# Space Weather Operations and Research Infrastructure: Workshop Part I

# Strategic Knowledge and Observation Gaps: Geospace

## Low altitude measurements gaps—Fields


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# Impacts most related to LEO Fields: E, B (δB)

| | Relevant quantities |
|---|---|
| **• Direct effects** | |
| - Thermospheric heating | **E** & δ**B**$_{Space}$,(**V**$_n$) |
| - GICs | d**B**$_{Ground}$/dt (ground) |
| - Navigation and guidance (B-field models) | **B** |
| **• Derived products:** | |
| - Convection (**E**) and Birkeland current distributions (δ**B**$_S$) | **E** or δ**B**$_{Space}$ |
| - Storm-time expansion of polar cap | **E** or δ**B**$_{Space}$ |
| - Polar cap potential | **E** |
| - Electromagnetic energy flux: heating vs neutral wind acceleration (**V**$_n$) | **E** & δ**B**$_{Space}$,(**V**$_n$) |
| - Electrojet locations/intensities | **E** & δ**B**$_{Space}$, δ**B**$_{Ground}$ |
| **• Models** | |
| - Real-time indices: AE, Dst for legacy specification models | δ**B**$_{Space}$ or δ**B**$_{Ground}$ |
| - Validation/check against physics based forecast models | **E** or δ**B**$_{Space}$ or δ**B**$_{Ground}$ |
| - Inputs to IT circulation models | **E** & δ**B**$_{Space}$ |
| **• Situational awareness and proxy relationships** | |
| - Timing & sudden transitions: shock, onset, substorm precursors and onset | **E** or δ**B**$_{Space}$ or δ**B**$_{Ground}$ |
| - Scintillation: regions of intense **E**-field | **E** |
| - Charging: regions of intense $J_{\|\|}$ | δ**B**$_{Space}$ |

# Techniques and capabilities

**Near term gap** (Drift meter row)

- E-field:

| | | | |
|---|---|---|---|
| - Drift meter: | satellite: DMSP, SWARM | 3-D ion flow | Requires enough $O^+/H^+$ at altitude; Few satellites, ~90 min real-time delays |
| - ISR: | AMISR (EISCAT) Aricebo, Jicamarca, Millstone Hill | $n_e$, $T_{e,i,n}$, $\mathbf{V}_i$, $\mathbf{V}_n$: (h) | Limited but very important coverage |
| - HF: | SuperDARN | $\mathbf{V}_{irreg}$ (reflection) 2-min res. | Large field of regard but requires irregularities; precipitation can absorb radar beam energy; real-time delay of a few minutes. |

**Near term gap** ('science' row)

- B-field:

| | | | |
|---|---|---|---|
| - Space | 'science': e.g. SWARM (DMSP) | Birkeland $\delta\mathbf{B}_S$ | High quality data (1 nT res.), a few orbits ~90 min real-time delays (not incl. processing) |
| | constellations e.g. Iridium | Birkeland $\delta\mathbf{B}_S$ | Coarser resolution (30 nT res.), global/continuous, few min. real-time delay (feasible w. processing). |
| - Ground | many locations | equiv. current $\delta\mathbf{B}_G$ | Fixed locations, accessible land masses, logistics for real-time |

# Principles: Ionospheric Electrodynamics

**Convection** $\mathbf{E}_c = -\mathbf{V}_c \times \mathbf{B} \qquad \mathbf{E}_c = -\nabla \varphi$ E ($\mathbf{V}_i$)

**Horizontal currents** $\mathbf{J}_{\perp,\mathrm{i}} = \underline{\underline{\boldsymbol{\Sigma}}} \cdot \mathbf{E}_\mathrm{C} = \Sigma_\mathrm{P} \mathbf{E}_\mathrm{C} + \Sigma_\mathrm{H} \mathbf{b} \times \mathbf{E}_\mathrm{C}$

$\psi$ = equivalent current potential

$\delta\mathbf{B}_G$, $n_e(h)$

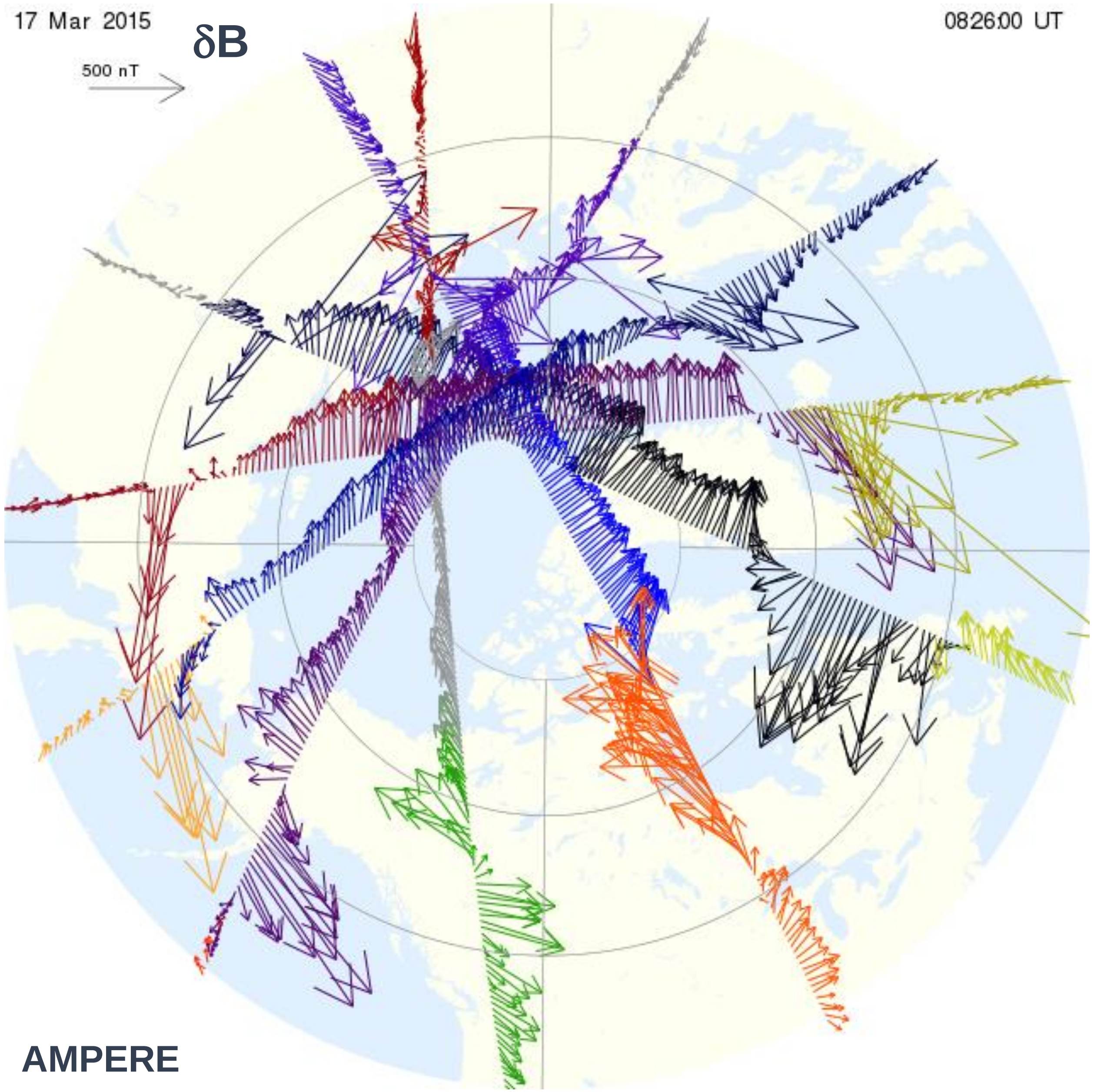
**Birkeland currents** $J_{\|} = \nabla \cdot \mathbf{J}_{\perp,\mathrm{i}} = \nabla \cdot (\underline{\underline{\boldsymbol{\Sigma}}} \cdot \mathbf{E}_\mathrm{C})$ $\delta\mathbf{B}_S$, $n_e(h)$

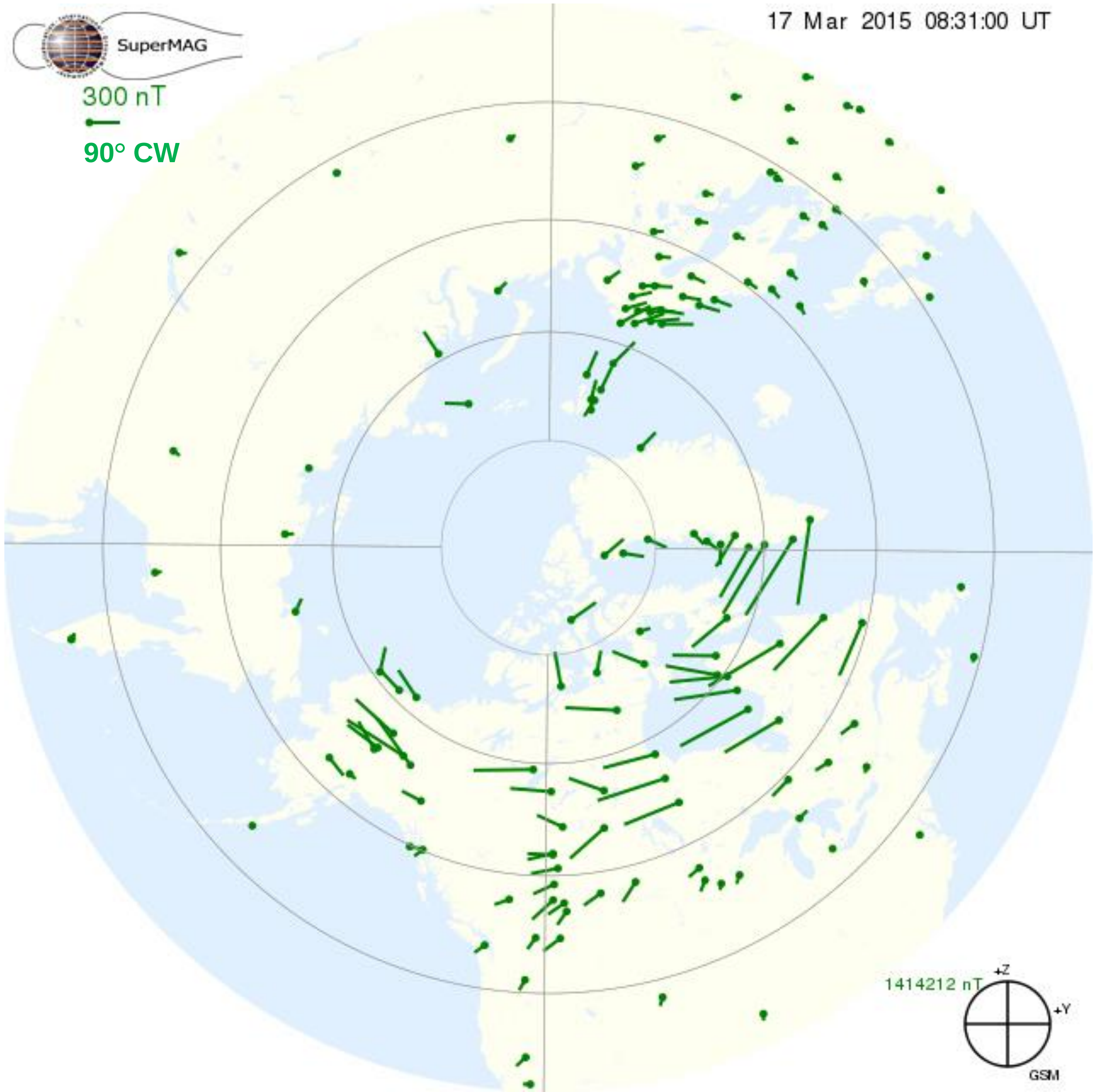
**Electrodynamics equations: 2 eqs, 5 unknowns**

$$\nabla^2 \psi = \Sigma_\mathrm{H} \nabla^2 \varphi + \nabla \Sigma_\mathrm{H} \cdot \nabla \varphi + \hat{\mathbf{r}} \cdot (\nabla \Sigma_\mathrm{P} \times \nabla \varphi)$$

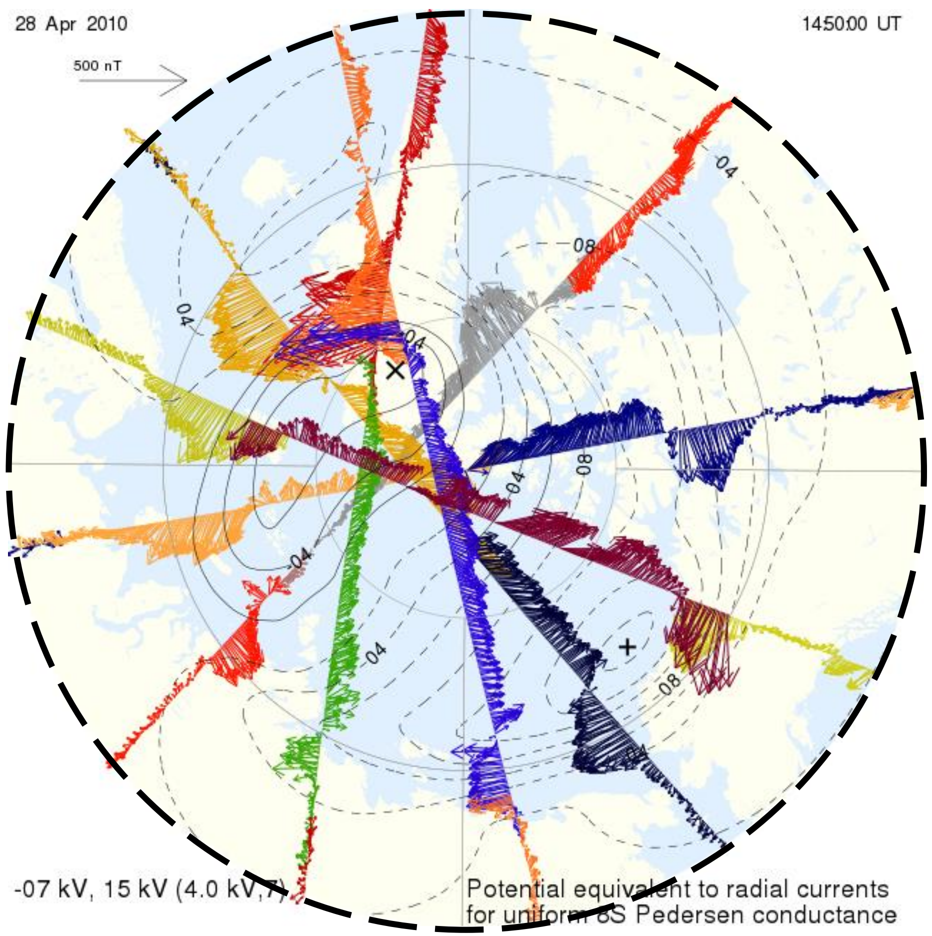
$$J_{\|} = -\Sigma_\mathrm{P} \nabla^2 \varphi - \nabla \Sigma_\mathrm{P} \cdot \nabla \varphi + \hat{\mathbf{r}} \cdot (\nabla \Sigma_\mathrm{H} \times \nabla \varphi)$$

# Different coverage/cadence – but consistent

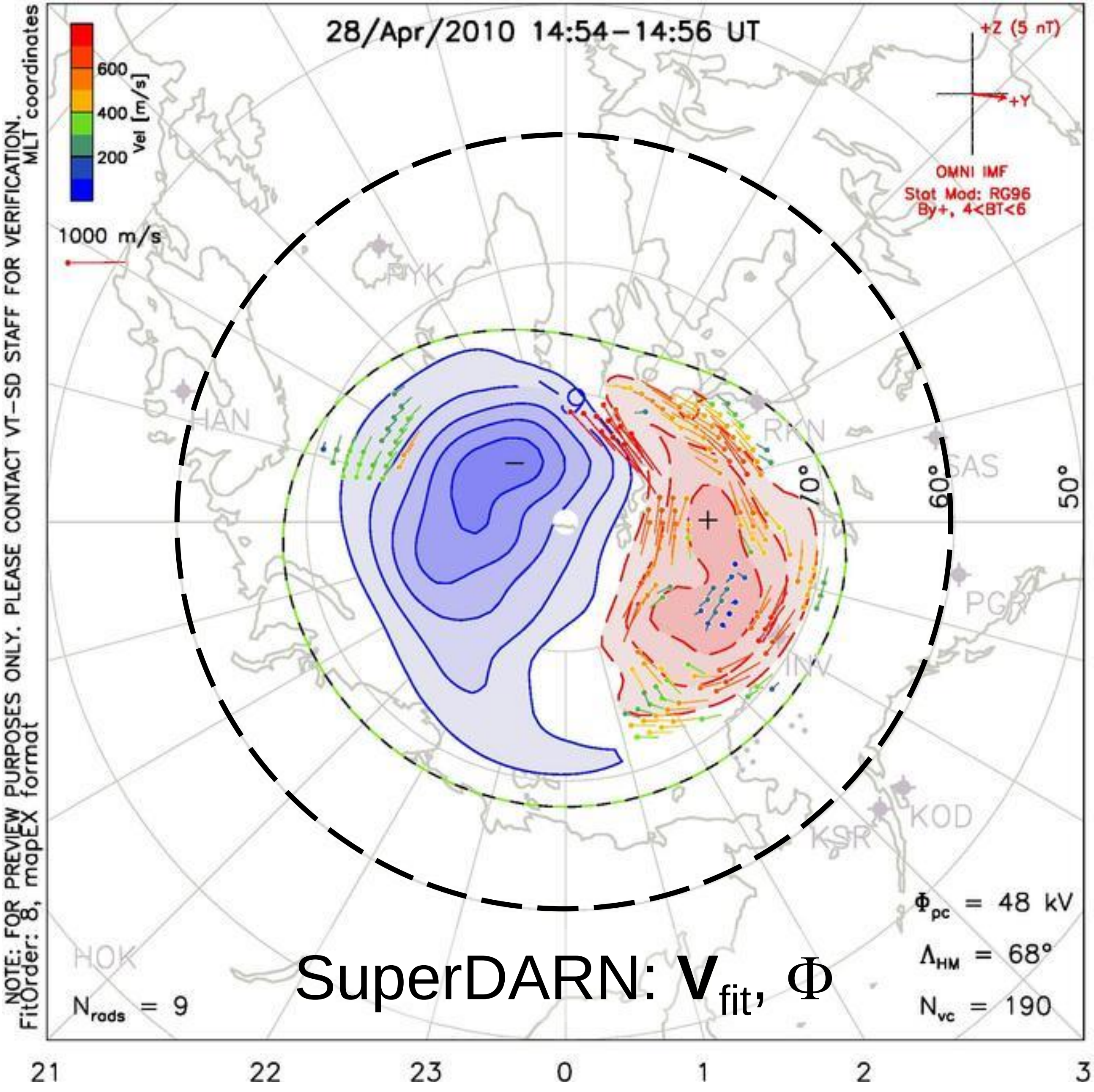


# Different coverage/cadence – but consistent



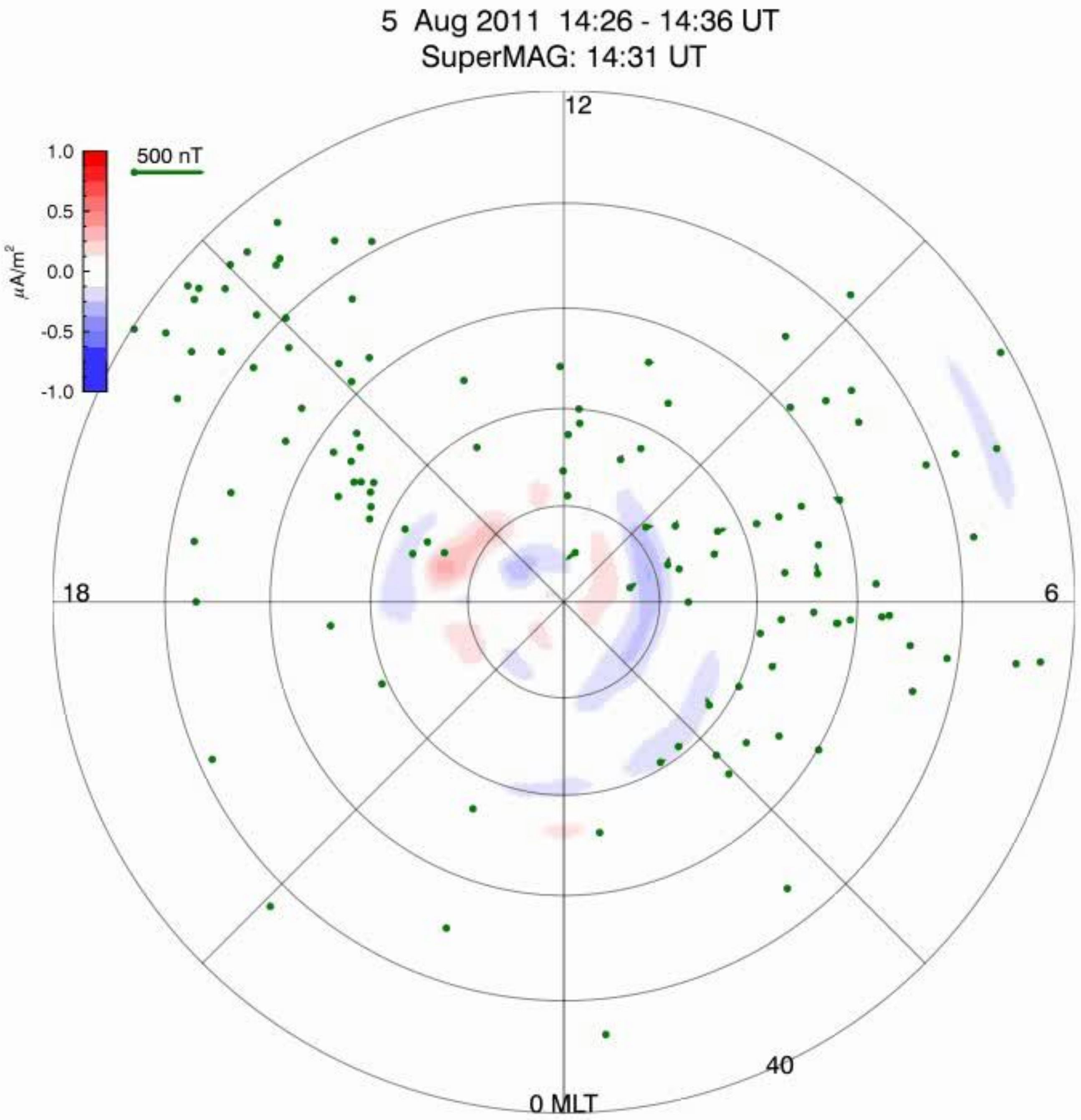

AMPERE: $\delta\mathbf{B}$, $\Phi$




SuperDARN: $\mathbf{V}_{fit}$, $\Phi$

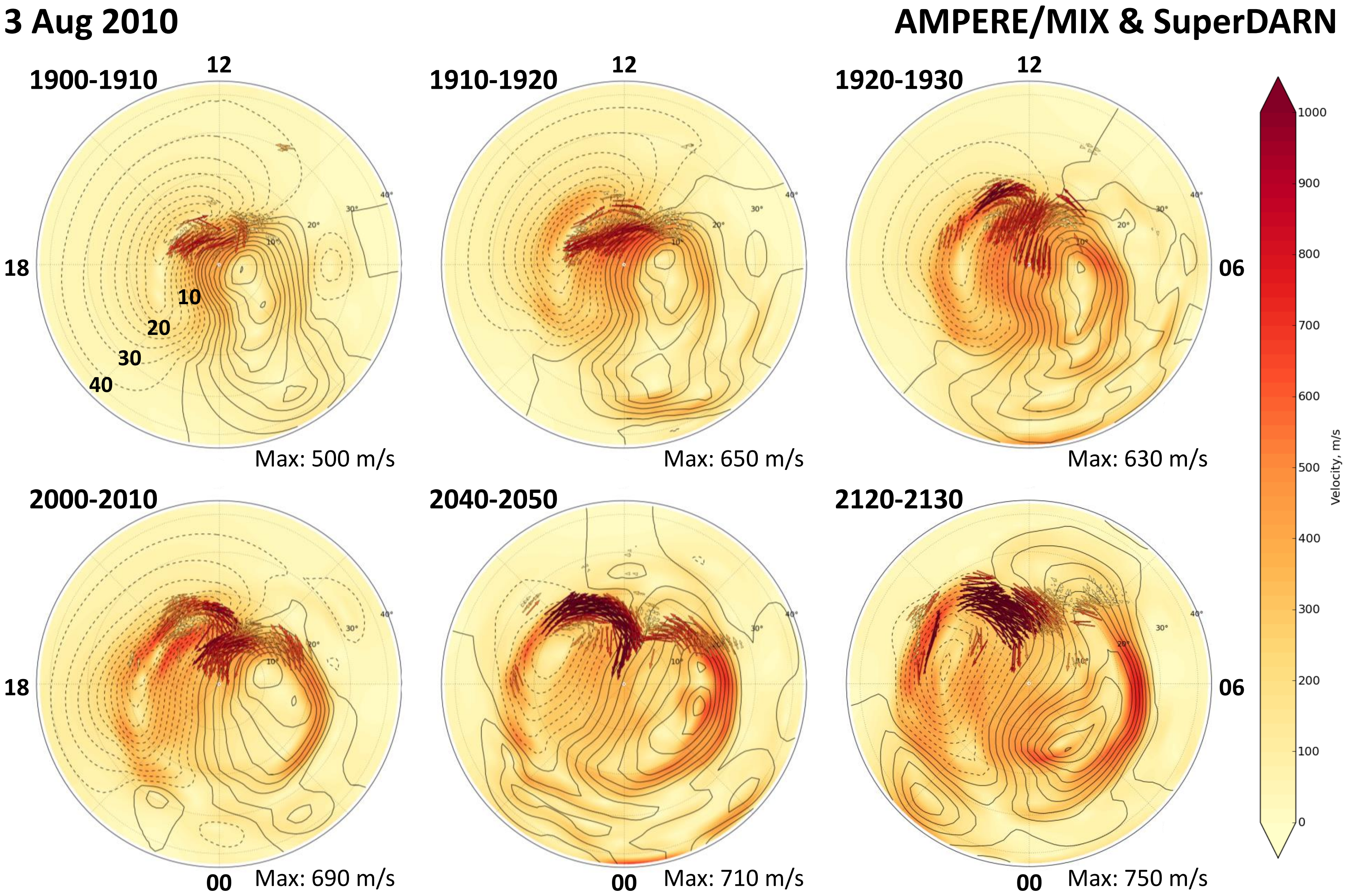
# Striking Consistencies

- Challenges in observations:
  - Uneven coverage between **E**, δ**B**$_S$, δ**B**$_G$
  - Sporadic returns for **E**
  - Land mass restrictions for δ**B**$_G$
  - 2-h local time separation for δ**B**$_S$
  - **Nonetheless: consistency when joint observations are obtained is striking.**
- Mitigation by assimilation:
  - Assimilation: use strengths of each asset to obtain highest achievable fidelity.
  - Depends on having at least one quasi-global asset to tie results together.
  - Various 'regularization' options are possible.
- Conductance challenge:
  - Conductances that are inconsistent with **E** and or $J_{||}$ leads to spurious heating. (Direct use of a statistical model is problematic.)
  - Some assimilative/optimized approach for conductance co-estimation is needed.



# Striking Consistencies

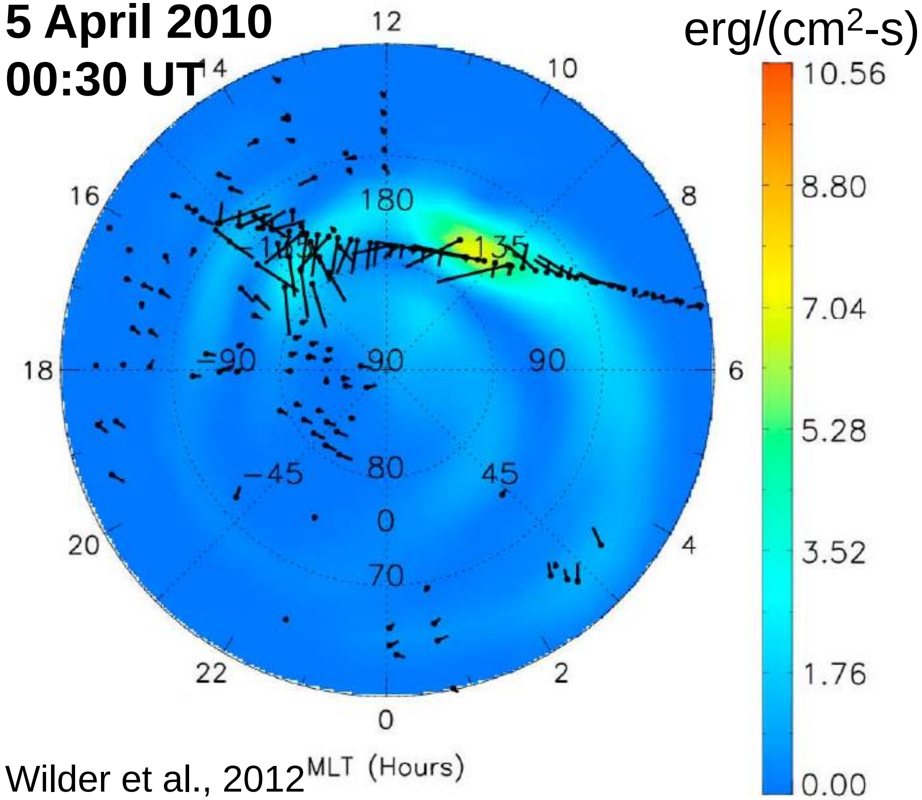
- Potential derived from $J_{||}$ using very crude assumption: 8S uniform $\Sigma_P$.
- Compare HF radar bi-static irregularity motions with inferred convection contours.
- Evolution in locations and directions agrees: they are reflecting the same underlying dynamics.



# Assimilation Successes in Research Studies

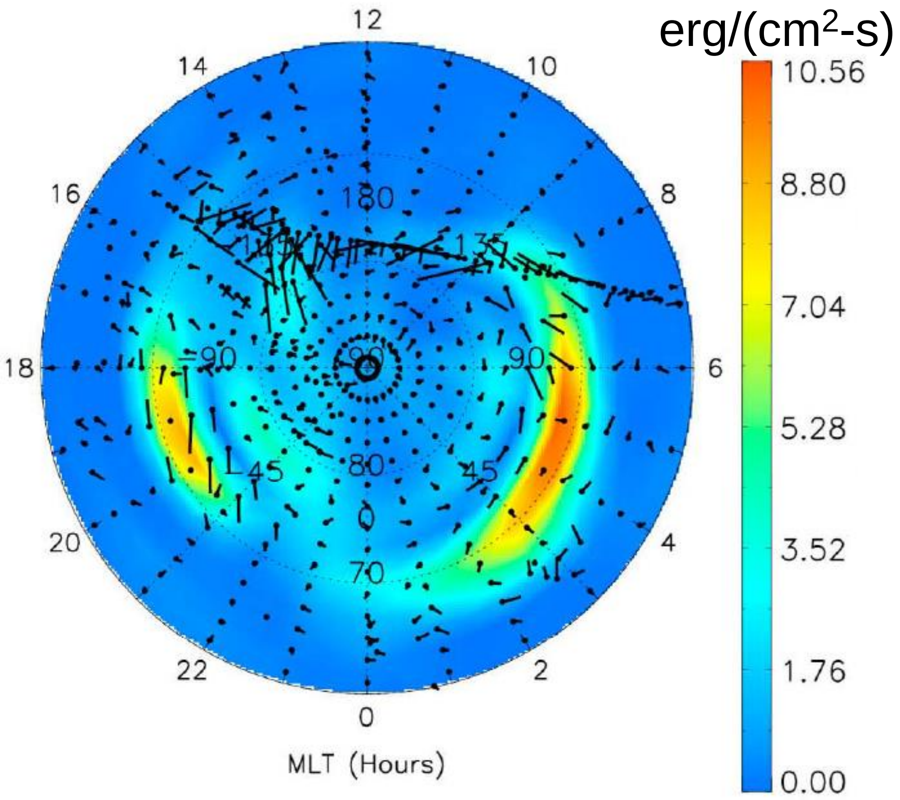
**AMIE: dB-ground, DMSP, SuperDARN**

**5 April 2010**
**00:30 UT**



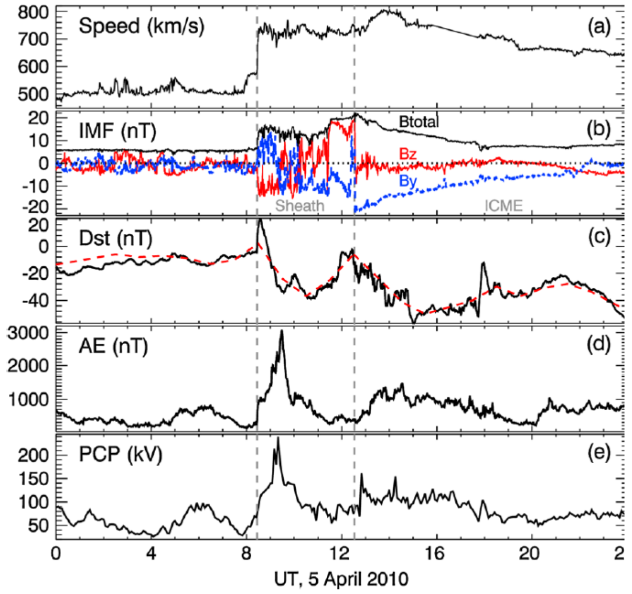

Wilder et al., 2012

**AMIE: AMPERE added**

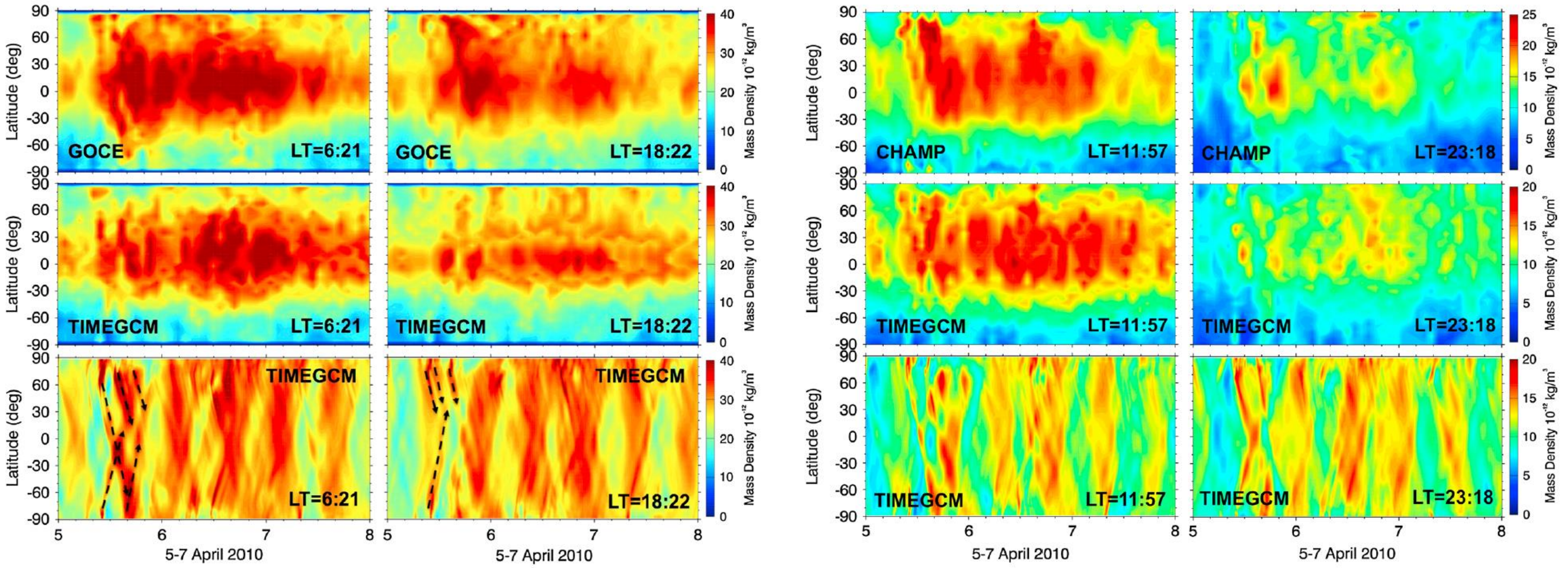



- Substantial modification of Joule heating distribution obtained by adding a globally distributed set of observations.

# Assimilation Successes in Research Studies




Lu et al., 2014




2010 April 5-6 AMIE:
- Radars & DMSP
- Ground mags
- AMPERE δ**B**

TIEGCM driven by assimilated results.

- Top: Observed thermospheric neutral dens (at eccentric satellite orbit).
- Middle: AMPERE-AMIE/TIEGCM densities (at eccentric satellite orbit).
- Bottom: AMPERE-AMIE/TIEGCM densities at constant altitude (reveal travelling atmospheric disturbances).
- End-to-end test against thermosphere: agreement is quite good.

# Observations: Gaps and Capabilities

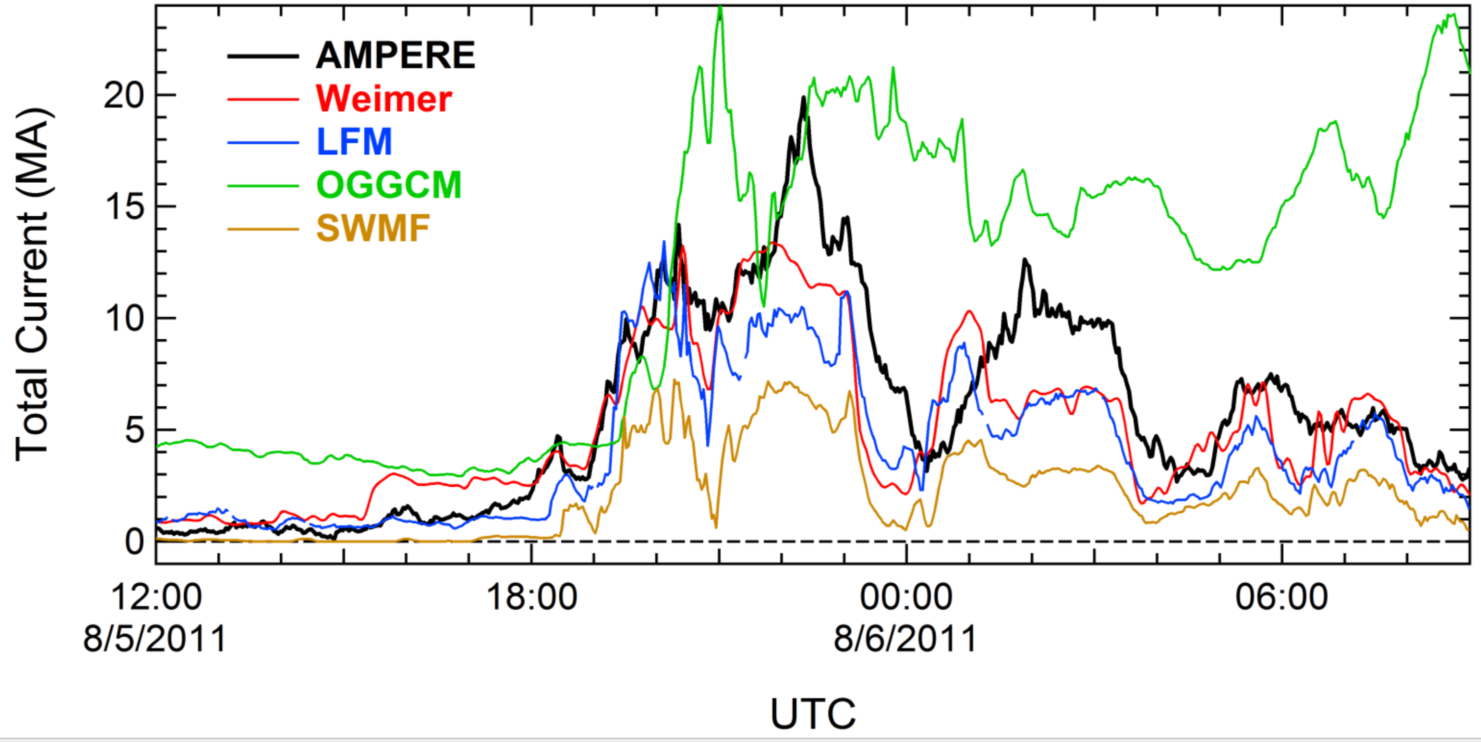
- Solution to a common problem: ‘everything everywhere’ is impossible:
  - Assimilation techniques can ingest disparately distributed observations to ‘invert’ for the actual high-latitude electrodynamics.
  - Need to acquire at least one global observation asset, complementary assets can be integrated via an assimilation framework to represent the natural electrodynamics leading to observed thermospheric responses.
  - Note: Observations that remain valid during intense storms (rare events) are critical. Empirical models do not provide capability for intense or extreme events that for which we have limited if any experience.
- Gap in observations: ‘polar blind spots’ is an impending problem.
  - Need a global suite of assets and complementary non-global observations in real-time. At present these would be: $\delta\mathbf{B}_{Space}$ global (AMPERE) and $\mathbf{E}_{SuperDARN}$, $\delta\mathbf{B}_{Ground}$, respectively.
  - Building an operational real-time capability is the key challenge here.
  - Constraints on conductances are needed to bound the assimilations. (Gap in particles and auroral imaging is a major problem here.)
  - GICs: Research gap – there is no data base of effects to allow determination of geospace dynamics responsible for actual GICs. Hence, it is very difficult to guide the models and simulations.
- Gap in assimilation capabilities:
  - Need an assimilation capability that is robust and fast.
  - Does not presently exist but is nearly within reach - the community is working in that direction.

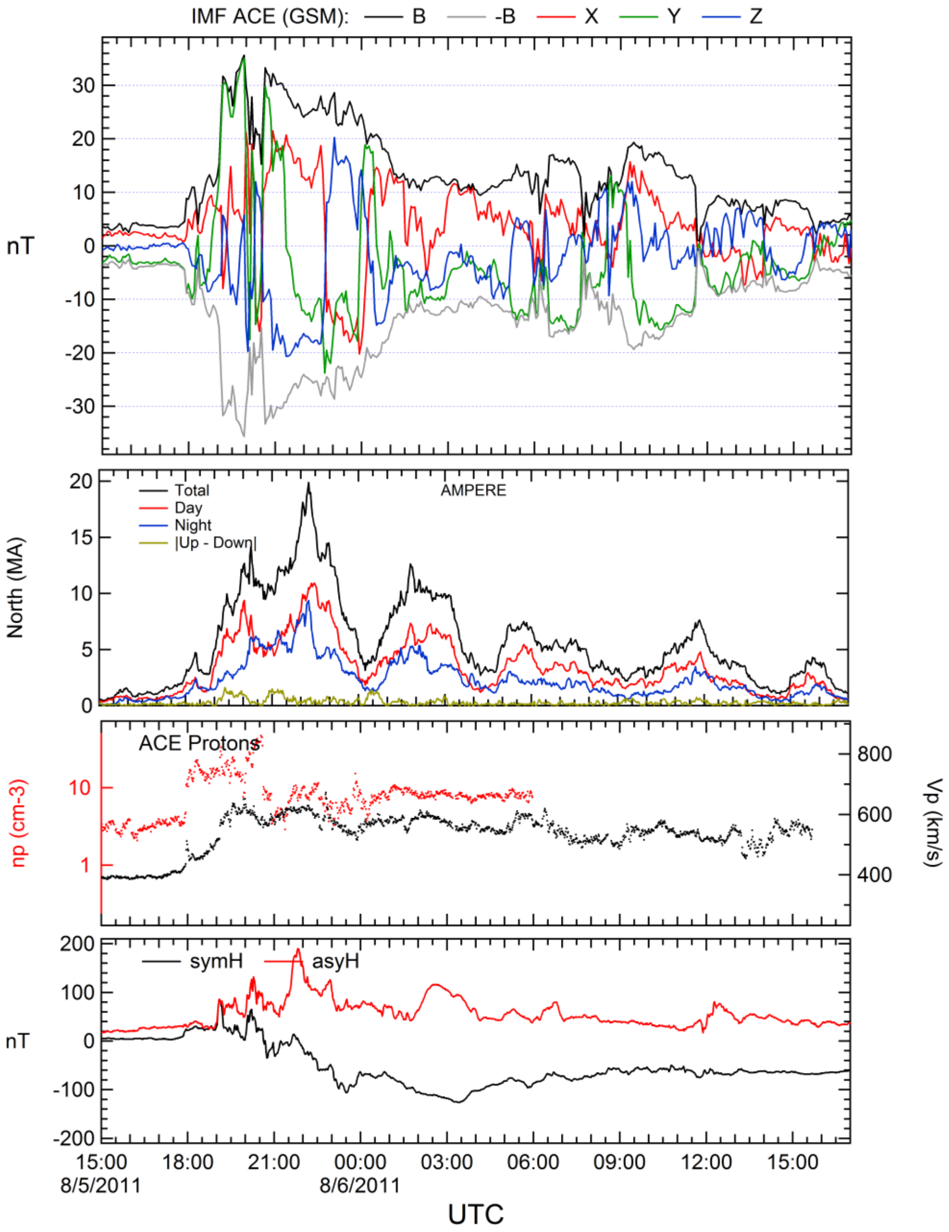
# Operational Model/Simulation Verification

- Intense and extreme events represent conditions that we cannot well validate before they happen.
- System may explore feedback mechanisms and non-linear dynamics that are not as prominently manifested under typical storm conditions.
- Need observations that provide a robust (i.e. always valid) and readily apparent (i.e. minimum of analysis) assessment of models/simulations used for operational forecast and specification.
- What could these observations be?
  - Global – covering all latitudes and all local times – ease of comparison at a glance.
  - Relatively immune to ionospheric conditions – i.e. ray path dependences not ideal.
  - Constellation observations at LEO are one possibility.
  - Comparisons between simulations and AMPERE to illustrate a hypothetical case and demonstrate that the physics-based simulations (research models) are improving markedly.

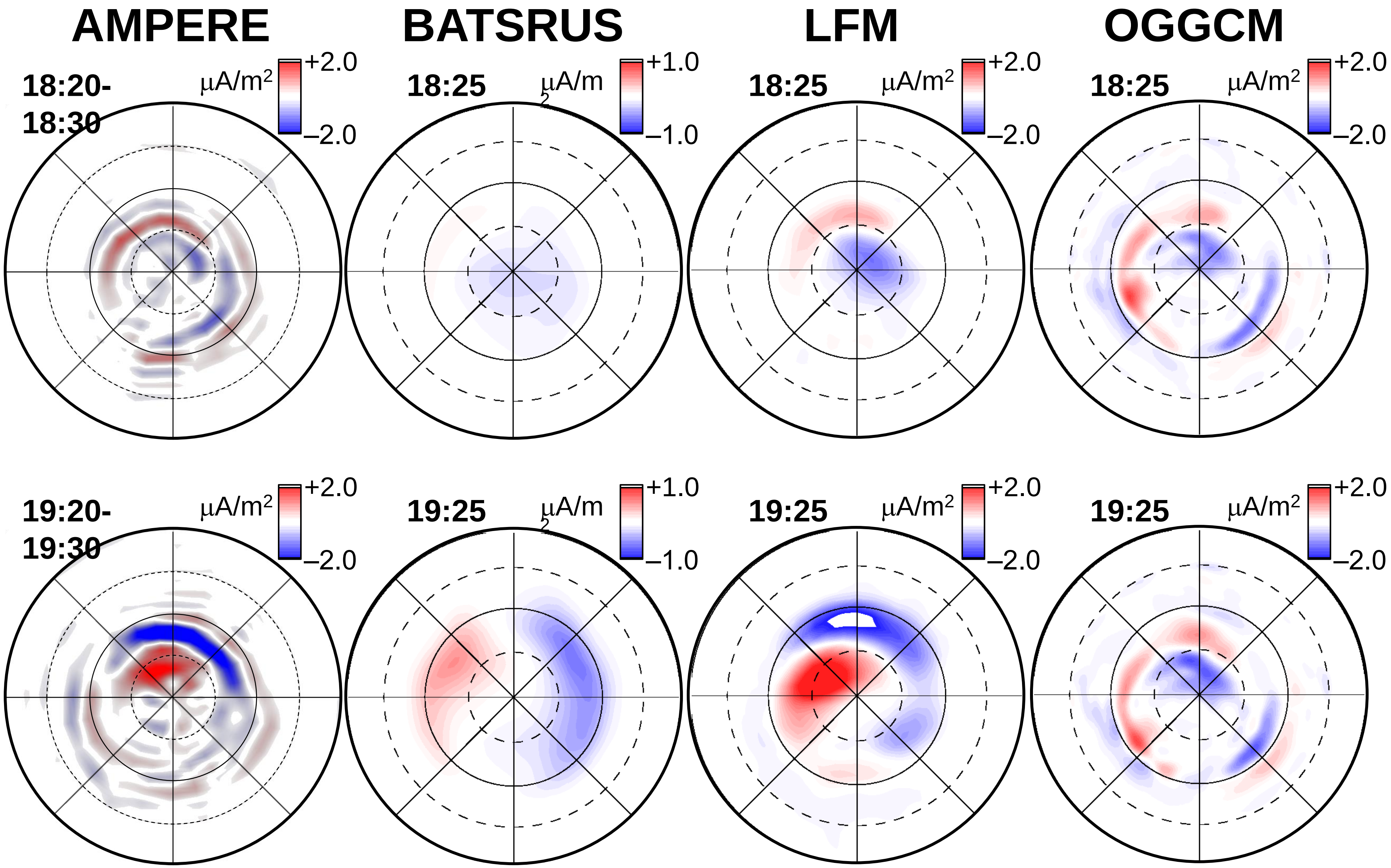
# First-cut comparisons: CCMC models circa 2016

- 2011 August 5-6 storm: AMPERE, Weimer ’05, LFM, OGGCM, SWMF (BATSRUS)
- Total current time series vary relative to AMPERE by factors of 2 to 4.
- Dynamics can be missing even though general behavior is not unreasonable.

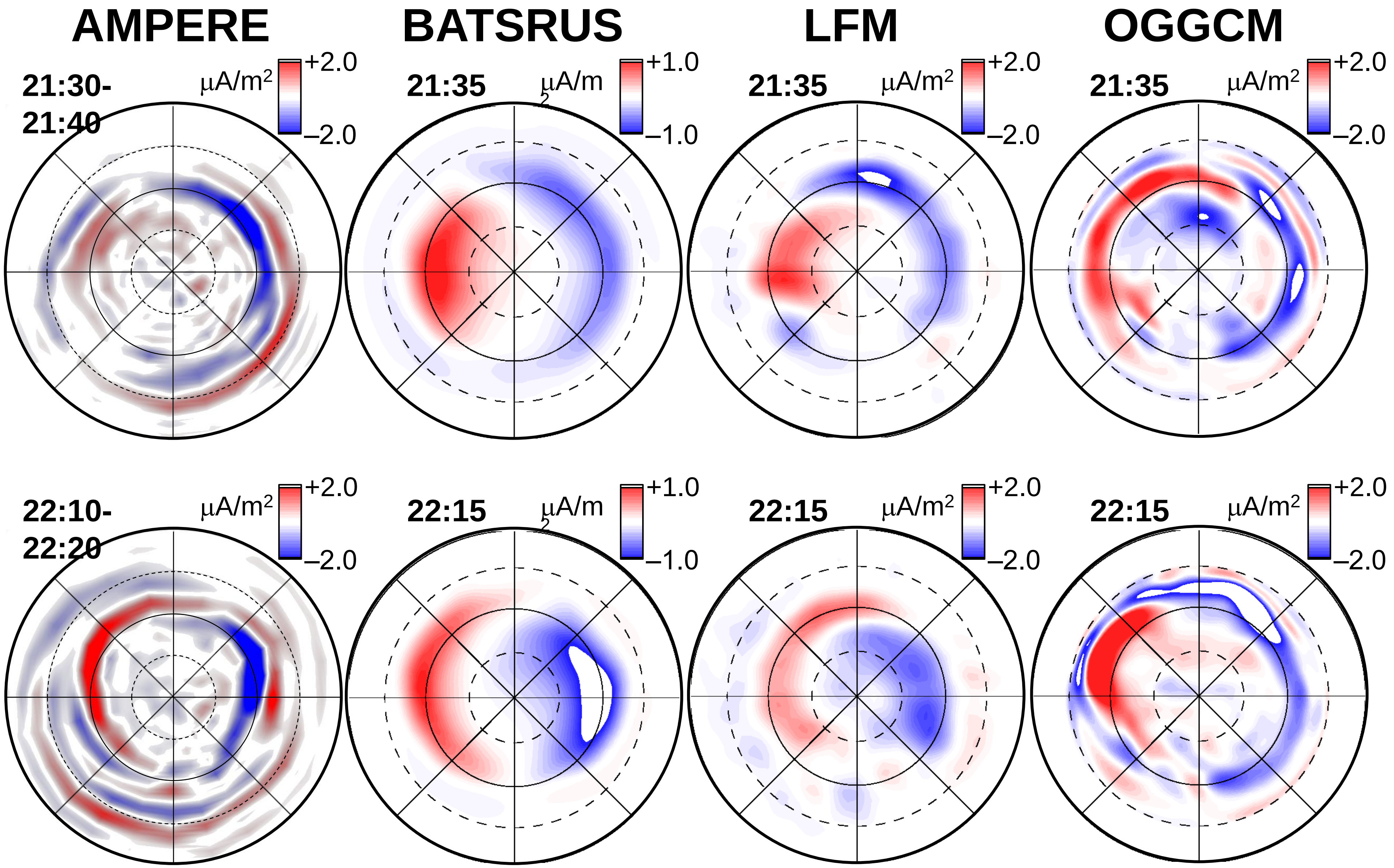


# 2011 5 August

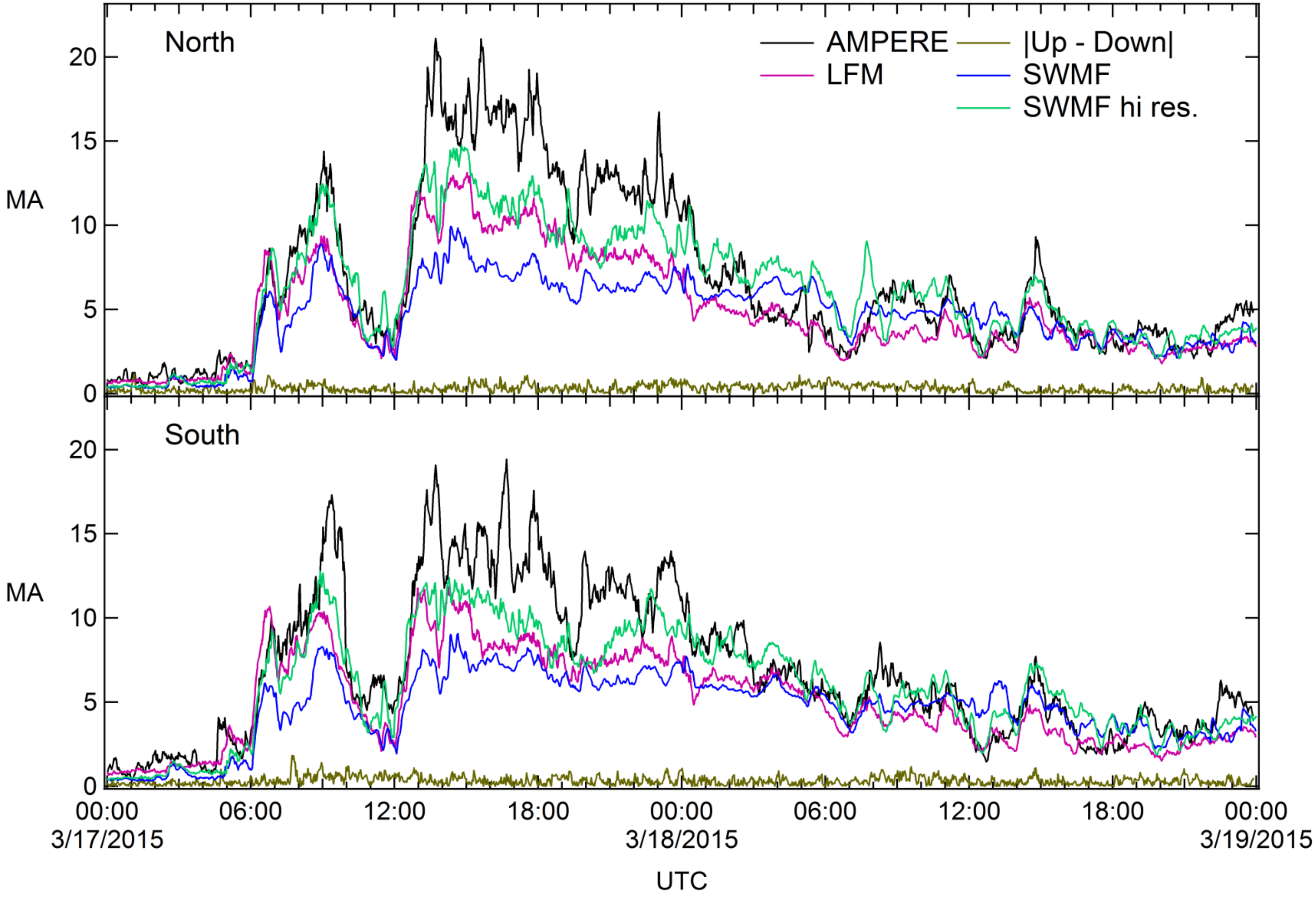


# 2011 5 August



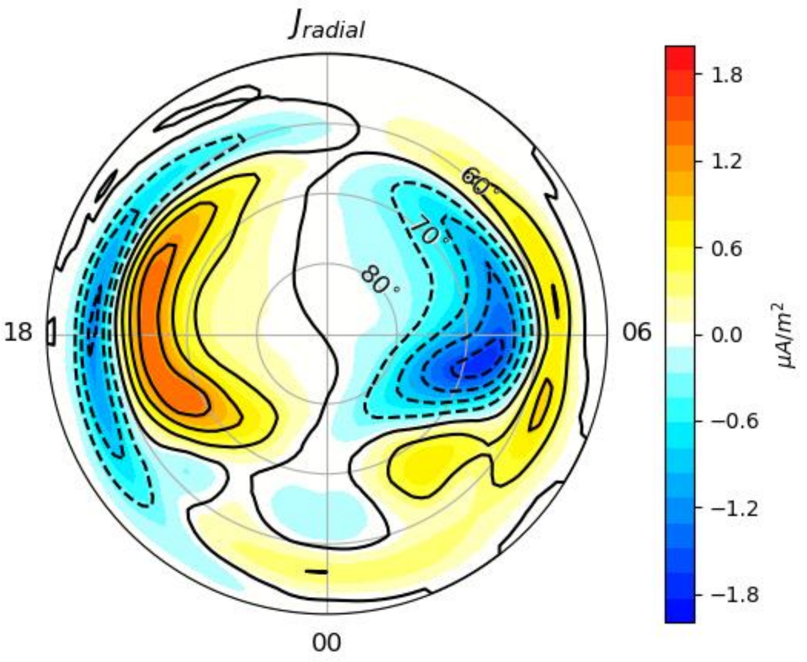
# More recent SWMF simulations

- SWMF – original vs high-resolution run.
- Total currents increased substantially.
- Distribution also is improved (next slide).

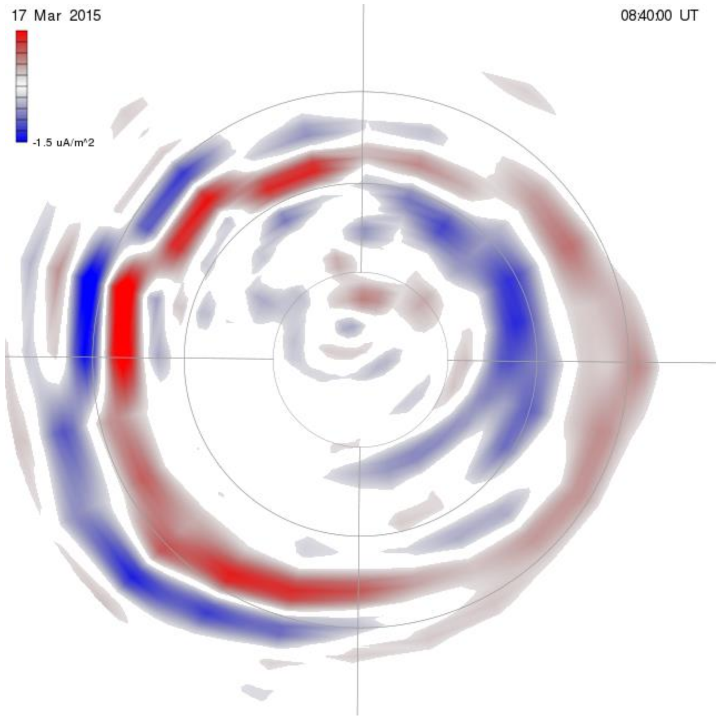


# More recent SWMF simulations

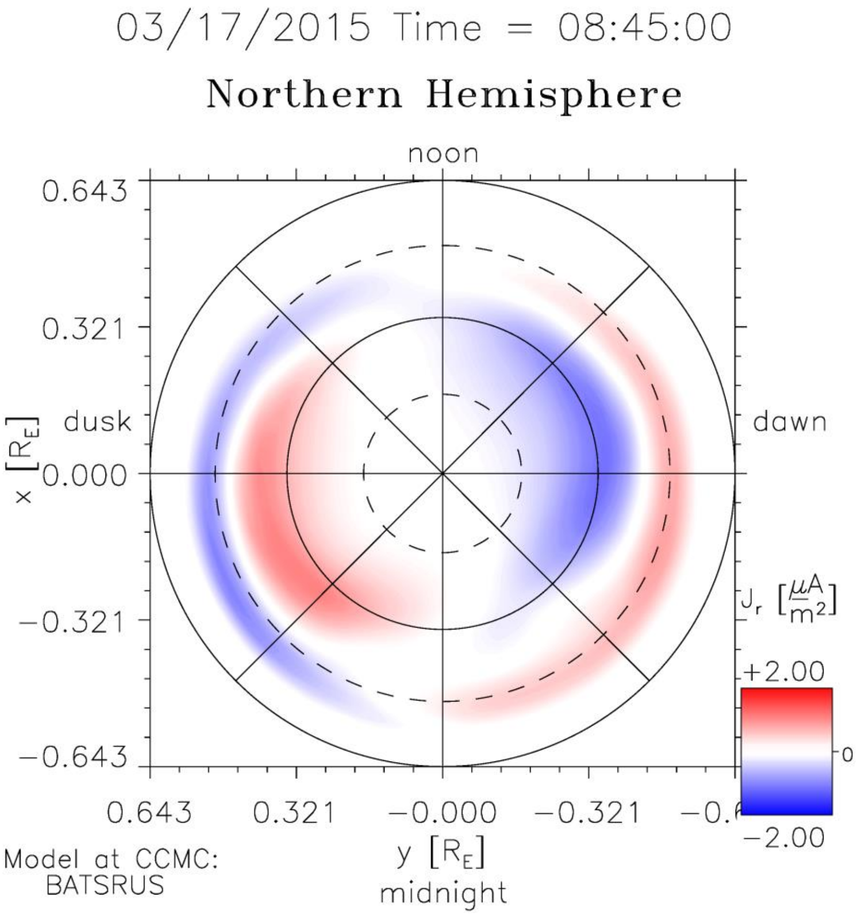
03/17/2015 08:45




SWMF (high res.)



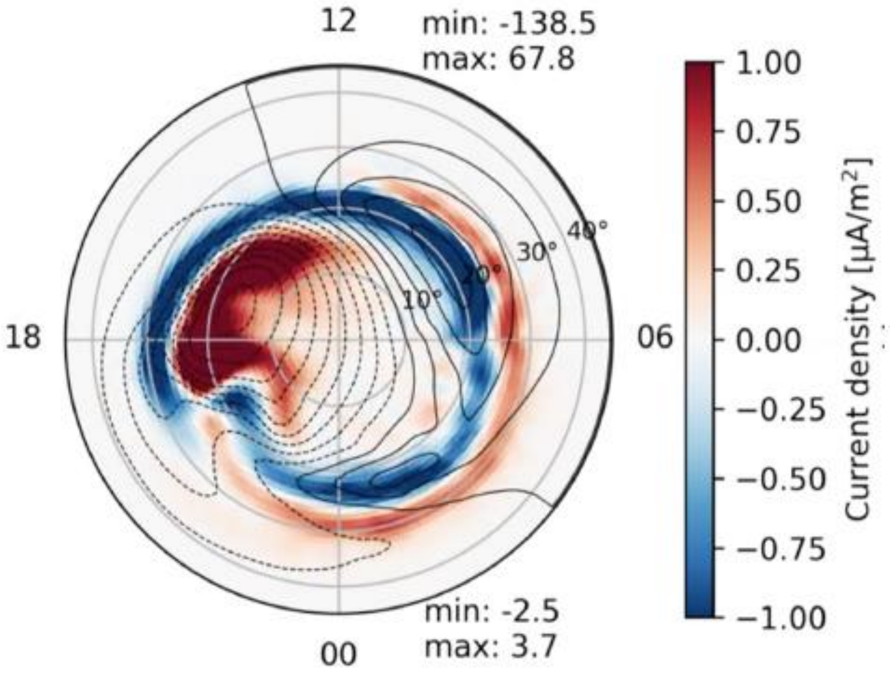

AMPERE 10-min

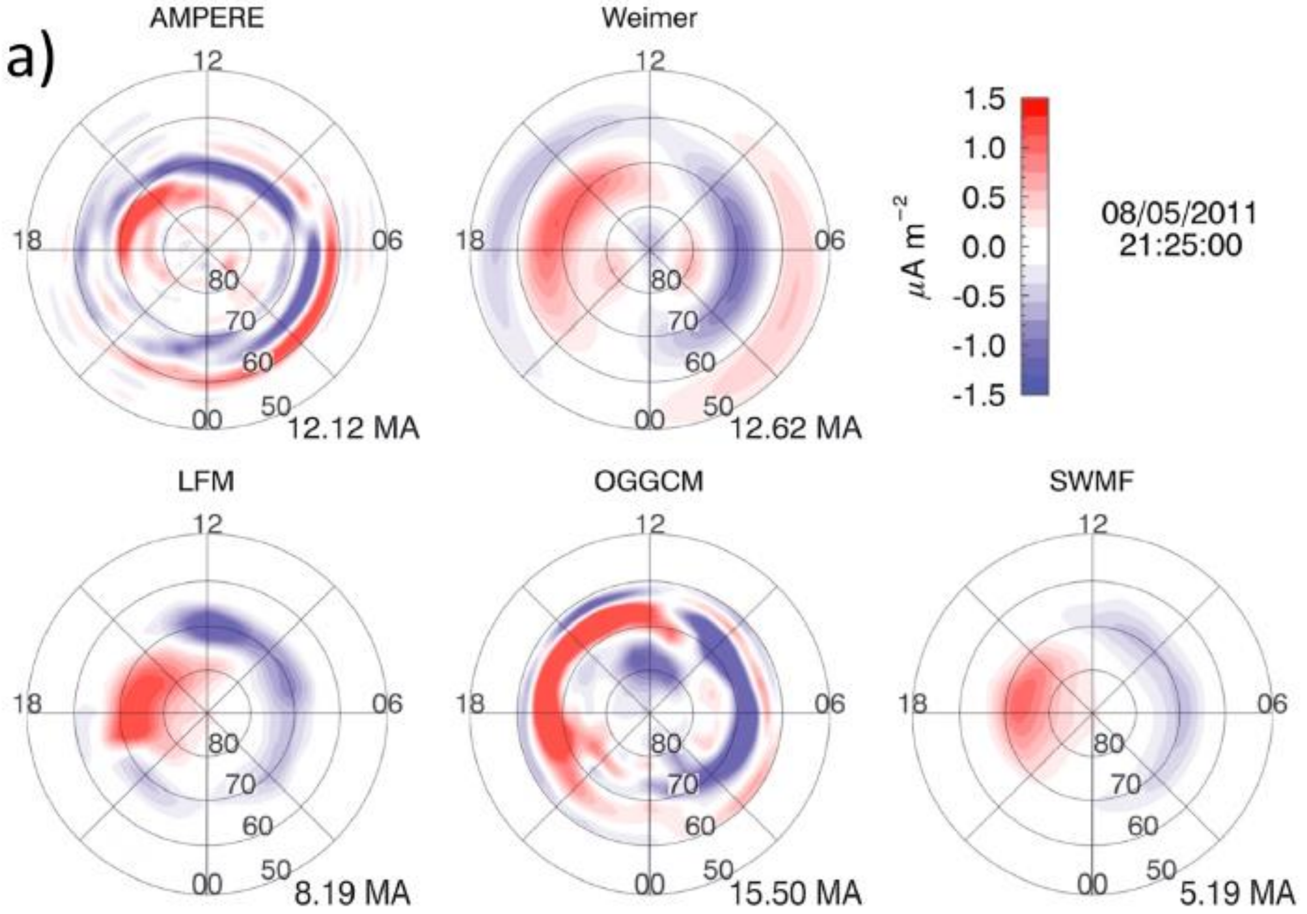



SWMF-CCMC (low res.)

# MHD-Ring current-IT: GAMERA+RCM+TIEGCM

- Initial results from a coupled self-consistent system simulation!
- AMPERE comparison is vastly improved. Great promise to understand the storm-time system.
- Advance from just four years ago is remarkable.

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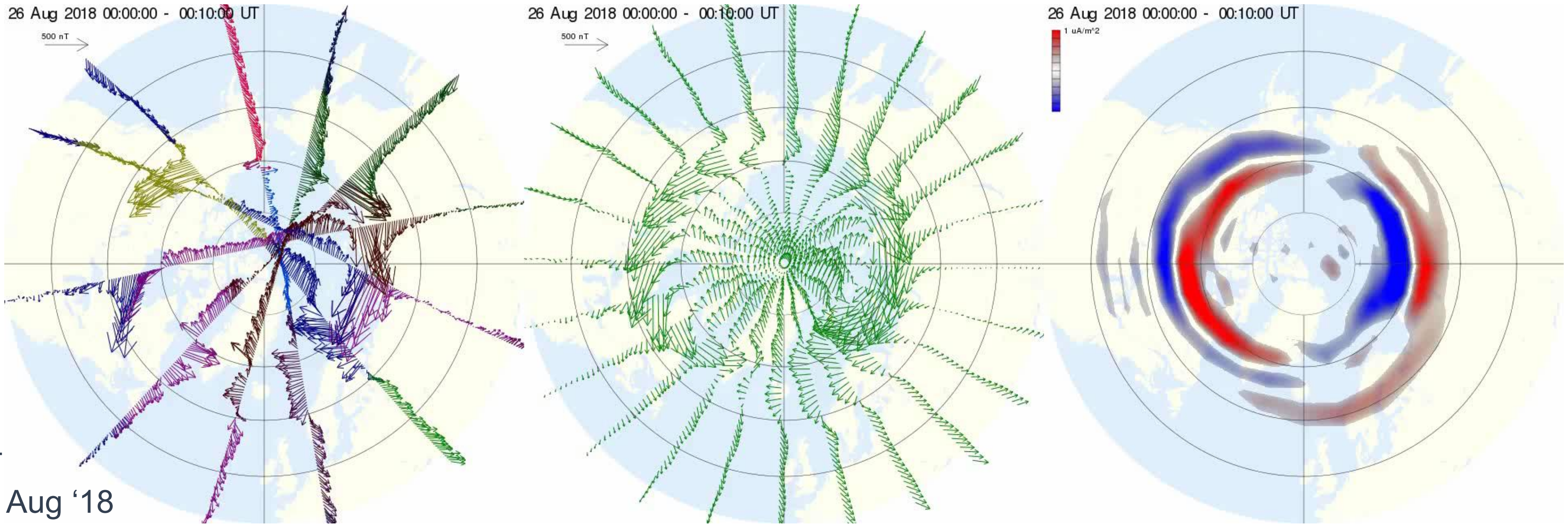
# Gaps to address

- Gap in observations:
  - Mid and high latitude gap in NOAA's space weather observations is a new 'polar blind spot' that needs to be filled in the near-term.
  - Need a global suite of assets and complementary observations in real-time. At present these would be: $\delta\mathbf{B}_{Space}$ global (AMPERE) and $\mathbf{E}_{SuperDARN}$, $\delta\mathbf{B}_{Ground}$, respectively.
  - Building this as an operational real-time capability is a challenge but feasible.
  - Loss of drift meter convection capability in space is source of concern: augmenting HF radars with these data is important. Should be included in a long-term plan.
  - Constraints on conductances are needed to bound the assimilations. Loss of particle and hyperspectral auroral imagery is a major decrement in capabilities. Should be included in a long-term plan.
- Gap in assimilation capabilities:
  - Need an assimilation capability that is robust and fast.
  - Does not presently exist but the community is working in that direction.
- Gap in operational simulation comparisons:
  - Need an observational capability that provides means to verify operational simulations: for intense or extreme conditions beyond range of cases available for validation.
  - Comparison with a direct simulation quantity.
  - Global, continuous, and valid for all levels of disturbance.

# Gap filling options

- ISR and HF radars: Implementing an operational real-time capability should not be a major challenge – but may require a commitment to ensure robust data flow.
- Ground magnetometers: Some real-time capability already exists. Coverage is important so identifying how to expand to more stations is key.
- Space magnetometers:
  - New asset (NEXT) is on orbit: 8 successful launches (2017-2019) give a new fully operational constellation.
  - Magnetometer calibrations just completed and release of data products for 2017-present in summer ’20.
  - NGA funded study of feasibility for use in WMM working with NOAA-NCEI – confirms low noise for geospace use.
  - Iridium is a satellite communications network supporting multiple operational needs for USG. Magnetic field data can be returned over the entire globe and delivered for science processing with ~3 minute latency.
  - Converting existing current best-effort systems to operational systems can be done.




NEXT
26-27 Aug ‘18

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