Heliosphere-Ionosphere-Thermosphere Coupling and Energy Budget in Geomagnetic Storms

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Outline:

Science Objective: estimate the ionosphere-thermosphere (IT) energy budget of CME- (and CIR/HSS-) driven geomagnetic storms.

Outstanding questions:

- How to quantify external driving in geomagnetic storms?
  - Overview solar wind driving of two strong CME-driven storms occurred around 75 – 79 DOY (in March) of 2013 and 2015;
- How to estimate storm-time energy budget of IT system?
  - Empirical approach and global circulation modeling (e.g., with GITM).
- Problems with conventional estimates of IT energy budget (<u>from the perspective of electromagnetic processes or currents</u>)
  - Controversy with Joule heating (current dissipation)
  - Poynting flux in IT

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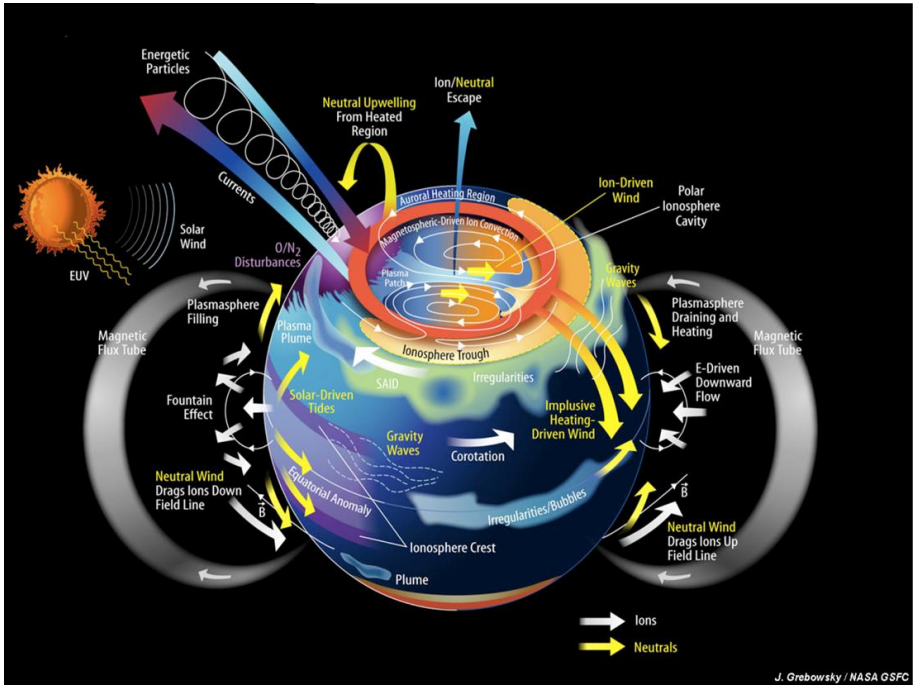
What drives Ionosphere-Thermosphere (IT) system?

From above:

- EUV radiation + flares;
- Particle precipitation (~1 to 10th keV) => auroral heating (AH);
- R1 and R2 currents closing into ionosphere and dissipation => Joule heating (JH);
- PPEF (Tsurutani et al., 2004; Solomon et al., 2012)
- E/m energy entry through high-latitude regions (Knipp et al., 2011; Huang et al., 2014; 2015) => Poynting flux;



Neutral winds, composition (O/N2) changes

Inside:

- Chemical heating

From below:

- Tides;

Focus: **storm-time energy input from above**

- **e/m energy input**

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How to estimate the net incoming energy?

The coupling function approach (solar wind - magnetosphere) :

Table 1. Twenty Candidate Solar Wind-Magnetosphere Coupling Functions and Their Origins in Roughly Historical Order

Name	Functional Form	Reference
B_z	B_z	*Dungey* [1961]
Velocity	v	*Crooker et al.* [1977]
Density	n	
p	$nv^2/2$	*Chapman and Ferraro* [1931]
Bs	B_z ($B_z < 0$); 0 ($B_z > 0$)	
Half-wave rectifier	vBs	*Burton et al.* [1975]
ε	$vB^2\sin^4(\theta_c/2)$	*Perrault and Akasofu* [1978]
ε_2	$vB_T{}^2\sin^4(\theta_c/2)$	Variant on ε
ε_3	$vB\sin^4(\theta_c/2)$	Variant on ε
Solar wind E-field	vB_T	
E_{KL}	$vB_T\sin^2(\theta_c/2)$	*Kan and Lee* [1979]
$E_{KL}{}^{1/2}$	$[vB_T\sin^2(\theta_c/2)]^{1/2}$	Variant on the Kan-Lee electric field
E_{KLV}	$v^{4/3}B_T\sin^2(\theta_c/2)p^{1/6}$	*Vasyliunas et al.* [1982]
E_{WAV}	$vB_T\sin^4(\theta_c/2)$	*Wygant et al.* [1983]
$E_{WAV}{}^2$	$[vB_T\sin^4(\theta_c/2)]^2$	Variant on E_{WAV}
$E_{WAV}{}^{1/2}$	$[vB_T\sin^4(\theta_c/2)]^{1/2}$	Variant on E_{WAV}
E_{WV}	$v^{4/3}B_T\sin^4(\theta_c/2)p^{1/6}$	*Vasyliunas et al.* [1982]
E_{SR}	$vB_T\sin^4(\theta_c/2)p^{1/2}$	*Scurry and Russell* [1991]
E_{TL}	$n^{1/2}v^2B_T\sin^6(\theta_c/2)$	*Temerin and Li* [2006]
$d\Phi_{MP}/dt$	$v^{4/3}B_T{}^{2/3}\sin^{8/3}(\theta_c/2)$	This paper

- Only ε-parameter (the Akasofu parameter) can be scaled to the energy units
- How much energy is transferred to the IT?

The Akasofu parameter

(Akasofu, 1979; Koskinen and Tanskanen, 2002)

The Kan-Lee electric field

(Kan and Lee, 1979) relates to reconnection in high-latitude magnetosphere

The Universal coupling function

(Newell et al., 2007; 2008)

a measure of the rate of opened magnetic flux at the Earth magnetopause during a dayside reconnection event

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How to estimate the incoming energy partitioning?

- Empirical formulae for JH_N (Knipp, 2005), at *equinox*

$$JH\ (GW) = 29.14*PC + 2.54*PC^2 + 0.21*Dst + 0.0023*Dst^2$$

- Tracer for JH: measurements of nitric oxide (NO) molecular emission in 3.5 µm with TIMED/SABER (Mlynczak et al., 2003; 2010; Lu et al., 2010; Verkhoglyadova et al., 2011)

- JH is derived with the AMIE (The Assimilative Mapping of Ionospheric Electrodynamics) (Richmond and Kamide, 1988)

- Auroral electron hemispheric power (HPe): the inter-calibrated NOAA POES (Polar Orbiting Environmental Satellite) and DMSP (Defense Meteorological Satellite Program) datasets (Emery et al., 2006, 2008)

- Empirical models for Hp, e.g., Zhang and Paxton (2008) based on TIMED/GUVI data :

- Empirical model for the Poynting flux (Cosgrove et al., 2014) based on FAST data

Total CME storm driving	Approx. contribution
ring current	~10%
Joule heating	> 60%
auroral heating	~20%
Poynting flux	?
?	?

Relative to ε-parameter (Turner et al., 2009)

Empirical models: averaged pattern, database limitations in time (solar cycle phase) and spatial coverage

$$HP = 38.66\ EXP(0.1967\ Kp) - 33.99 (GW)\ for\ Kp \leqslant 5.0,$$

$$HP = 4.592\ EXP(0.4731\ Kp) + 20.47\ (GW)\ for\ Kp > 5.0.$$

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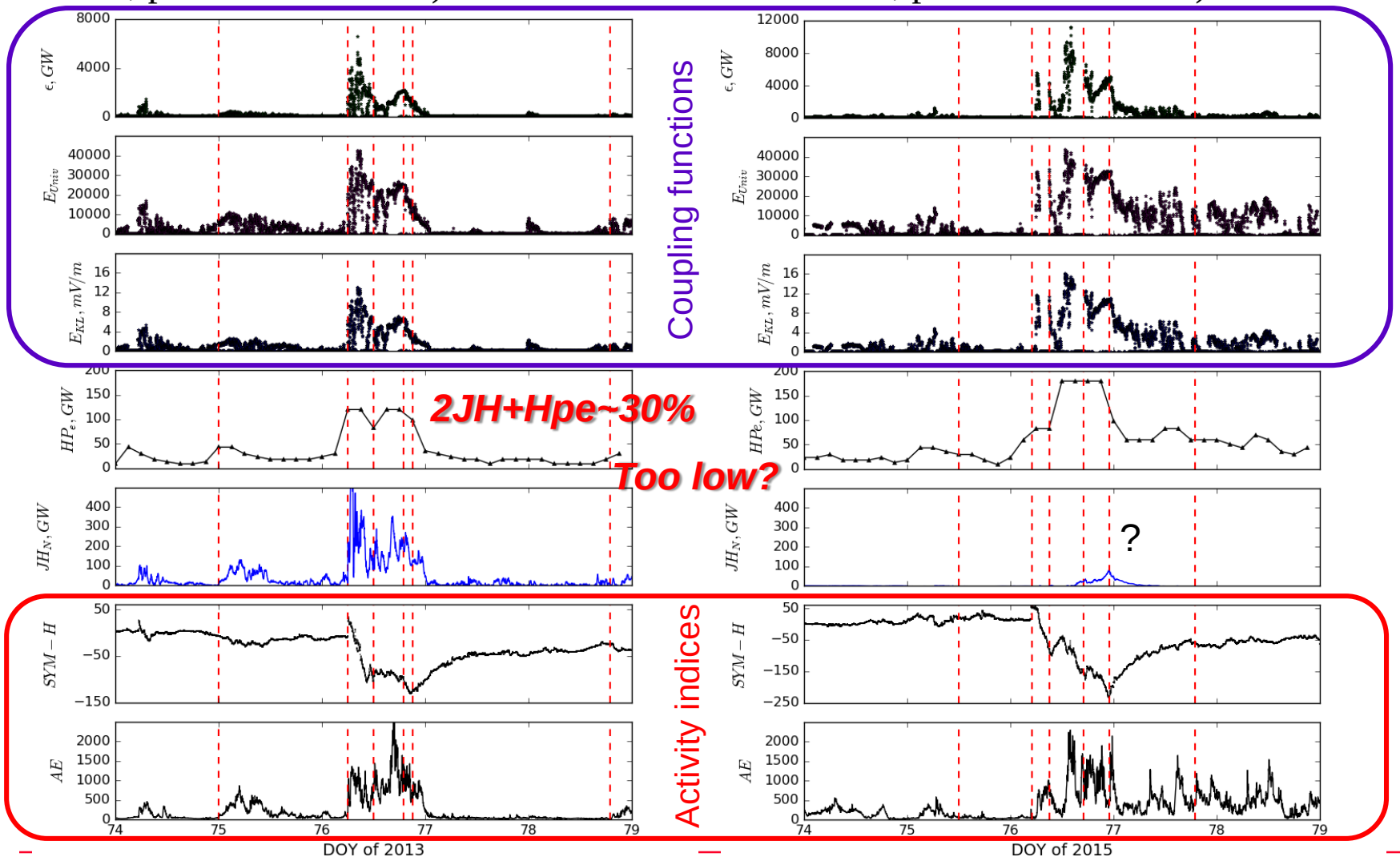
Examples for CME storms:

March 2013 storm (minimum SYM-H is ~ -107 nT, peak AE is ~ 2500)

March 2015 storm (minimum SYM-H is ~ -234 nT, peak AE is ~ 2400)



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How to model the incoming energy partitioning (in GCM)?

We run **Global Ionosphere Thermosphere Model (GITM):** 3D non-hydrostatic model for 10 neutral and 9 ion species (Ridley et al., 2006) with the following inputs:

1. Solar irradiance: **F10.7**
2. High-latitude electric and magnetic field potential patterns and field-aligned currents (FAC): empirical **Weimer05 model** (Weimer, 2005), can use AMIE input
3. Particle precipitation: **Ovation Prime** (Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting) model (Newell et al., 2009). The model predicts intensity for 4 types of auroras at different locations and estimates southward auroral boundary.

Energy partitioning calculated in the model:

- EUV heating (from photo-absorption for 5 major species)
- Photoelectron heating (from photoionization)
- Joule heating
- Auroral heating (based on Ovation Prime)
- Chemical heating (solar radiation driven)

- Thermal conduction (due to eddy diffusion)
- NO cooling
- O cooling
- CO2 cooling

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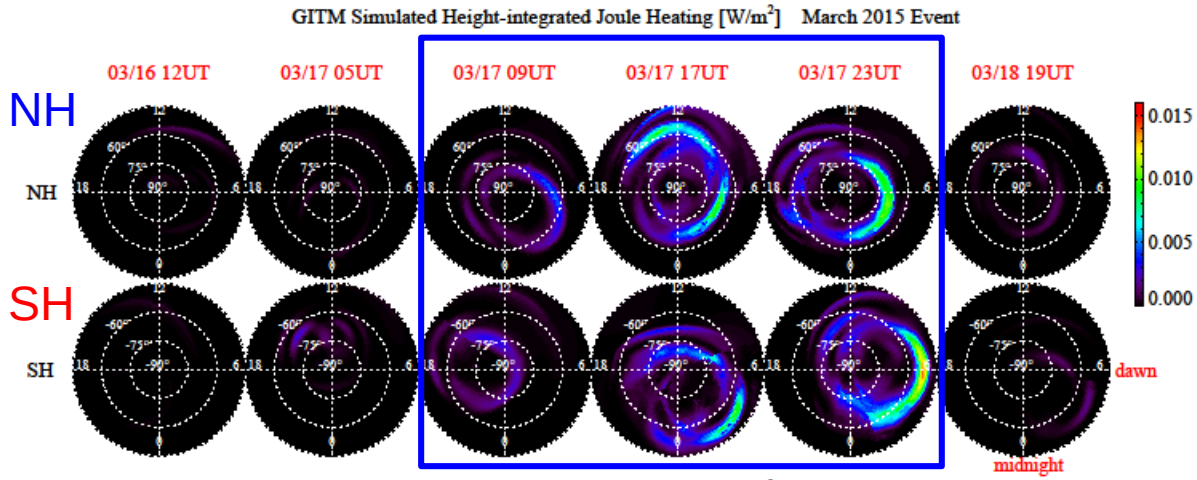
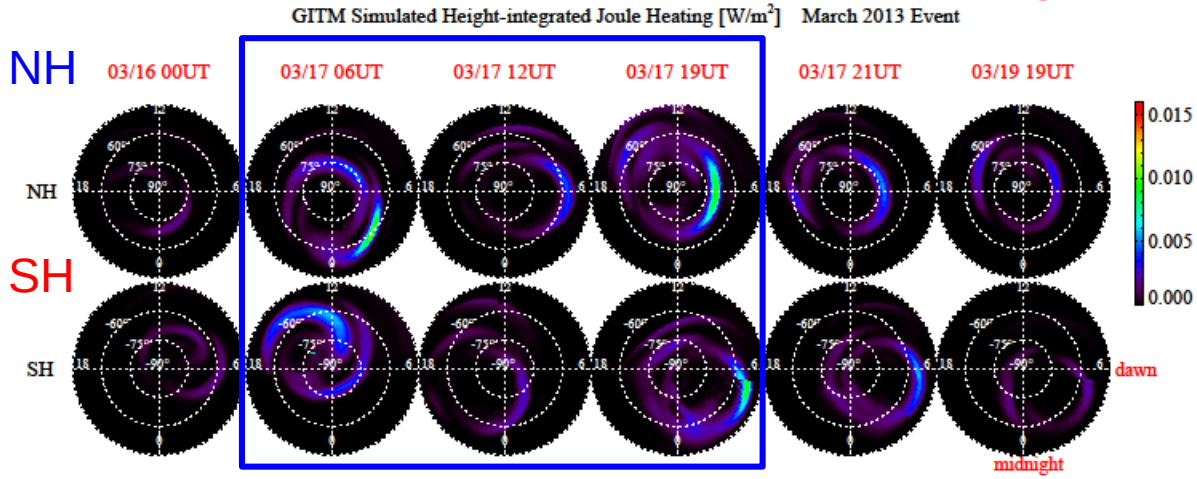
GITM modeling results: Joule heating

Height-integrated (100 km - 600 km)

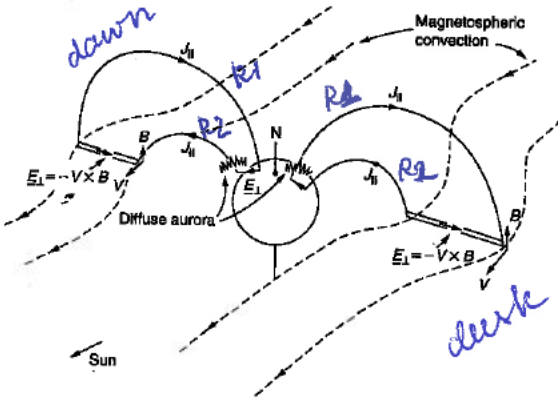




Storms' main phase

JH pattern and peak values are reasonable, controlled by Weimer05

Geographic coordinates



FAC system (*Kelley, 2009*)

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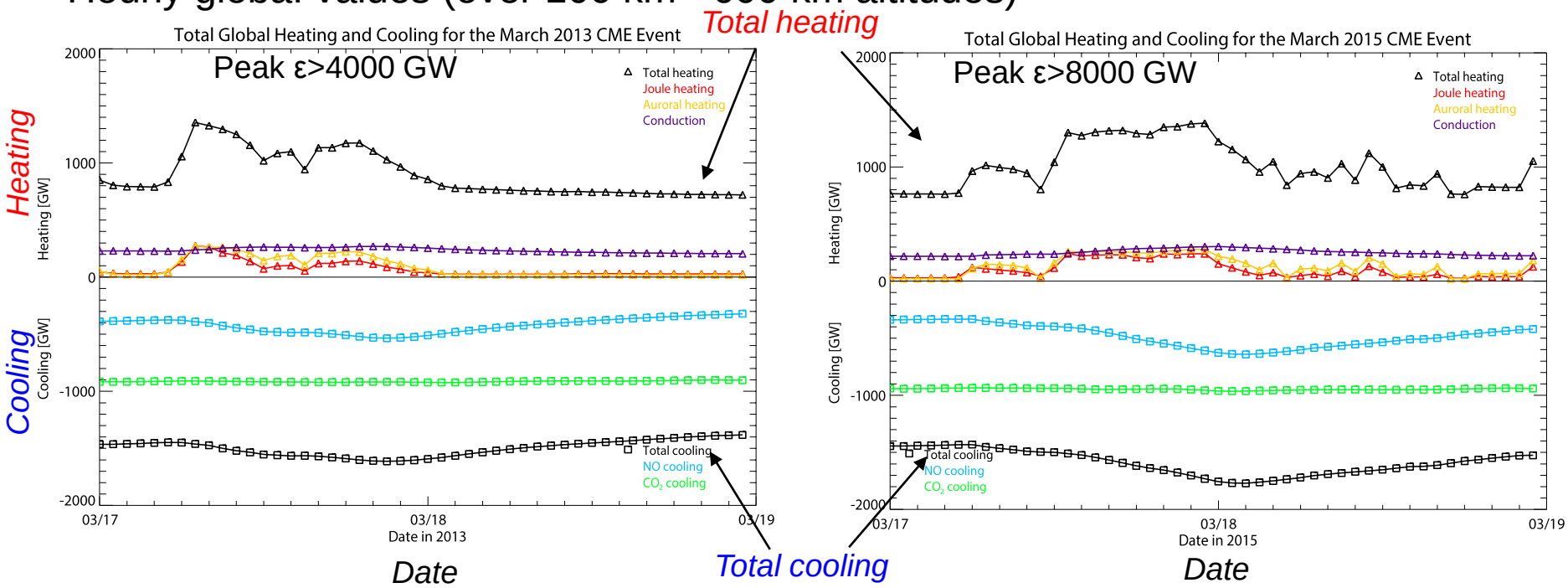
Modeling results: energy budget

Hourly global values (over 100 km - 600 km altitudes)



- Total heating and cooling do not balance each other
- Is JH too low? JH is modeled in GITM as the neutral-ion collisional heating (Deng and Ridley, 2007; Zhu and Ridley, 2016).

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How do we calculate JH?

1. By definition, Joule heating is due to electric current dissipation (Cole, 1961; Richmond, 2010):

$$P_J = j \cdot E = \sigma_p E^2$$

2. Joule heating is estimated directly from the relative ion-neutral drift (Thayer and Semeter, 2004; Ridley et al., 2006) as frictional heating:

$$P_J = \sum_{i,n} \frac{n_i M_i}{\rho} \nu_{in} (\overrightarrow{u_i} - \overrightarrow{u_n})^2,$$

where n_i is the ion number density, M_i is the mean ion mass, ρ is the neutral atmosphere mass density, ν_{in} is the ion-neutral collision frequency, $\overrightarrow{u_i}$ and $\overrightarrow{u_n}$ are the ion and neutral velocities, respectively.

These two definitions are used interchangeably, but they are equivalent under specific assumptions! (Brekke, 1997; Thayer and Semeter, 2004)

Direct inclusion of E-variability in NCAR-TIEGCM increased JH by 100% (Deng et al., 2007);

Time-dependent effects or inductive electromagnetic fields could theoretically contribute up to 20% of the ionospheric field-aligned current (Vanhamäki, Amm and Viljanen, 2007).

A factor of 2.5 was suggested to account for small-scale structures in high-latitude electric fields (Emery et al. 1999).

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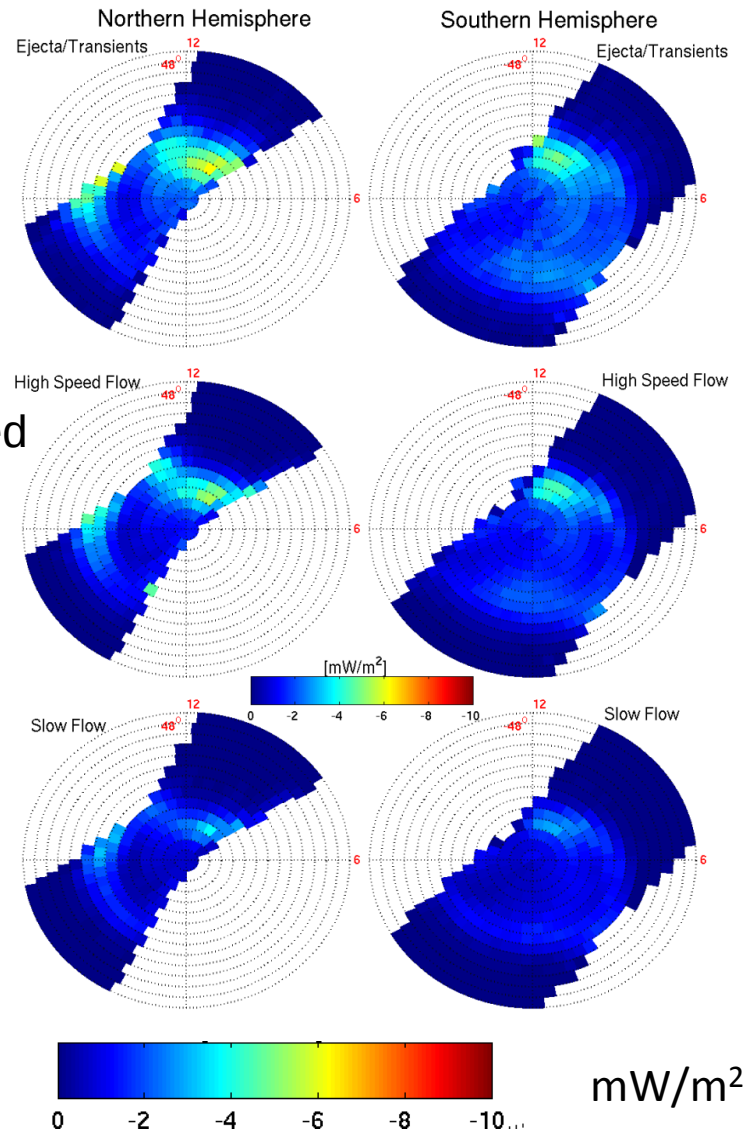
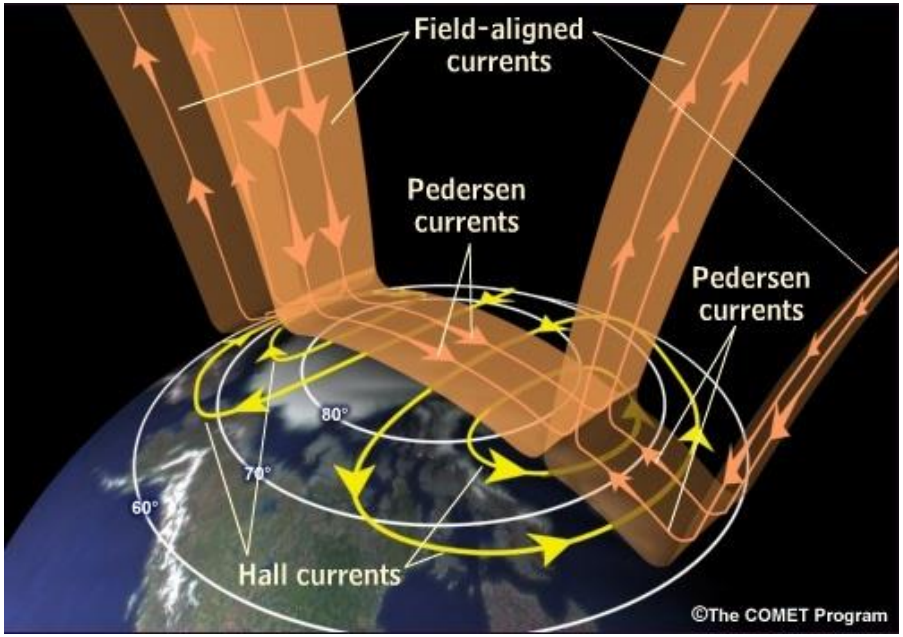
DMSP Measurements of Poynting Flux into the Ionosphere-Thermosphere System

Ejecta / Transients (~23%)

High Speed Flow (~44%)

Slow Flow (~33%)





$$\mathbf{S} = \left(\mathbf{E} \times \delta\mathbf{B}_{DMSP\,Horizontal}\right) / \mu_0$$

$$S_{\parallel} = (E_x \delta B_y - E_y \delta B_x) / \mu_0$$

(Huang and Burke, 2004)

where

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B}_{IGRF} \quad \text{and} \quad \delta\mathbf{B}_{DMSP\,Horizontal} = \mathbf{B}_{DMSP} - \mathbf{B}_{Main}$$

Courtesy of D. Knipp and Y. Huang

mW/m²

see Rastatter et al., 2016

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Conclusions: current challenges

- We need to have a better estimate of energy coming into the IT system from above and from below
  - E.g., from GCM coupled with middle/low atmosphere, WACCM-X
- Empirical models are useful and can be potentially utilized in forecasting, but they miss fine structures and temporal variability of currents and particle precipitation (*which variability scales are important*?).

What is missing in the IT energy budget? **Potentially important for forecasting**

- Effects of time-varying electric fields need to be accounted for, possibly as inductive-dynamic M-I-T coupling via Alfven waves (Lysak, 2004; Tu et al., 2014).
- *Source/heating term:* IT energy budget needs to include Poynting flux (Knipp et al., 2011; Huang, et al., 2014; Rastatter et al., 2016).
- *Sink term:* consistent Joule heating definition across global circulation models. *Does it correlate with the Poynting flux?*

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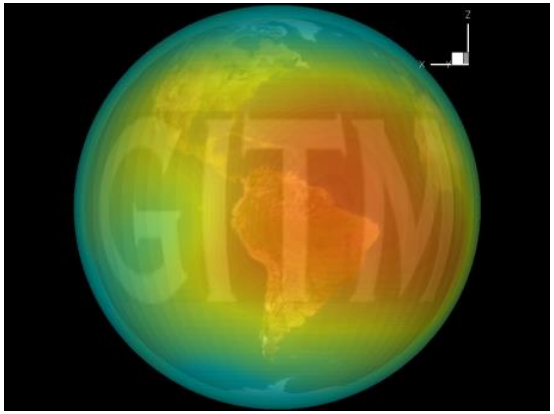
Global Ionosphere-Thermosphere Model

Developers: Aaron J. Ridley, Yue Deng and Gábor Tóth [Ridley et al., 2006, JASTP]

- **Governing equations**
  - **continuity, momentum, and energy equations**
  - **10 neutral and 9 ion species**
  - **include most of the physical processes that are present in the upper atmosphere, such as solar EUV heating, auroral particle precipitation, chemical reactions, ion-neutral and neutral-neutral collisions, viscosity, heat conduction, radiative cooling, and high-latitude electric field**
  - **allow non-hydrostatic solutions**

- **Computational grid**
  - **based on geographic longitude, latitude, and altitude**
  - **Flexible computational domain and grid resolution; 3D or 1D simulation**

- **Initial and boundary conditions are obtained from empirical atmospheric models MSIS and HWM. The boundary conditions are supplied by two layers of ghost cells.**



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