from: M. Burleigh, K. Deshpande, C. Heale, J. Snively, and many others

Snively et al (Wed. rocket session)

Huba et al (2008)

Zettergren et al (Thurs. Big Data session)

Yigit et al (2016)
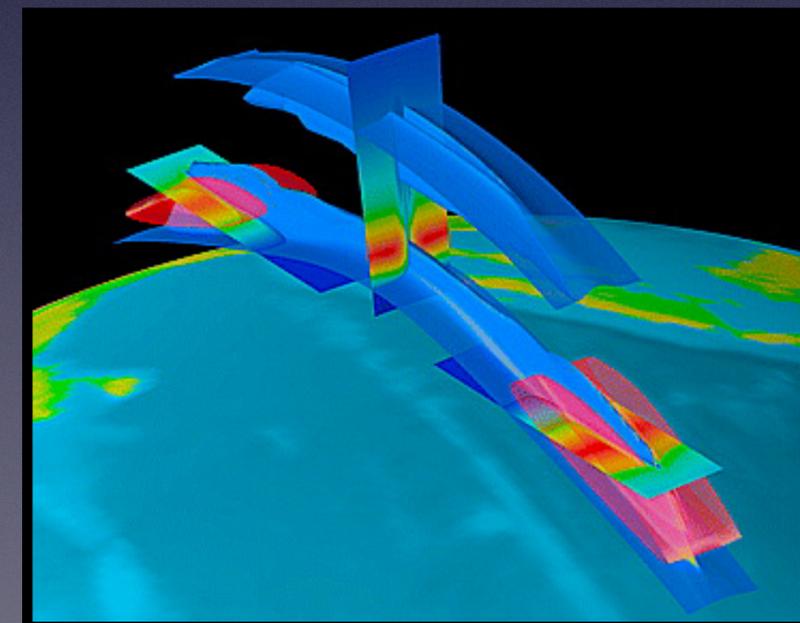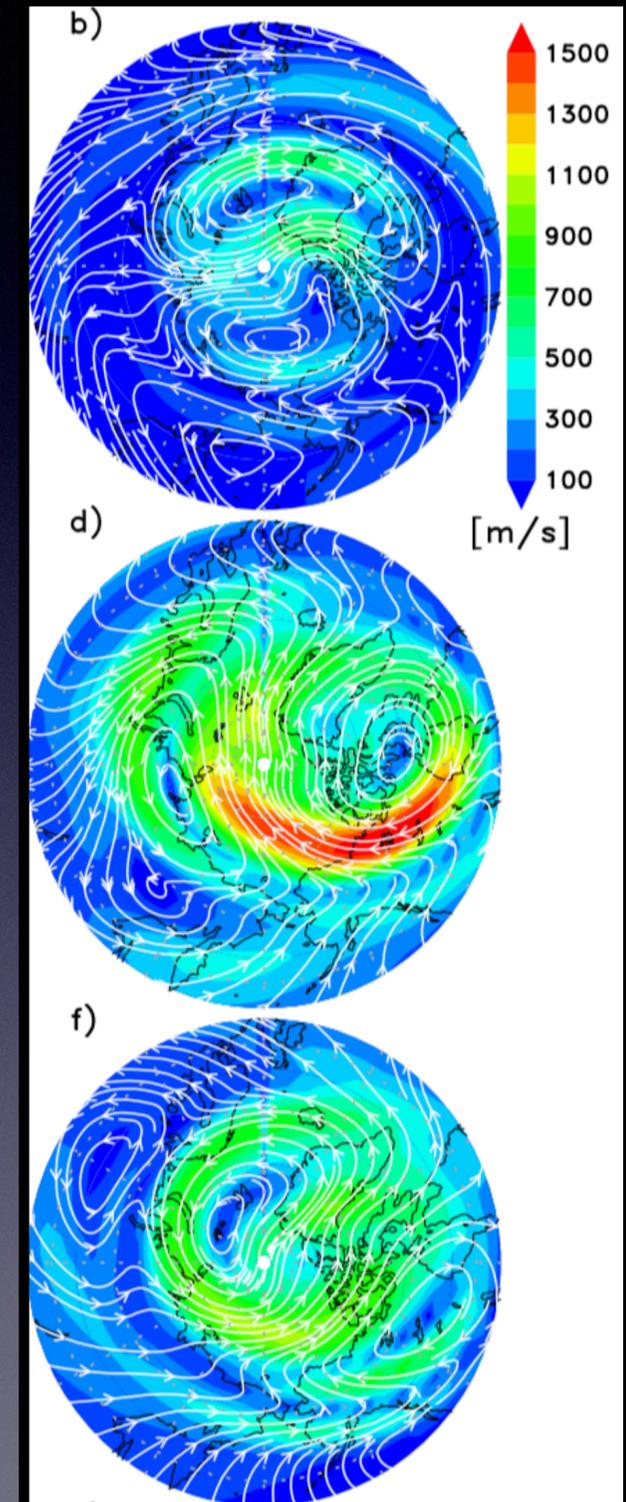
Outline

- GC workshop themes as related to multiscale *modeling*

- Multi-scale system and coupling approaches

  - small —> large

  - large —> small

  - data-driven multi-scale modeling

- Future: multiscale modeling advances?

  - challenges?

  - approaches?

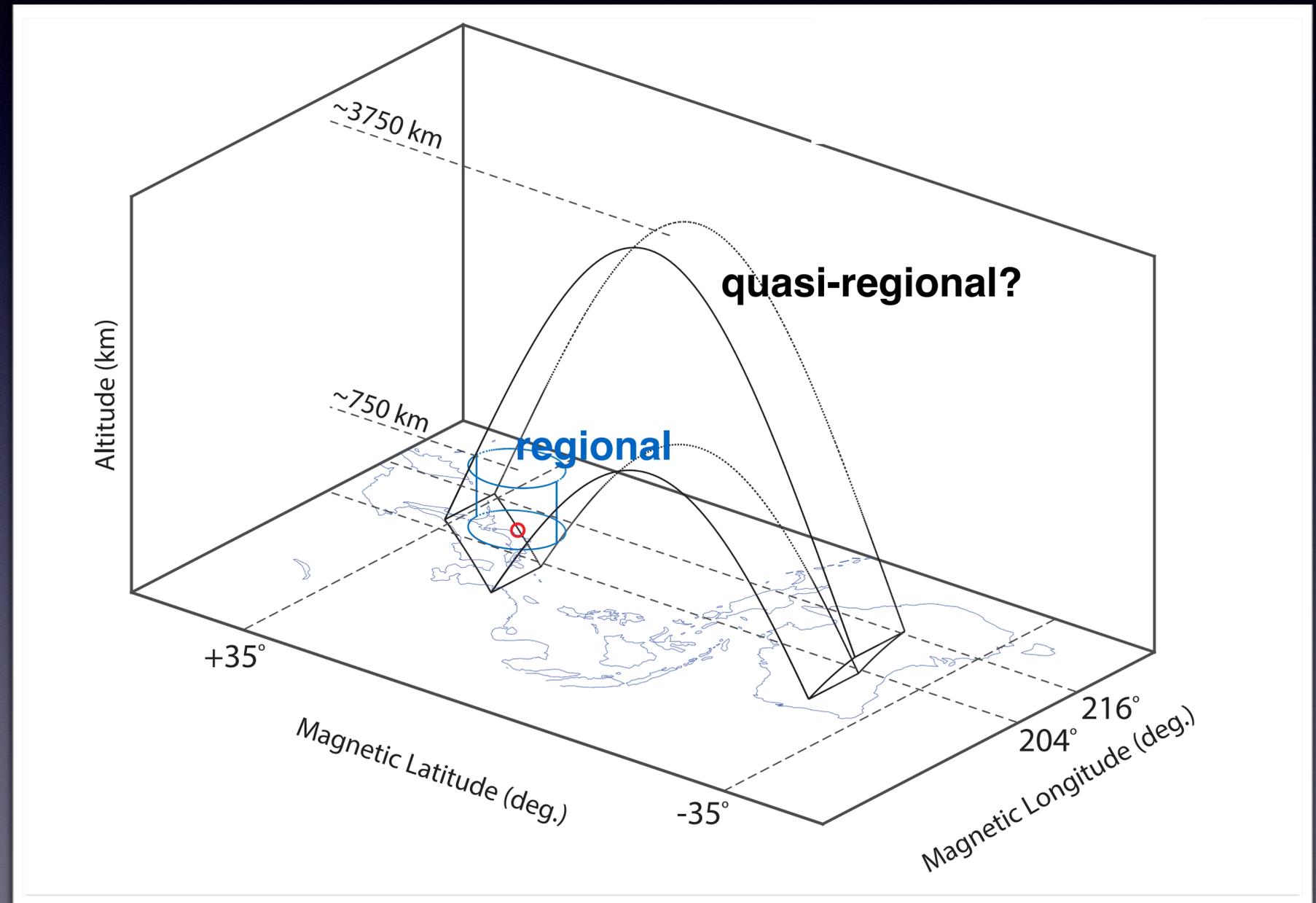# Connection to Grand Challenge session: global ~~vs.~~ and local scale modeling
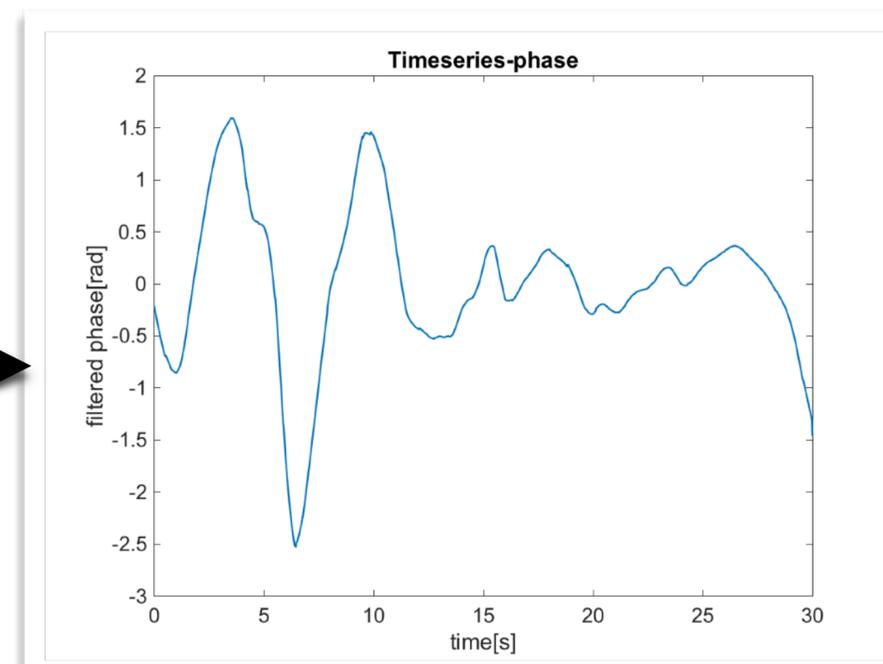
Motivation

- In many important situations, *small-scale processes have been shown to matter to global-scale dynamics*

- Large- and small- scale models tend to be operated independently, preventing an accurate assessment of cross-scale coupling impacts.

- Driving models at multiple scales is a bit of an art at this point

Science question(s)

- *How much can we improve physical understanding and reproducibility of multi-scale coupling processes in the IT system?*

  - small-scale and meso-scale intense particle precipitation events

  - meso- and small- scale IT structures (including waves/AGWs) and their relation to driving.

  - ionospheric density structuring and conductance at multiple scales (patches and instabilities: GDI, KHI, and FBI)

Large-to-small scale coupling: BG state impacts on instabilities

- Ionospheric instabilities (GDI, KHI, GRTI) depend on background atmosphere-ionosphere state and time history

- E.g. time and space dependent flows + photoionization + cusp precipitation led to formation of large-scale polar cap patches

- **Patches can undergo turbulent cascade to smaller scales** - details of resulting irregularities depend sensitively on physical processes included in the models and spatial resolution

- These details, in turn, affect modeled GNSS phase scintillation (below)

dense dayside plasma

patch formation

propagation and internal structuring

0830 UT   Kp = 5   c)

2/20/2013 5:00:00 UT

Deshpande et al (GC Tuesday session)
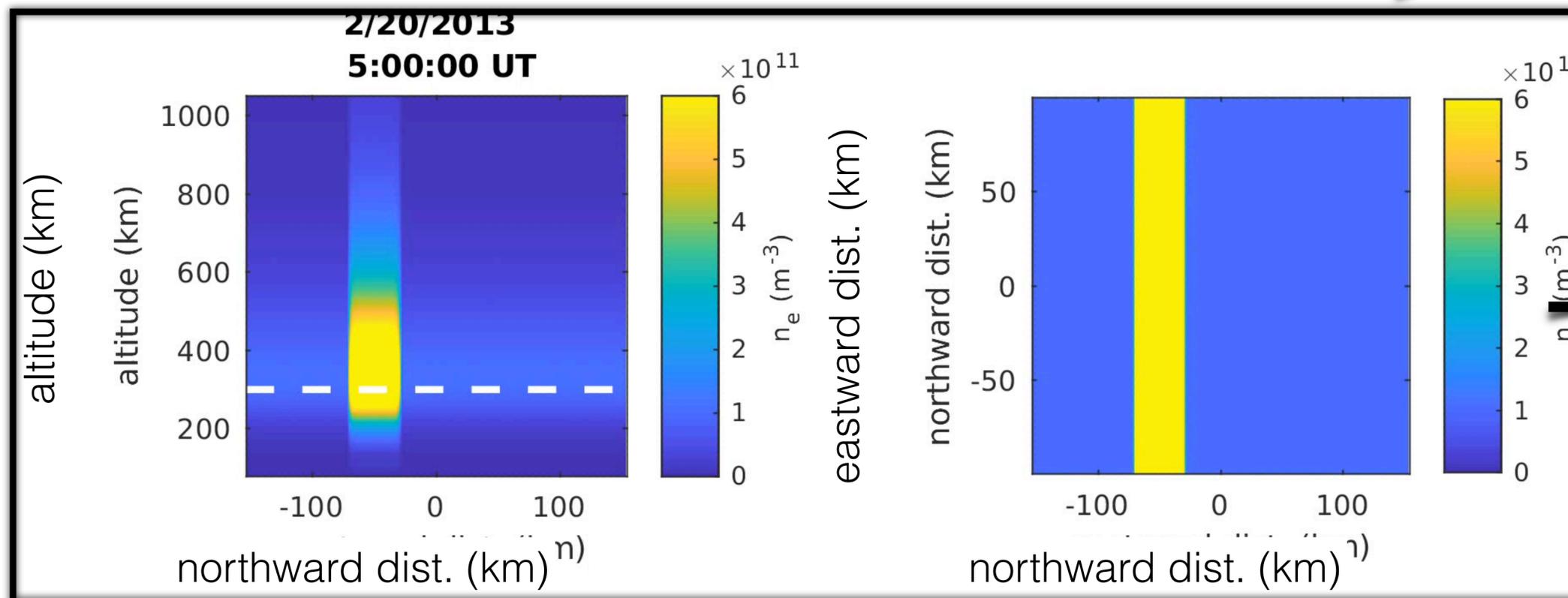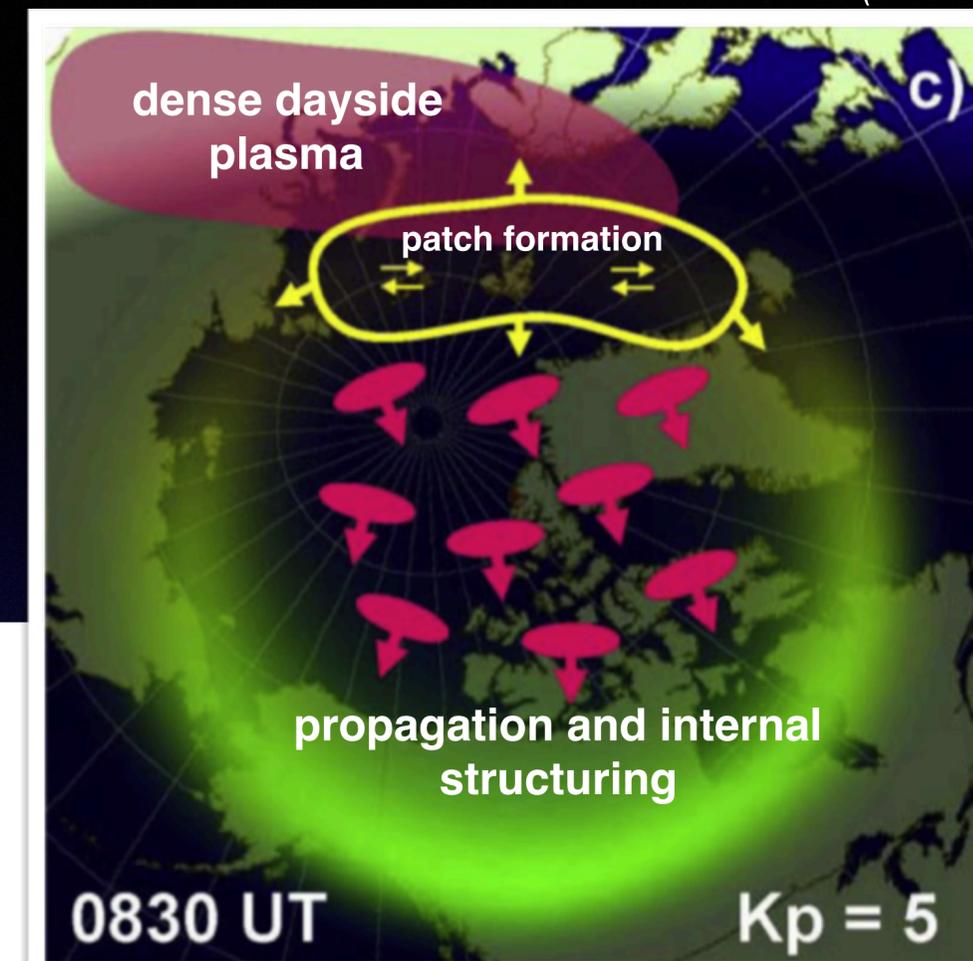
Small-to-large scale coupling: GW effects on plasma transport

- *Burleigh et al (2018)*: simulation of TID event observed via Sondrestrom ISR driven by a medium-scale GW consistent with ion parallel drift data (a *data-inspired* case study)

· **Strong variations in background plasma density and temperature result from breaking and dissipation of nonlinear GWs**

- Degree of nonlinearity/breaking strongly affects ionospheric response; strongest waves do not have as much of an effect on ionospheric plasma density while "moderate" nonlinearity has a marked effect…

Burleigh et al (2018, in review)
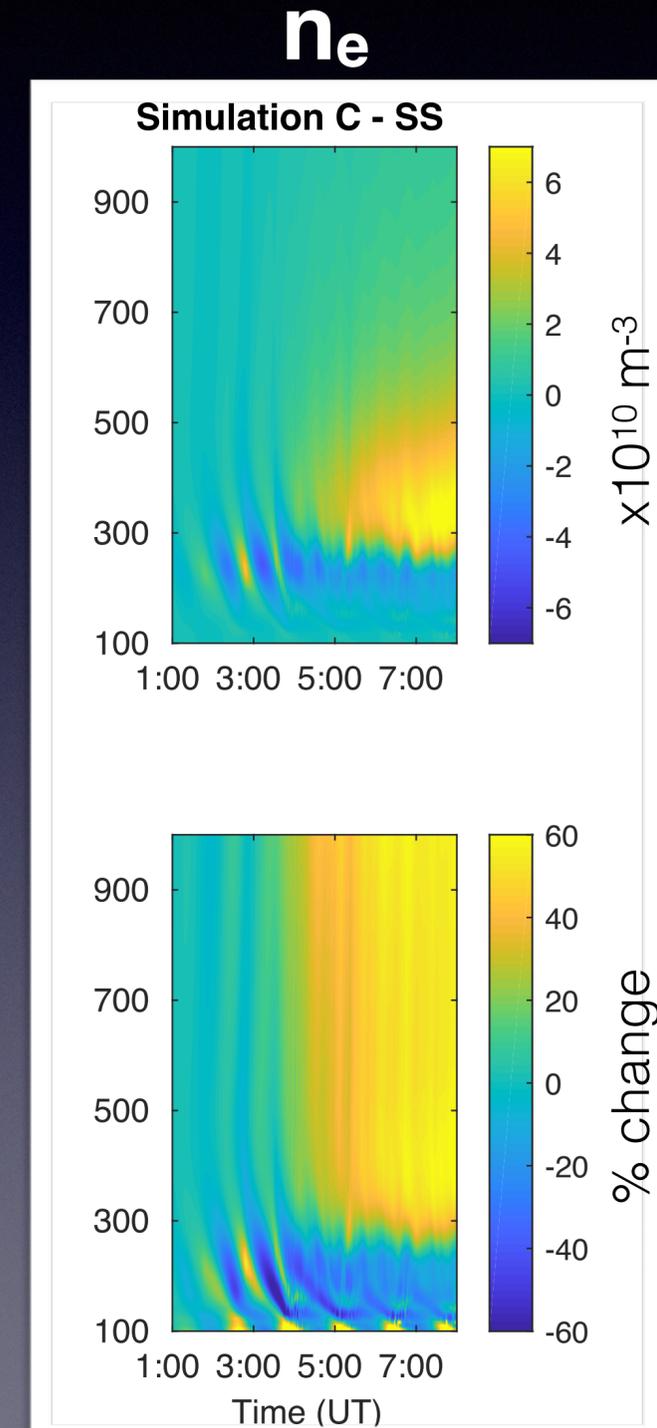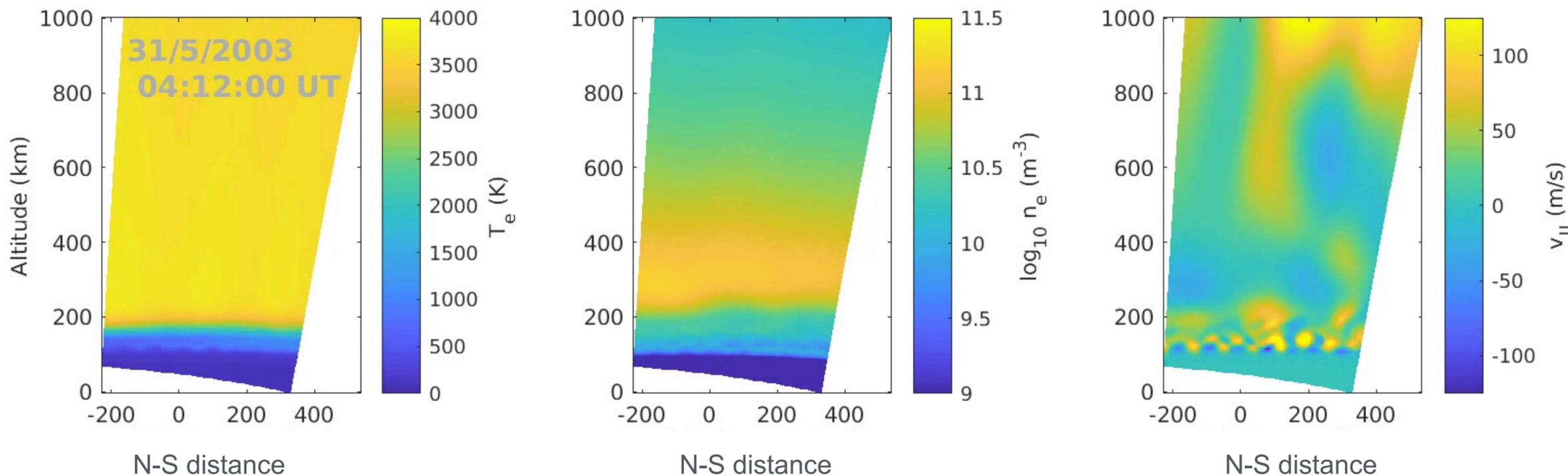
Small-to-large scale coupling: micro-turbulence effects

Wiltberger et al (2017)

- Farley-Buneman instability (FBI) and electron heating

  - Reduces plasma recombination rates

  - Increases conductance, altering ionospheric electrodynamics (which are constrained by current continuity)

- **The effect is large enough to change the global distribution of conductance and the m'spheric response during storms**
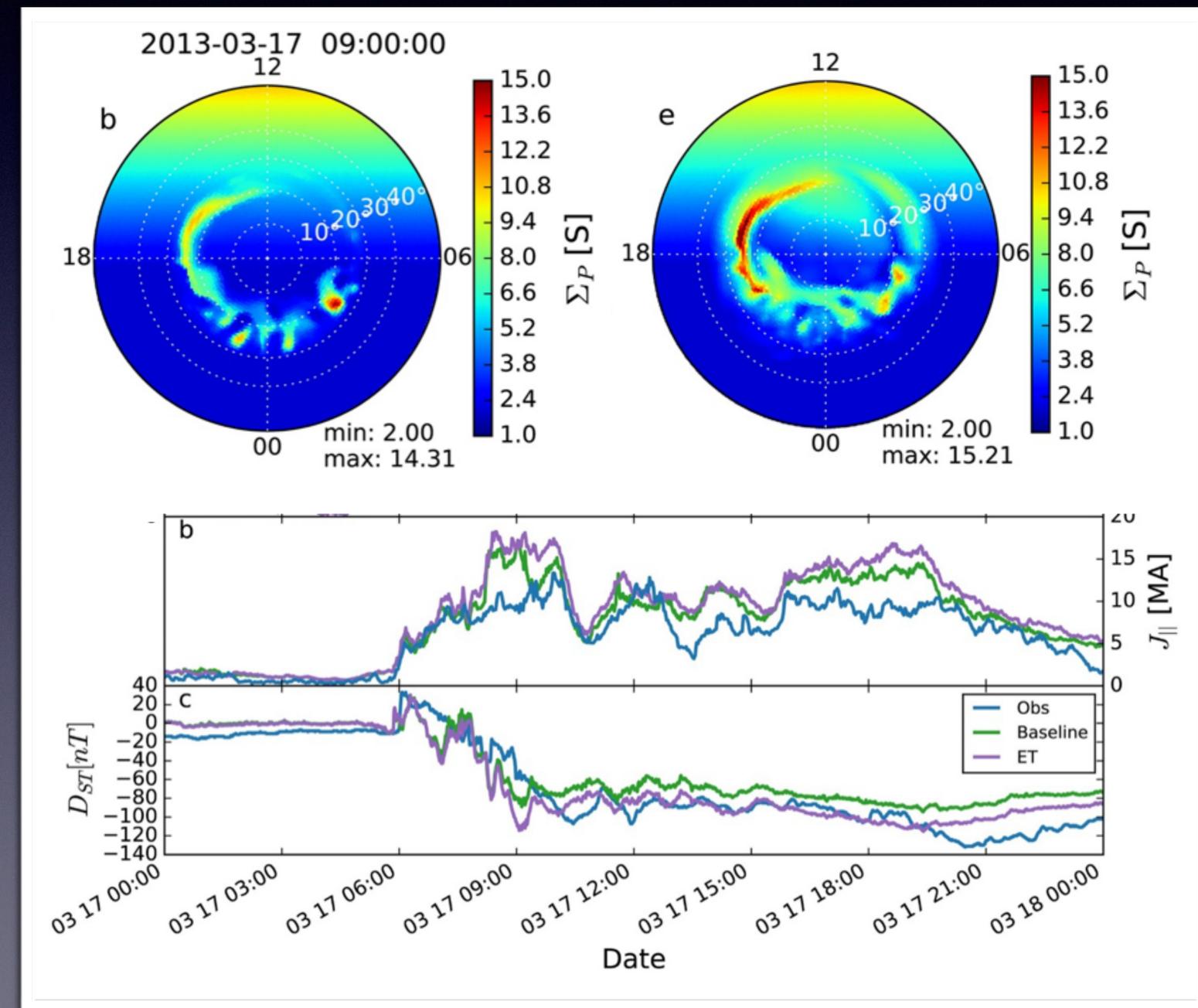
Oppenheim and Dimant, (2013)
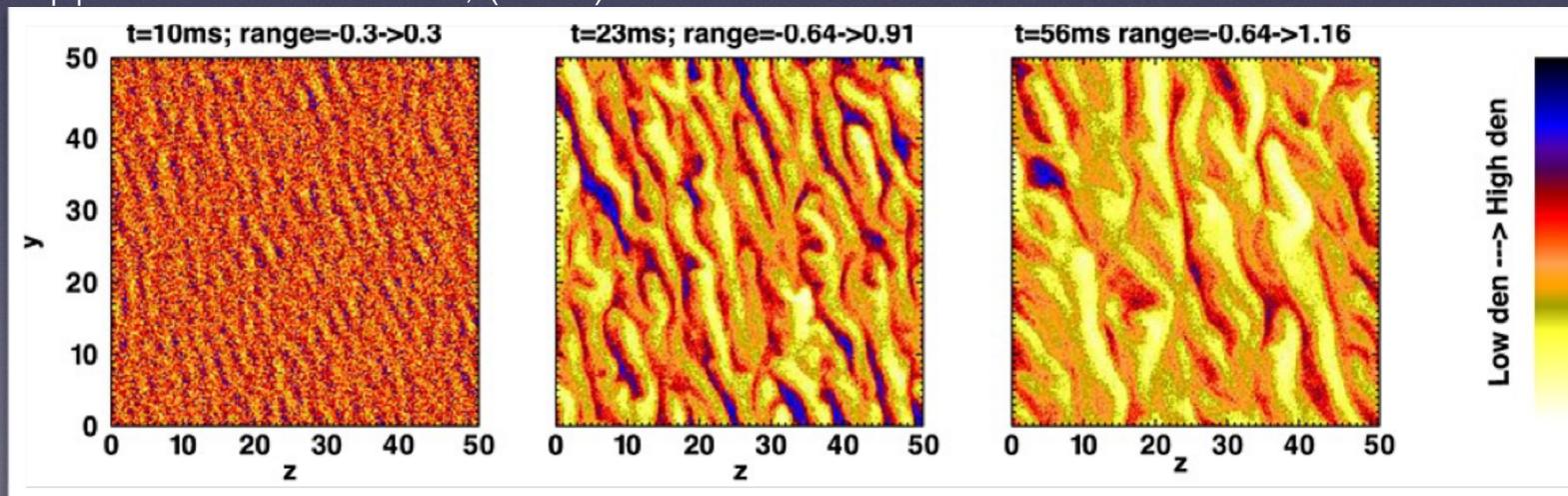
Small-to-large scale coupling: shock-acoustic wave modification of background atmosphere-ionosphere

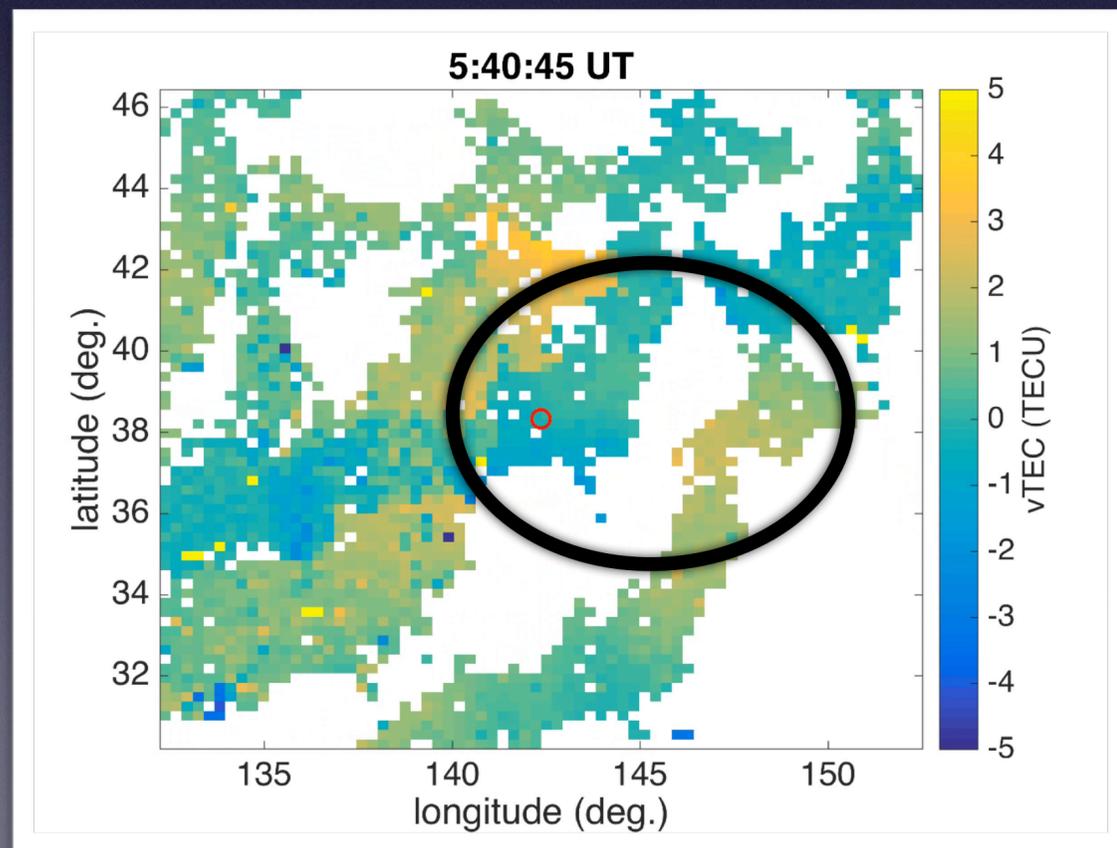- Post-seismic ionospheric perturbations to TEC observed following M 9.1 Tohoku earthquake off the coast of Japan (below).

- *Zettergren et al (2017)* modeled strong shock-acoustic waves which were responsible for semi-permanent thermosphere-ionosopheric effects lasting more than an hour after the EQ (right).

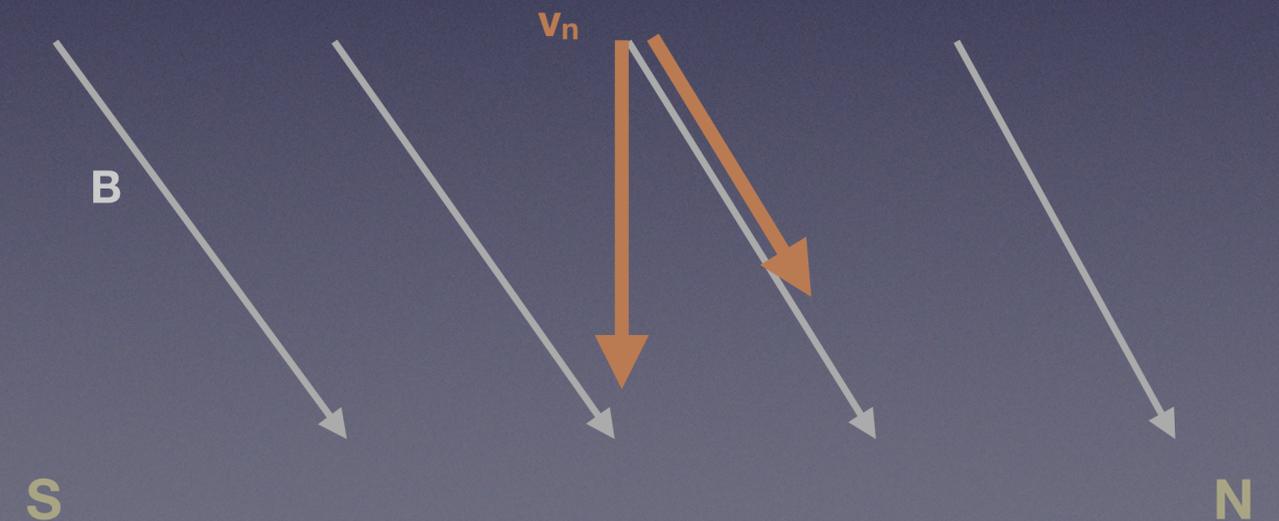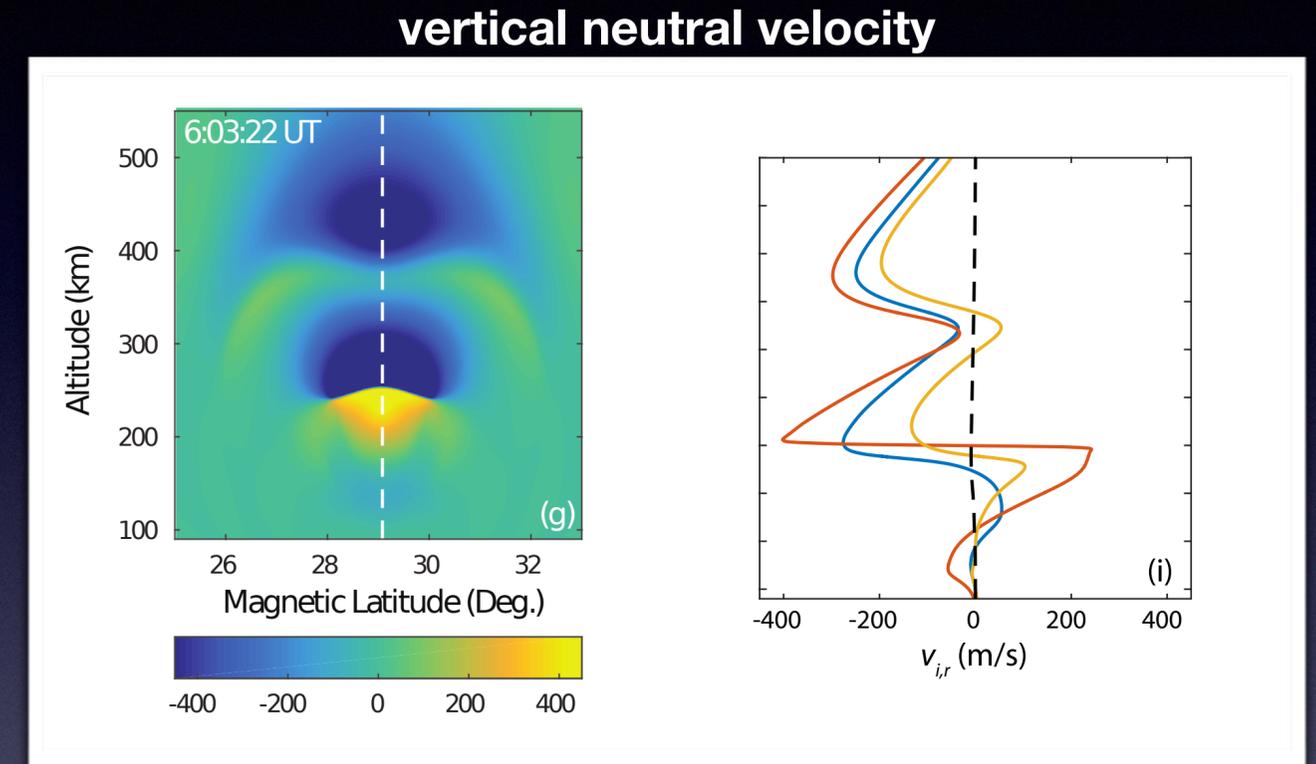**vertical neutral velocity**

Thermosphere response dominated by downward neutral velocities, forcing northward and downward ionospheric plasma flow

Downward transport results in more plasma recombination

Northward transport causes removal of plasma from depletion region and pileup of density to north

see Zettergren et al (waves session today)

Scale-dependent inputs: Joule heating

- *Codrescu et al (1995)* pointed out importance of small-scale electric field variability

- Modeled by *Deng et al (2009)* via inclusion of a statistical model of electric field variations.

- Thermospheric temperatures vary by ~100 K; densities varied by ~40%

- Another layer of complexity to the joule heating is the fact that undermesolving the background field can also have large effects on thermospheric behavior, e.g. Yigit et al, (2011).

(a) Polar average T_n

(b) Distribution of temperature difference at 400 km

(c) Percentage difference of polar average density

(d) Distribution of density percentage difference at 400 km
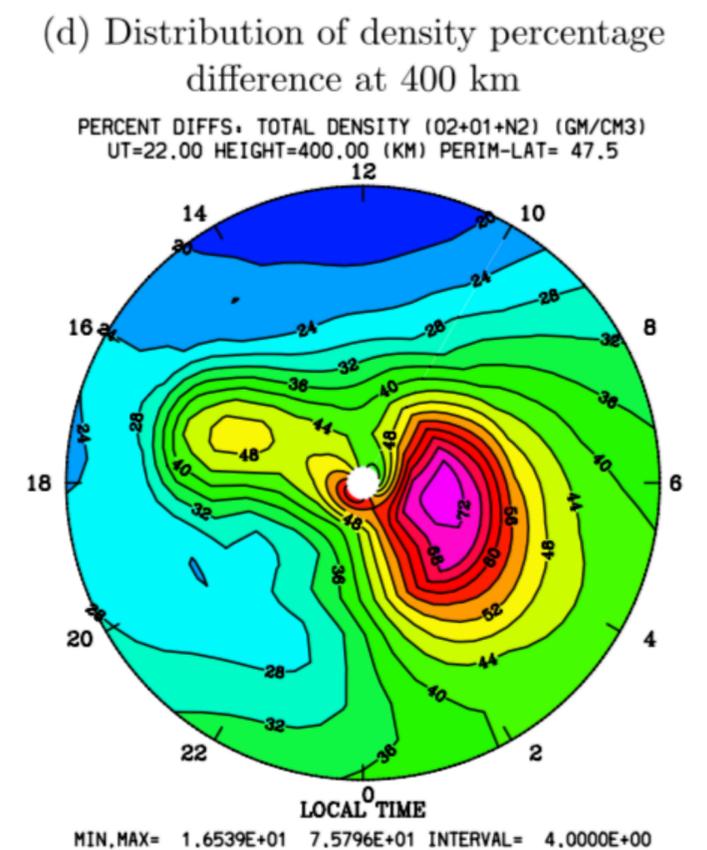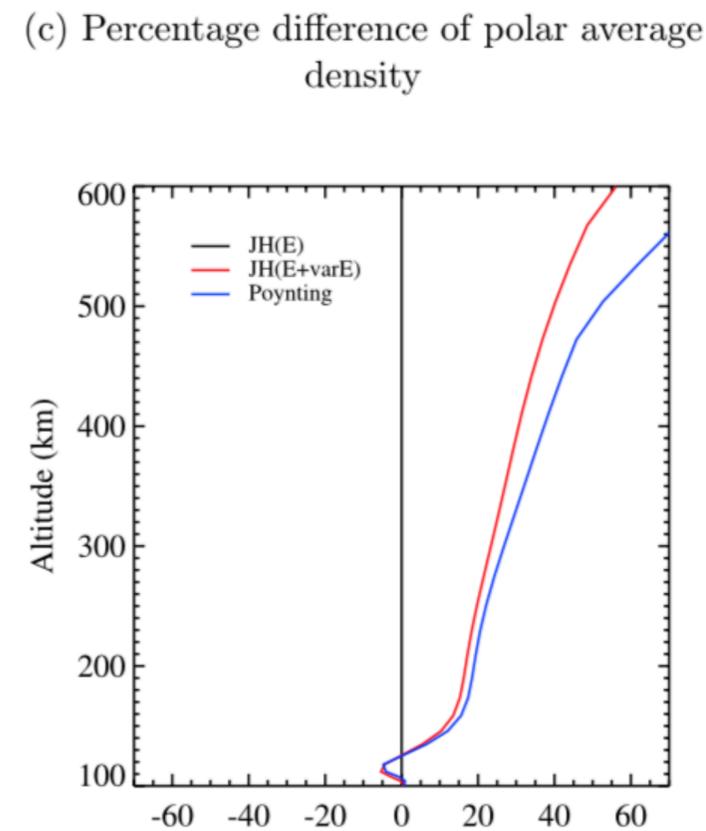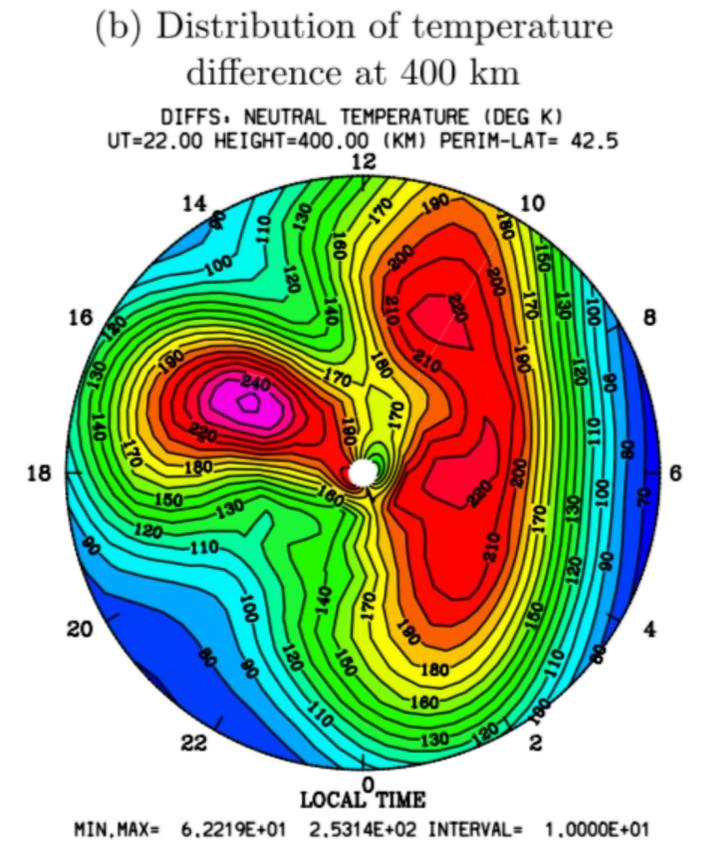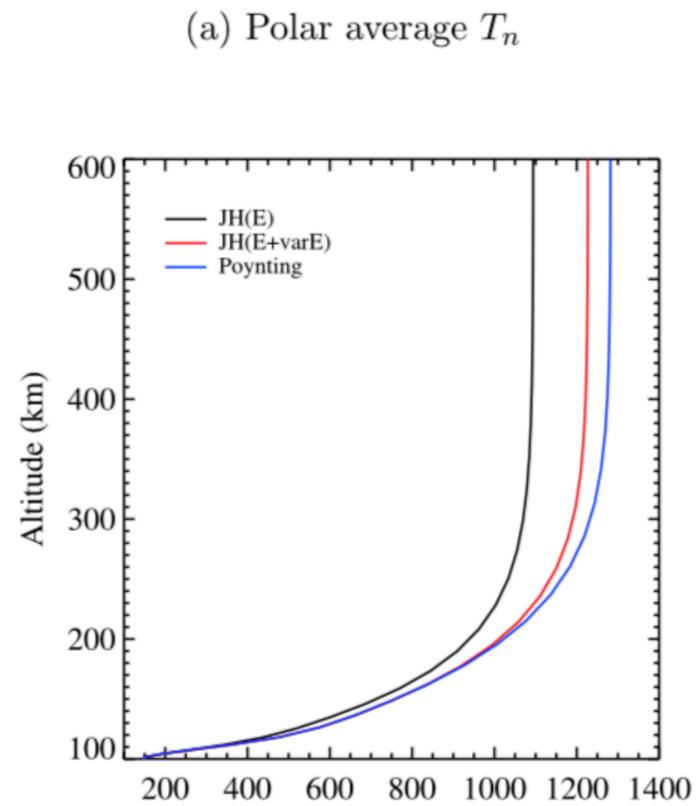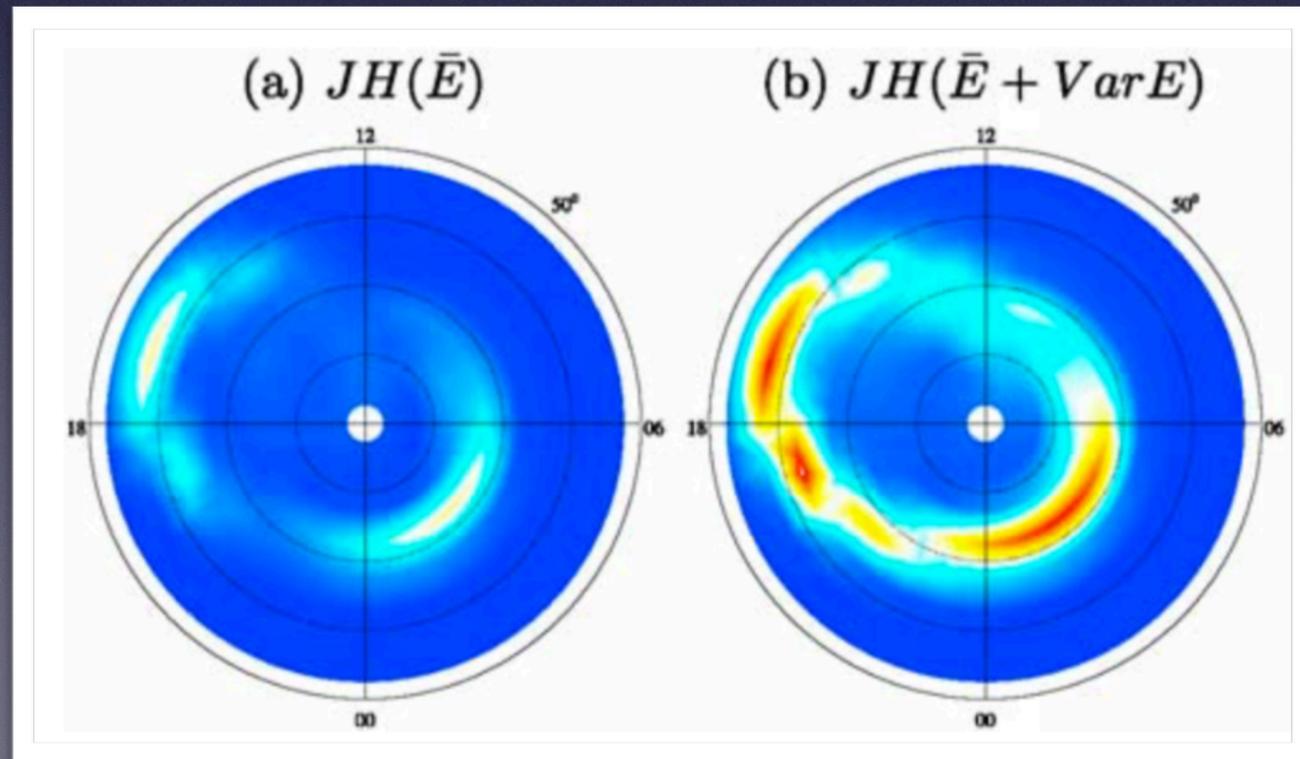
*Scale-dependent inputs
2: auroral currents

Snapshot during flight

- *Lynch et al (2015)* observed and performed data-driven modeling case studies of sounding rocket (MICA) passage through an auroral arc.

- Different smoothing for electric field model inputs led to VERY different model results for field-aligned current parameters of interest.

- **Scale-dependent inputs not only matter for the global scale models, but they also have a huge effect on local-scale modeling studies!**

Lynch et al (2015, GC session today)
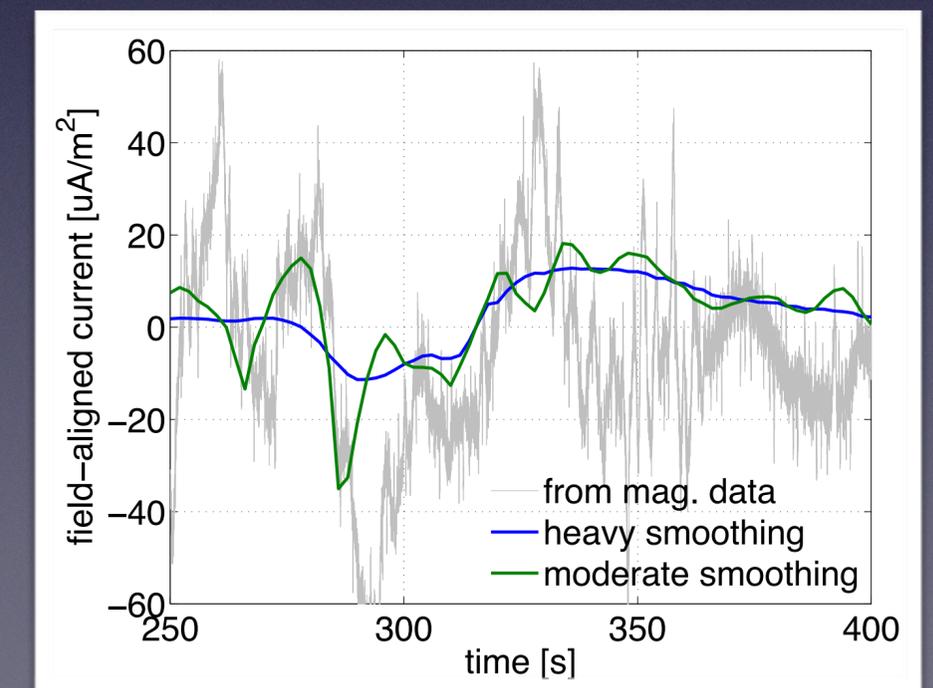
Parallel current along rocket trajectory

Multi-scale model coupling

Varney et al (2015)

- Two-way multi scale coupling (small <—> large) is an ultimate goal but very challenging in many cases

  - *However, it is clear that basically all coupling processes involve some sort of feedback between components.*

- Ionospheric outflow into the magnetosphere is an example of a physical processes needing a self-consistent treatment.

  - Energy input from m'sphere causes outflow, which then mass-loads the magnetosphere and alters reconnection.

- *Varney et al, (2016a,b)* have integrated a model of non thermal ion outflows with the multifluid LFM global magnetospheric model

- Ion energization controlled partly by parameterized wave heating

- **Polar cap ionospheric and global magnetospheric state (here the presence of sawtooth oscillations in open flux and CPCP) affected by relatively small-scale phenomena**

IPWM

Number Flux

Parallel Velocity

IPWM+MFLFM

Varney et al (2016a,b)
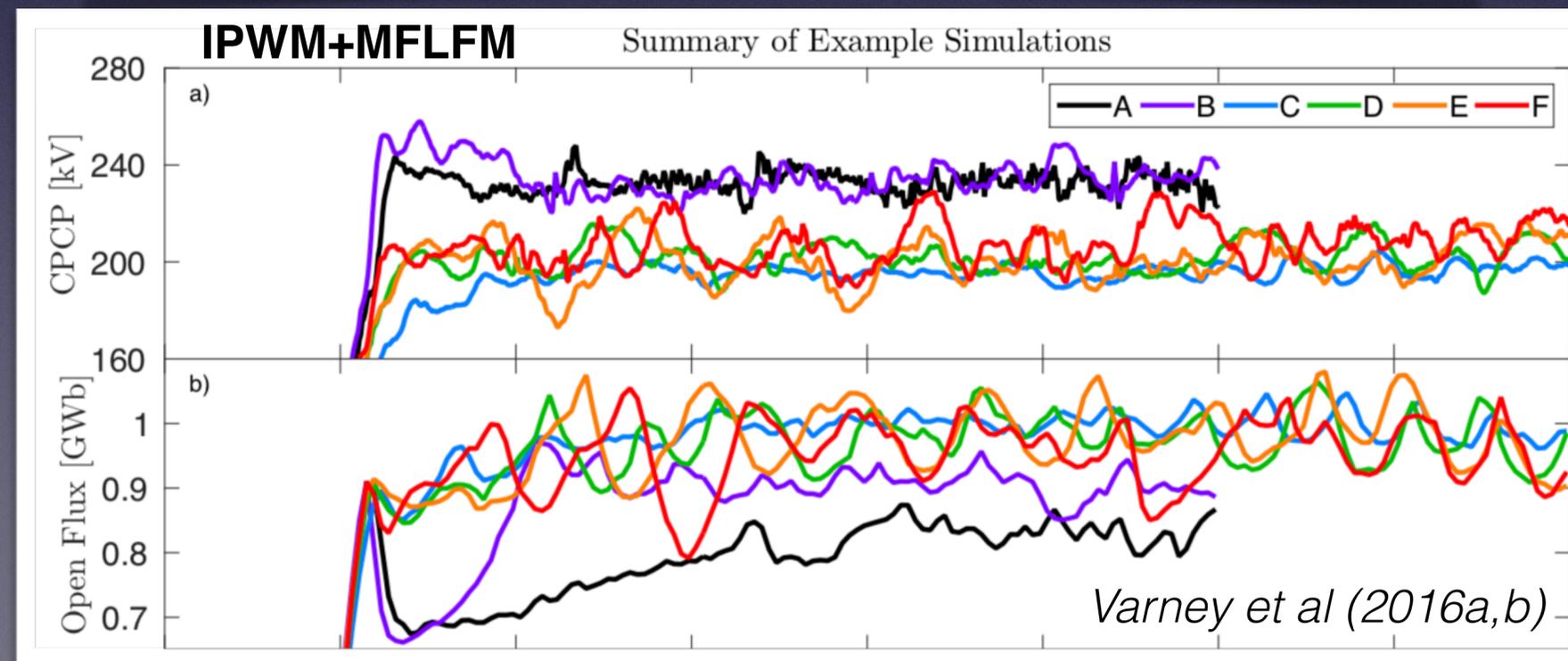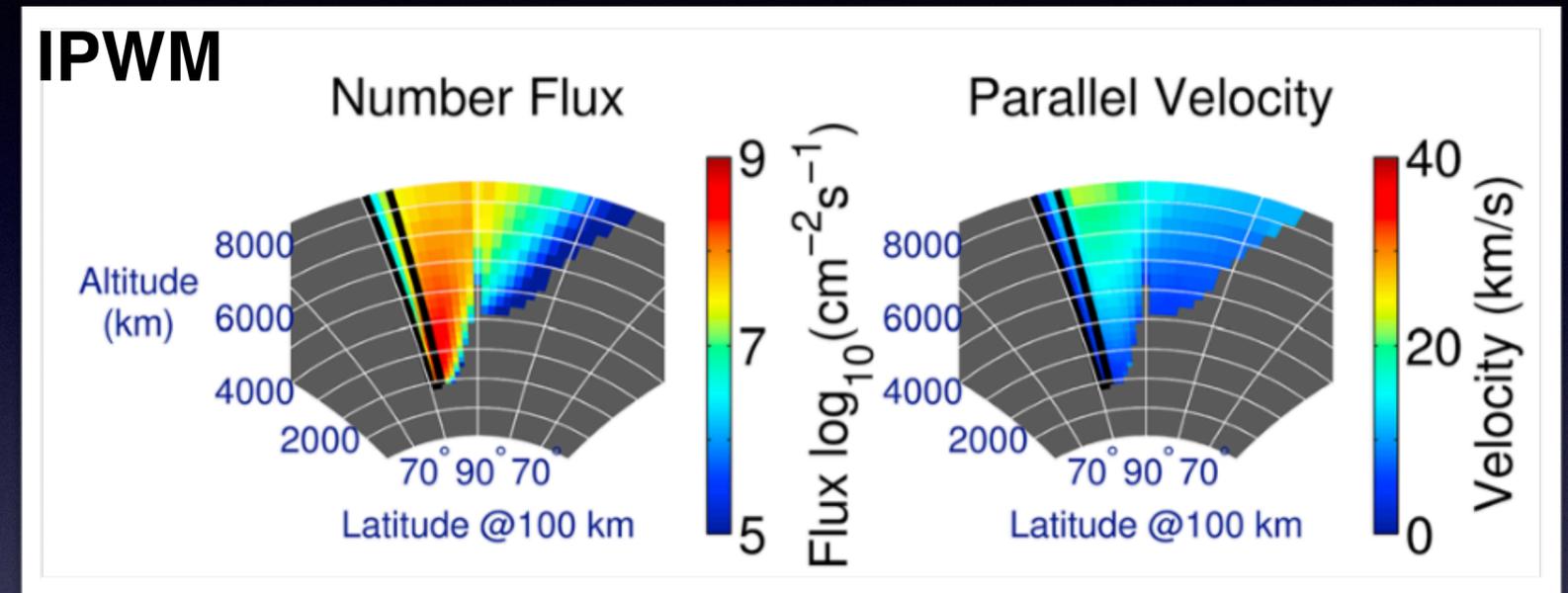
Resolved GW simulations

- *Liu et al (2014)* presented high-resolution (0.25 degrees x 0.1 scale heights) WACCM modeling of gravity waves and their effects in the lower and middle atmosphere.

- Reasonable agreement with TIMED/SABER data analysis demonstrate effectiveness of high-resolution modeling methods

- **Small scale waves feed into tidal amplitudes and other larger-scale features and generally improve agreement with observations**

- See also *Yigit et al (2008,2009)* who have developed a parameterization of effects of GW dissipation in GCMs

Liu et al (2014)
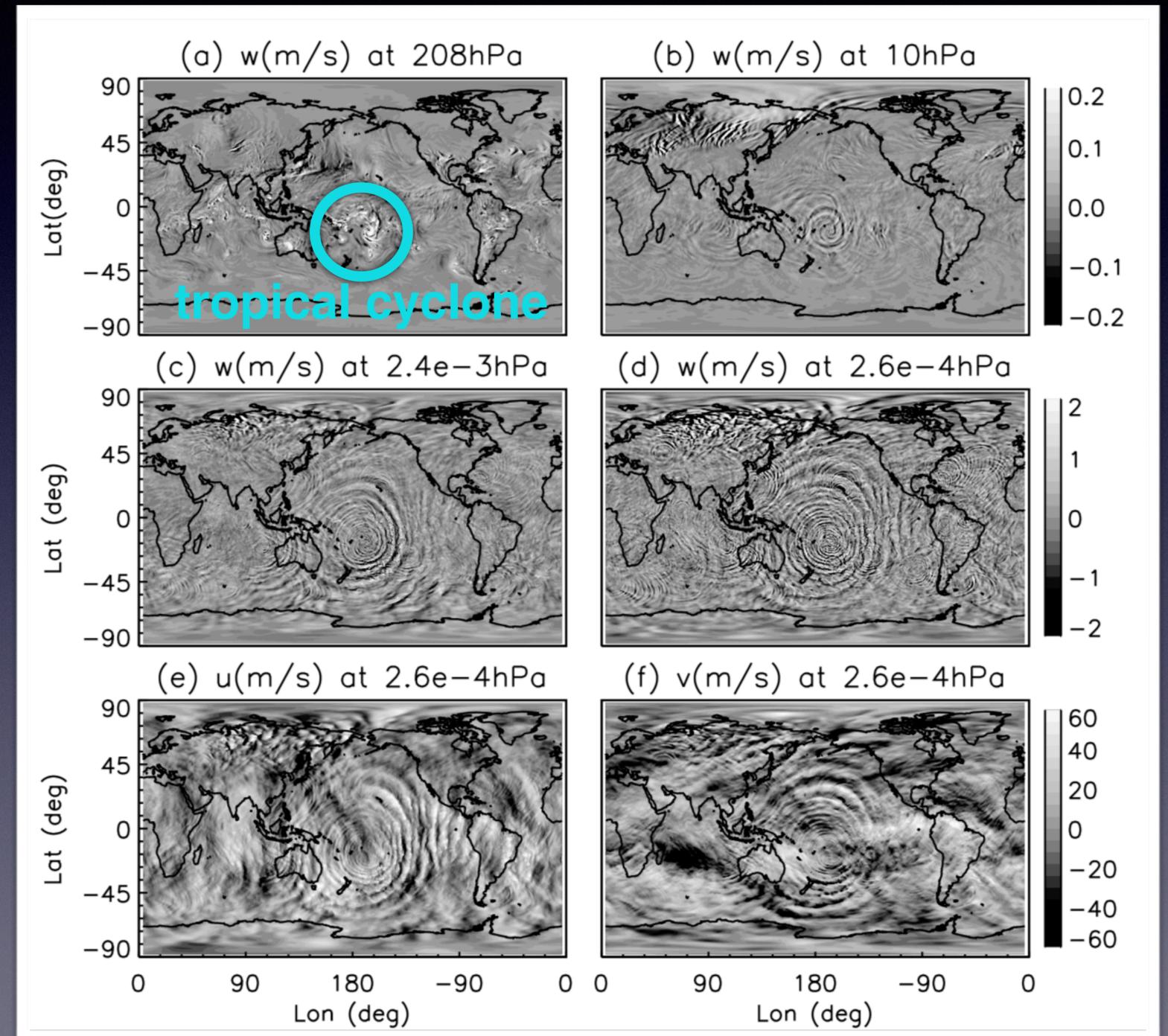
Multi-scale modeling **challenges** (opportunities)

Serious technical challenges exist for modelers:

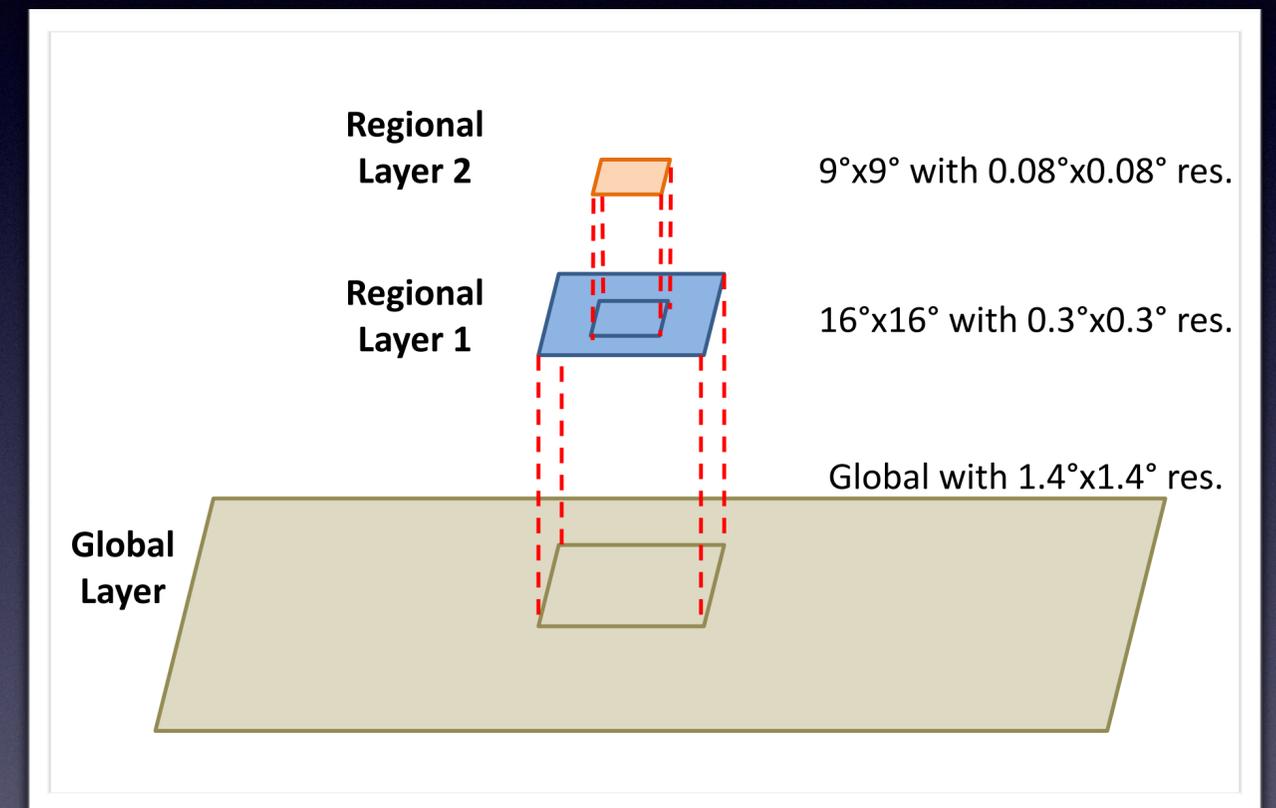- **Immense amounts of (model) data (100s of GB to TB) need to be saved and/or passed between coupled models** making memory and storage management onerous and adversely impacting model performance and complicating reproducibility

- **Computational requirements can be rather extreme** for efforts pushing the envelope on resolution

    - E.g. our small-scale simulations require in excess of 250M grid points and we still struggle to cover more than 10 degrees of lat/lon.

    - Global model resolution better than 0.25 degrees is fairly uncommon.

    - Single simulations at high res can take days to complete on hundreds of cores - too expensive to do true parameter space studies.

    - Explicit (CFL-limited) methods get disproportionately more expensive at small scales since time step is grid resolution dependent, most good advection schemes are explicit

- **Overcoming software limitations - e.g. flexibility, scalability, missing physics, coupling - a constant issue**

    - There are MANY methods available for dealing with the problems we face; however, they take time to implement and may require serious code restructuring along with some trial and error.

    - Much effort is required to do a good job designing, optimizing, parallelizing, and distributing codes. Upkeep is necessary.

Most of these issues are exacerbated by introduction of multi-scale/multi-physics elements into the models!

Approaches to multi-scale modeling

- **Basic parameterizations** (e.g. Joule heating) have been quite effective at capture some global consequences of small-scale physics;

  - Background-sensitive parameterizations in global models may help assess global scale consequences of small-scale dynamics.

  - *Good data coverage needed; in the case of ion outflow example (Varney et al, 2016a,b) it is clear that we do not have what is needed…*

  - *Small-scale modeling is critical to informing development of parameterizations and assessing their effectiveness.*

- **Coupling models of different scale** can provide some benefits and an avenue for immediate advancement

  - Variable resolution mesh schemes can be useful.

  - Physics needed in models may depend on resolution; numerical needs depend on physics…

  - **Resolved simulations** are a path forward but until we can model the full spectrum of waves/precipitation/electric fields this approach brings up issues: *to what degree does partially resolving processes improve fidelity of results?*

- Much software development is required to implement basically any approach to multi-scale modeling — **Open Sourcing and code-sharing can increase number of developers refining and adding functionality to a project.**

Regional Layer 2 — 9°x9° with 0.08°x0.08° res.

Regional Layer 1 — 16°x16° with 0.3°x0.3° res.

Global Layer — Global with 1.4°x1.4° res.

Deng et al, (GC session Wednesday)

Concluding remarks

- *Discussion here is meant as an overview of past work that can be categorized as multiscale and is necessarily somewhat superficial in terms of physical detail —> translation - please correct me if I've cited or described your work improperly.*

· **A large variety of physical systems and compelling problems exist that involve multi scale coupling —** ranging from the global m'spheric behavior to middle atmospheric turbulence.

· **Attempts to capture multi-scale processes in models, while incomplete, have yielded important new insights into MITM system (Magnetosphere-Ionosphere-Thermosphere-Mesosphere) behavior.**

· **Some approaches for future advance seem promising but *computing resources* and *model development/coupling* require significant resources and attention.**

· **For many processes (e.g. outflow) we do not have data coverage necessary to sufficiently constrain our models and parameterizations.**

· **Please consider attending our GC workshop today through Wednesday!**

· **Please also consider submitting to our related AGU session — *SA004. Cross-scale Coupling and Energy Transfer in the Magnetosphere-Ionosphere-Thermosphere System: Toshi Nishimura, Olga Verkhoglyadova, Yue Deng, Cheryl Huang***

Auxiliary Slides

Large-to-small scale coupling: atmospheric wave-wave coupling

- Something from C. Heale about wave-wave coupling across scales

Small-to-large scale coupling: GW effects in global models

- GWs present a particularly difficult problem for atmospheric models since they are known to cover a wide range of scales (10s of km to thousands of km) and impact background atmospheric state

- *Yigit et al (2009)* parameterize effects of dissipation of upward propagation GWs in the CMAT2 GCM.

- Include effects of:

  - Viscosity

  - Wave breaking

  - Newtonian cooling

  - Ionospheric drag

- Parameterization driven by a source spectrum of GWs above the tropopause

- **Results demonstrate that the parameterization are partially successful in bringing GCM simulated winds into agree with empirical models**
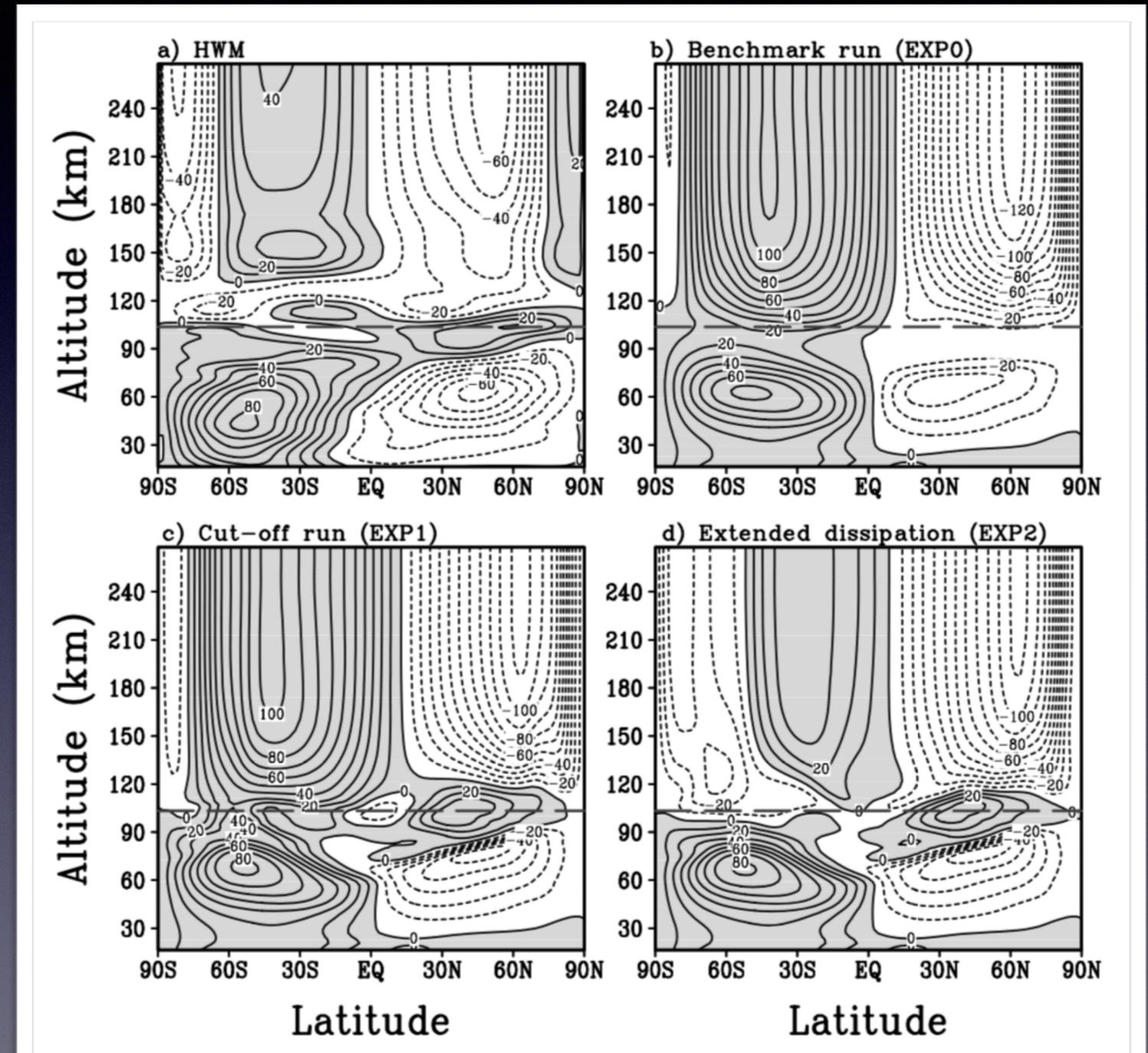
Scale-dependent inputs: Joule heating II

- *Yigit et al (2011)* model Joule heating at different resolutions and demonstrate ~40% effects on the amount of energy delivered to atmosphere at high vs. low resolutions

  - low: 5 x 5 deg. (lat. x lon.)

  - high: 2.5 x 0.3125 deg.

- Results partially a consequence of resolving input electric field peaks better

- **Better-resolved average field input results in more accurate representations of Joule heating**

Joule Heating, 22 Dec 0000 UT, 370km
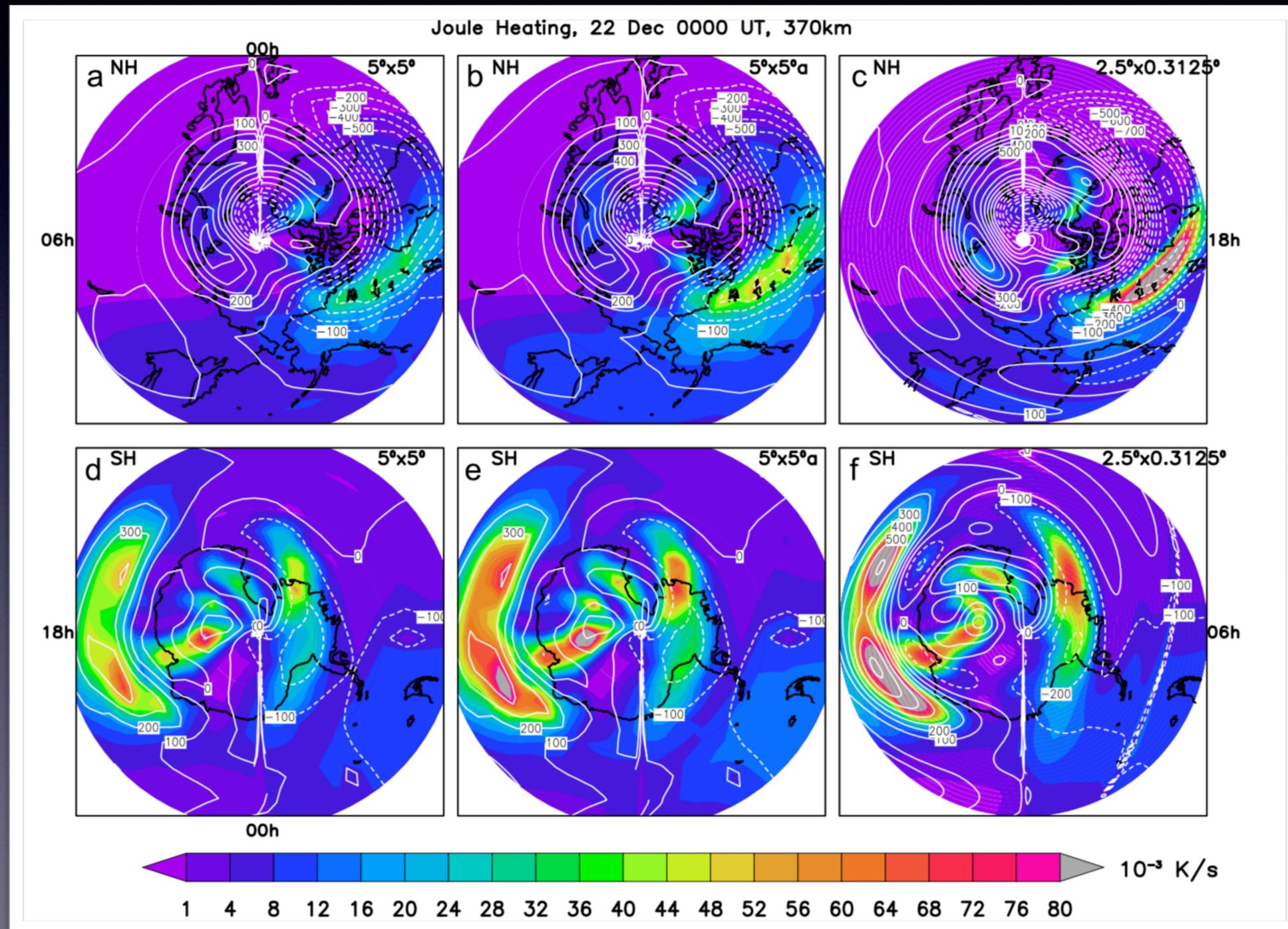
Extra plots
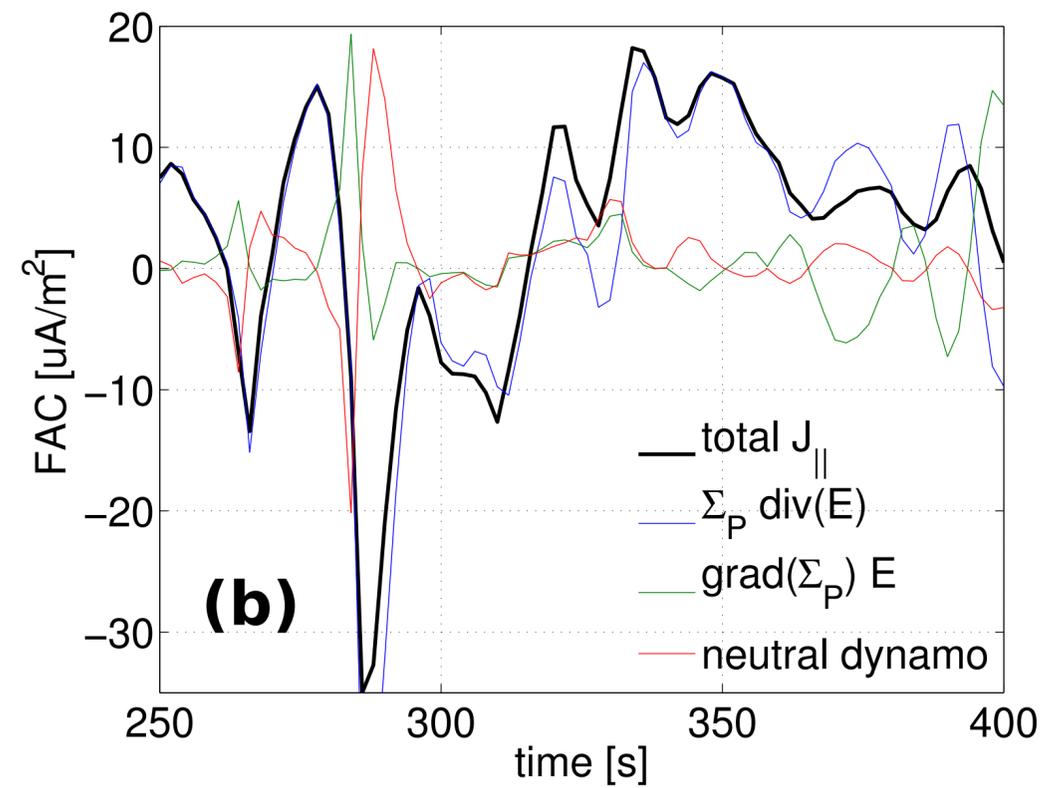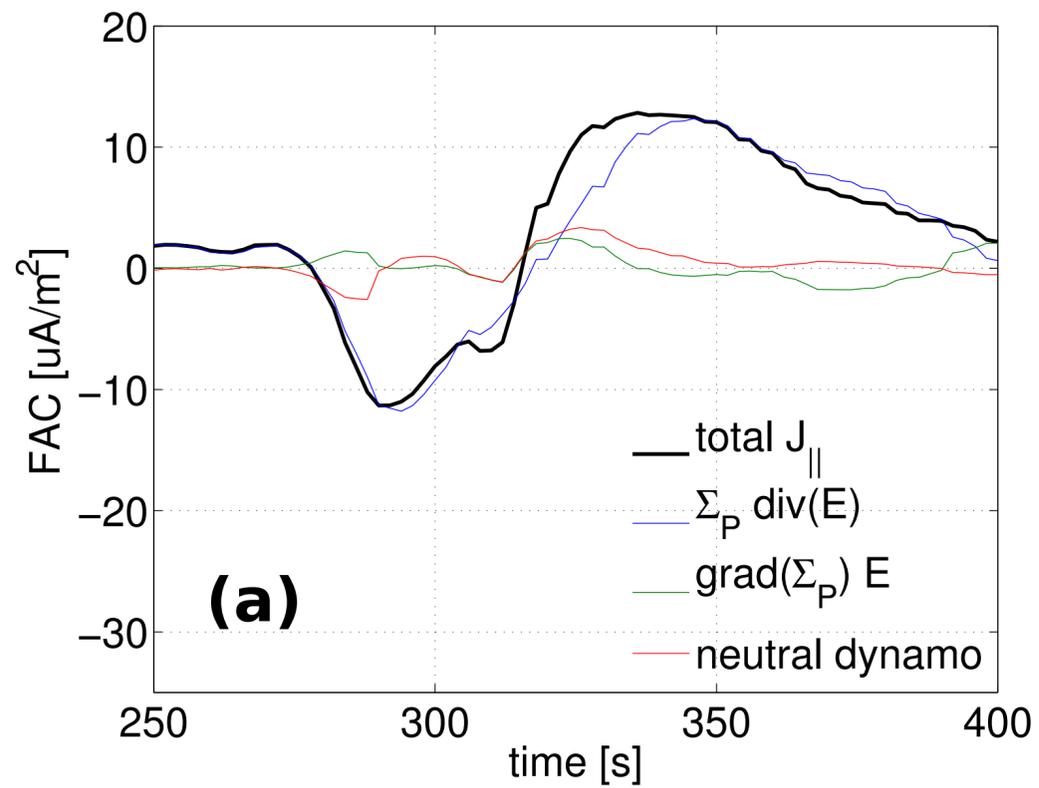
Panel Slides

Multiscale approaches to boosting model resolution

- Non-uniform mesh capabilities useful when it is known a priori where more resolution is needed.

  - Relatively easy to implement; yet limited since mesh step size in a particular direction can only change with with that coordinate. Also if have have a particularly stiff problem then poor resolution at boundaries may hurt.

- Nested grids (static with time)

  - More complicated to implement since it will alter message passing schemes; more flexible since step size can change in both directions

- AMR methods may be useful when we do not know a priori where high resolution is needed

  - Significant in terms of development investment, and incurs some processing overhead. Need some sort of local time stepping to really take advantage but that is dicey.

- **None of these address issue of new physics, e.g. ion inertia, becoming important at small scales so we still need distinct models for large and small scales.**