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Energy budget of the ionosphere-thermosphere system at multi-scale and its importance for space weather

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How to quantify energy input into the MIT?

Coupling functions (solar wind - magnetosphere):

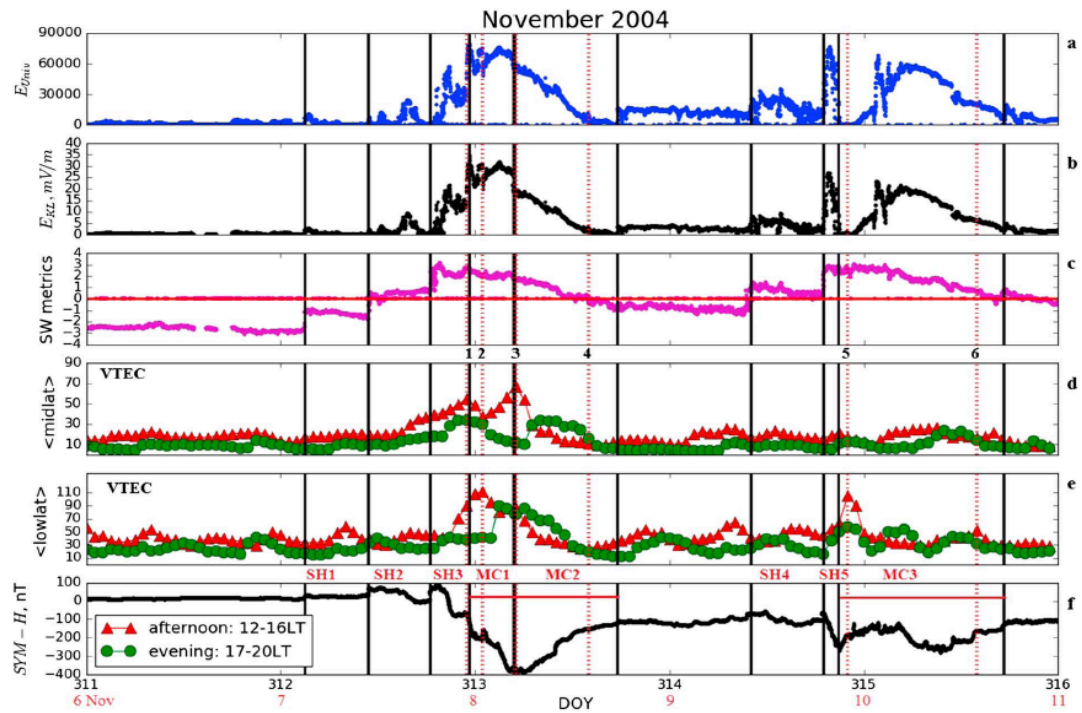
$$\varepsilon(t) = VB^2 \sin^4 \frac{\theta}{2} l_0^2$$ Akasofu parameter (Akasofu, 1979)

$$E_{\mathrm{Univ}} = \frac{d\Phi}{dt} = V^{4/3} B_T^{2/3} \sin^{8/3}(\theta_c/2),$$ Universal coupling function (Newell et al., 2007; 2008)

$$E_{\mathrm{KL}} = VB_T^2 \sin^2(\theta_c/2).$$ Kan-Lee electric field (Kan and Lee, 1979)

$$S1 = 3.19 \ln(V) + 0.445 \ln(N) + 0.916 \ln(B_T) + 0.0138\, \theta_c - 23$$ (Borovsky 2014; Borovsky and Denton, 2014; +)

Relationship between efficiency of the SW coupling and ionospheric responses (in TEC=Total Electron Content)

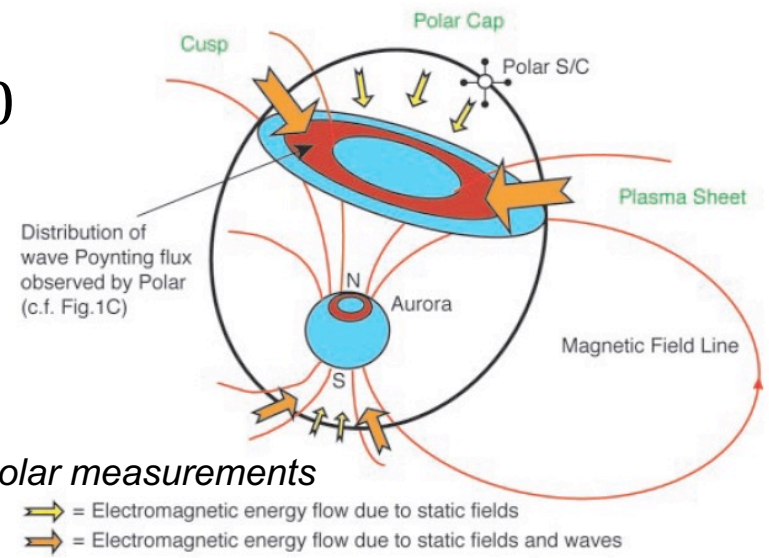


(Verkhoglyadova et al., JGR, 2017a)

Electromagnetic energy input and dissipation

Poynting's Theorem:

$$\frac{\partial w}{\partial t} + \nabla.\left(\frac{\boldsymbol{E}\times\boldsymbol{B}}{\mu_0}\right) + \boldsymbol{J}.\boldsymbol{E} = 0$$



Source: Poynting Flux (PF)

$$\vec{S} = \frac{1}{\mu_0}[\vec{E}\times\vec{B}]$$

Knipp, 2004, 2011; Huang, 2014, 2016; Cosgrove, 2014;

PF inferred from Polar measurements (Keiling+, 2002)

Sink: Joule heating (JH)

$$Q_J = \sigma_p(\mathbf{E} + \mathbf{U_n}\times\mathbf{B})^2$$

Lu et al., 1995; Deng et al., 2018

$$\vec{j}\cdot\vec{E} = \vec{j}\cdot\vec{E}' + \vec{V}_n\cdot\vec{j}\times\vec{B}$$

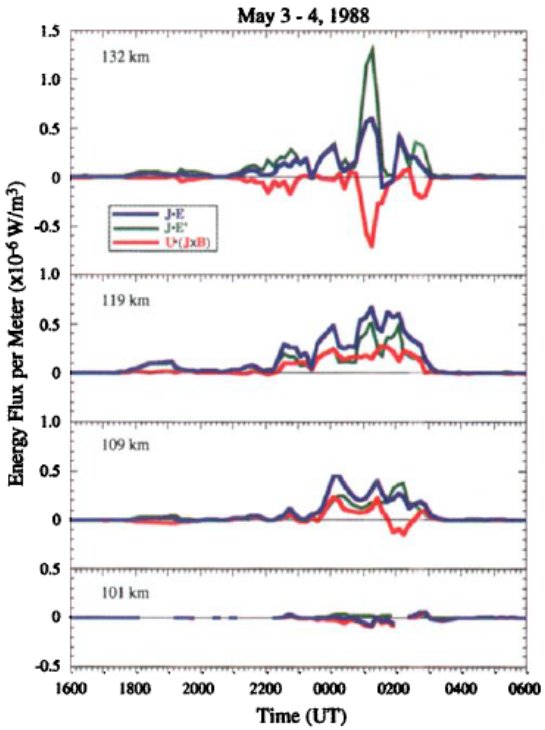
Thayer, 1998, 2000; Thayer and Semeter, 2004

$$Q_J = \sum_t n_t m_t \sum_k \nu_{tk}(\boldsymbol{u_n} - \boldsymbol{u_i})^2$$

Zhu and Ridley, 2016; Verkhoglyadova et al., 2017b

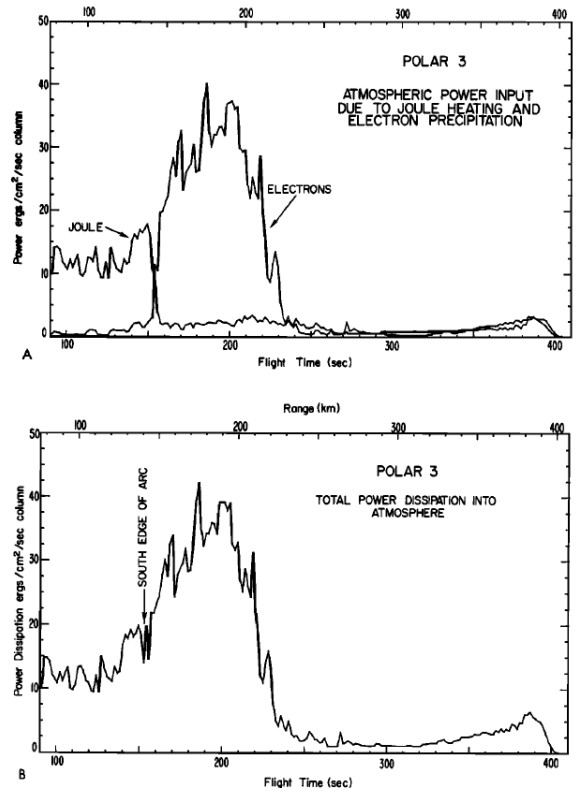
How do we estimate JH from observations?

Incoherent Scatter Radar



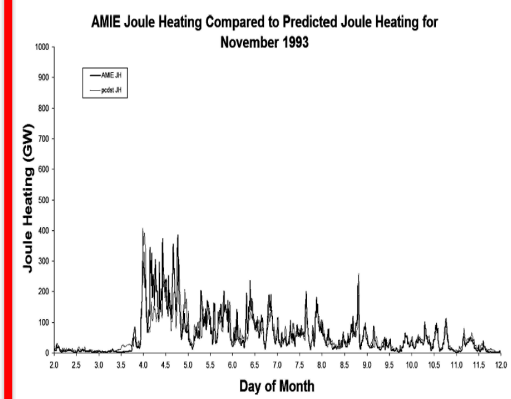
e.g., Thayer, 1998; Fujii et al., 1998; Fujii et al., 1999; Thayer, 2000, Cosgrove et al., 2009

Rocket-based Estimates



e.g., *Evans et al., 1977*; *Sangalli et al., 2009; Hurd et al., 2016*

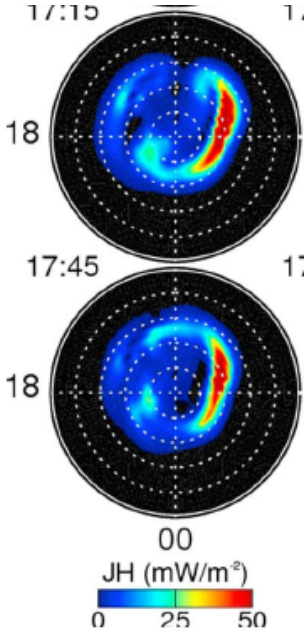
Satellite-based



The Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure

e.g., *Lu et al., 1995; Chun et al., 1999*; *Knipp et al., 2004; McHarg et al., 2005*

Modeling of the IT energy budget



Lu et al., 2016

Physics-based models:

TIEGCM, GITM, CTIPe, SAMI3, GEMINI
(Lu et al., 1995; 1998; 2010; 2016; Thayer et al., 1995; Deng and Ridley, 2007; Matsuo and Richmond, 2008; Deng et al., 2009; 2011; Zettergren et al., 2014; Zhu and Ridley, 2016; Verkhoglyadova et al., 2016; 2017; +)

Problem of mesoscale drivers:
First-principles models specify large-scale electromagnetic processes and are ill equipped to predict **small-scale energy fluxes and dissipation patterns** (*Codrescu et al., 2000; Deng and Ridley, 2007*)

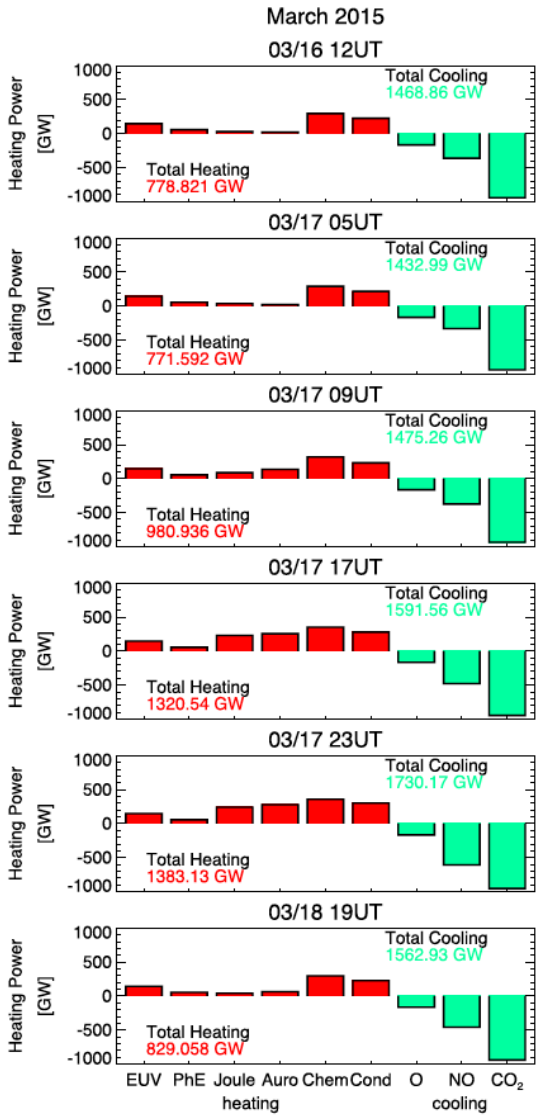
Empirical models (based on statistics):

- Joule heating: Northern hemisphere *(Knipp et al., 2004)*

$$\mathrm{JH(GW)} = 24.89 \times \mathrm{PC} + 3.41 \times \mathrm{PC}^2 + 0.41 \times \mathrm{Dst} + 0.0015 \times \mathrm{Dst}^2$$

- W05 based *(Weimer, 2005; Rastätter et al., 2016)*

Quantifying energy budget with GITM



GITM Modeling set-up: OMNI (solar wind), Weimer05 (high-latitude electrodynamics), Ovation Prime (auroral particle precipitation), F10.7 (solar EUV)

Modeled IT region: from 100 km to 600 km in altitude;

Energy partitioning:

Heating

- EUV heating
- Photoelectron heating
- **Joule heating**
- **Auroral heating**
- Other heating sources (chemical, etc.)

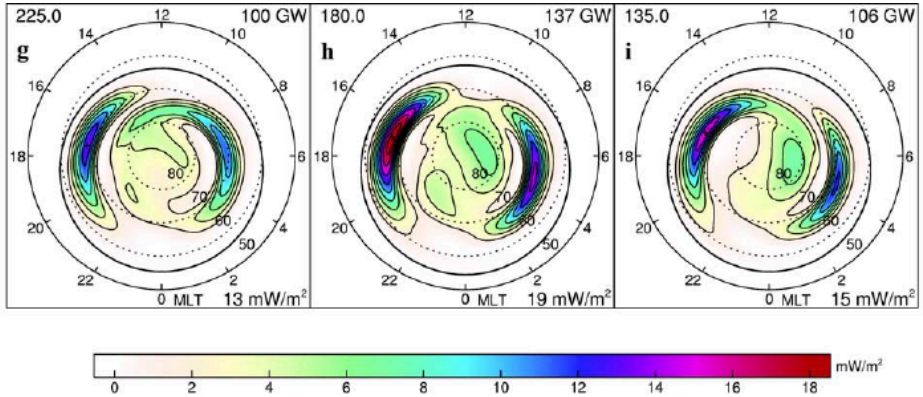
Cooling

- **NO cooling**
- O cooling
- **CO2 cooling**

The global height-integrated power budget for the March 2015 storm. The estimated values are averaged over the globe *(Verkhoglyadova et al., 2017).*

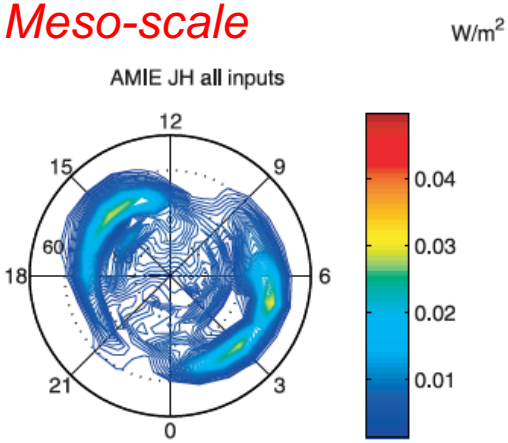
Joule heating across scales

Large scale



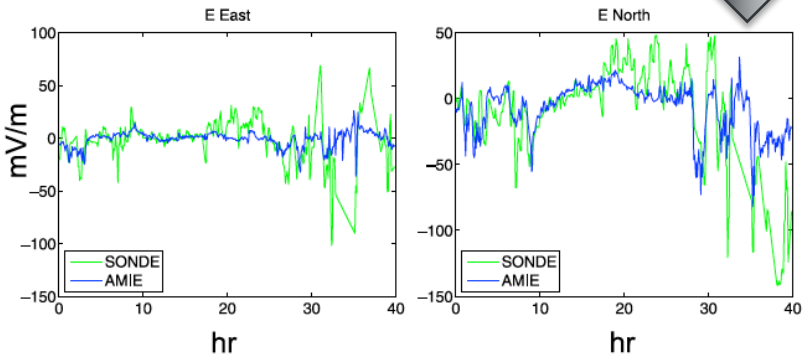
Empirical model at 110 km altitude (*Weimer, JGR, 2005*)

Meso-scale



AMIE reconstruction of Joule heating for 11:10 UT on 15 May 1997 (*McHarg et al., 2005*)

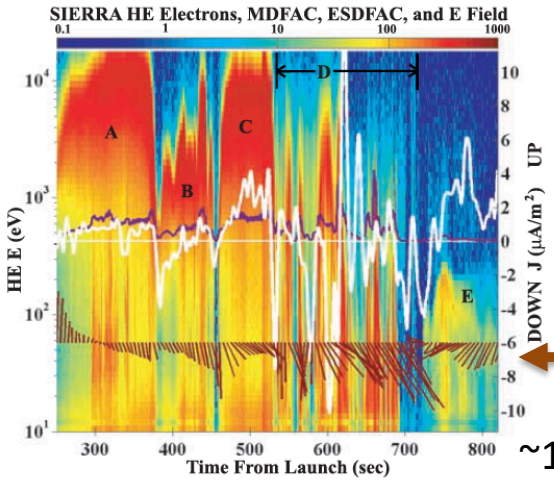
Small scale



Radar measurements: eastward and northward E components measured by Sondrestrom (green) and modeled by AMIE (blue) starting 9 Jan 1997 (*Cosgrove et al., 2009*) ~1-10s km

✓ ***JH estimation depends on spatial and temporal resolutions of the method***

Alfvénic processes: small scales



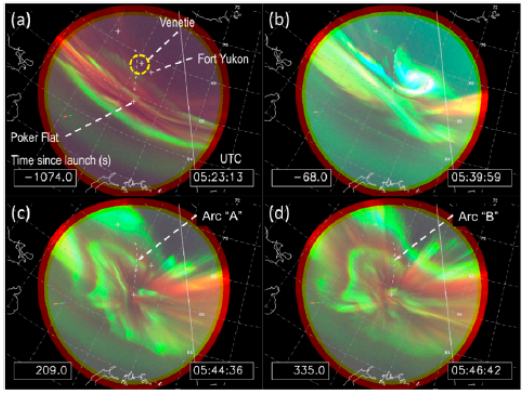
NASA SIERRA rocket mission (Klatt et al., 2005)

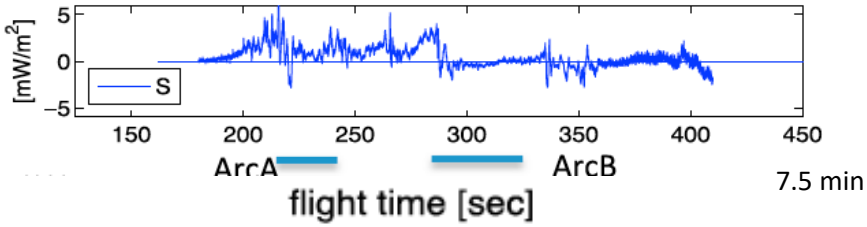
14 January 2002 above PFISR (<735 km)
Differential electron flux (left axis) and
FAC structures (right axis)

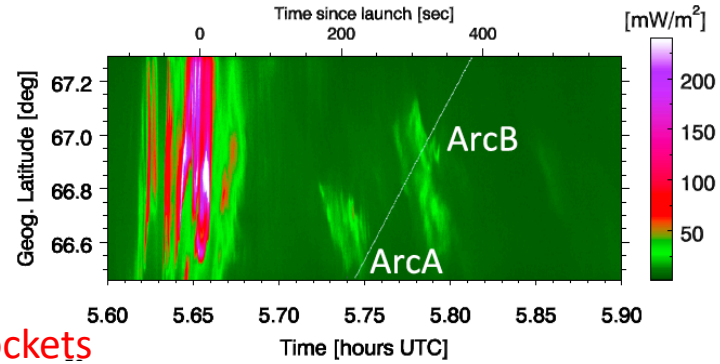
E field ~ 100 mV/m

~13 min

Ground-based + rocket campaign (Lynch et al., 2014):
Poynting flux from MICA on 19 Feb 2012 at <325 km







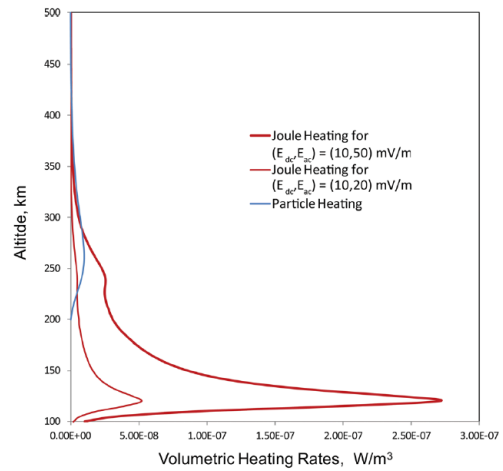
Under-utilized dataset for energy budget: sounding rockets

Wave contribution to the IT Energy Budget

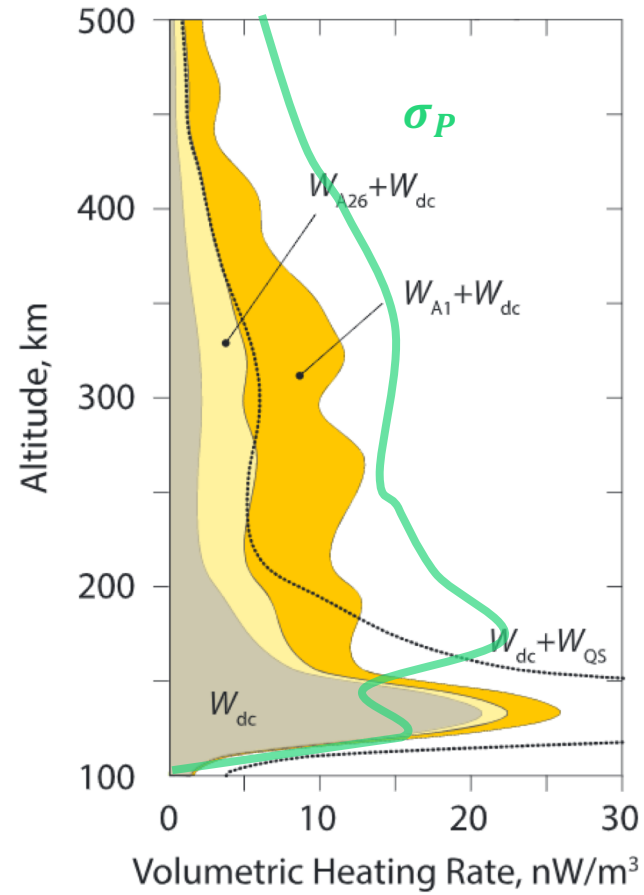
- *Observational and theoretical studies*

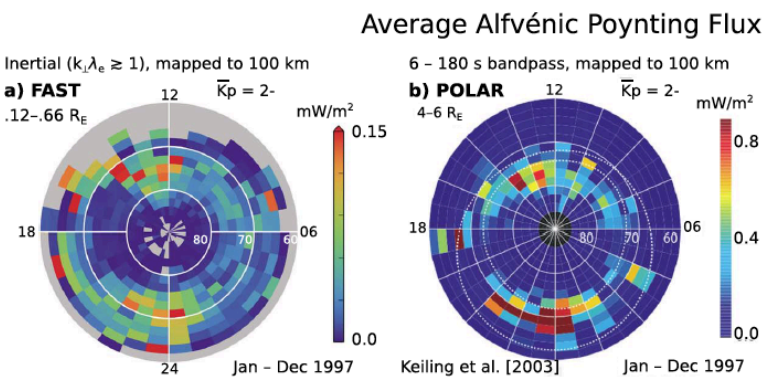
<u>Heating by Alfvén waves</u> (depending on the frequency range and propagation mode): Verkhoglyadova et al., 2018; Lotko et al., 2018)

AC field estimates taken from observations (Alebono, FAST) Brinkman et al., 2016



Lotko and Zhang, 2019





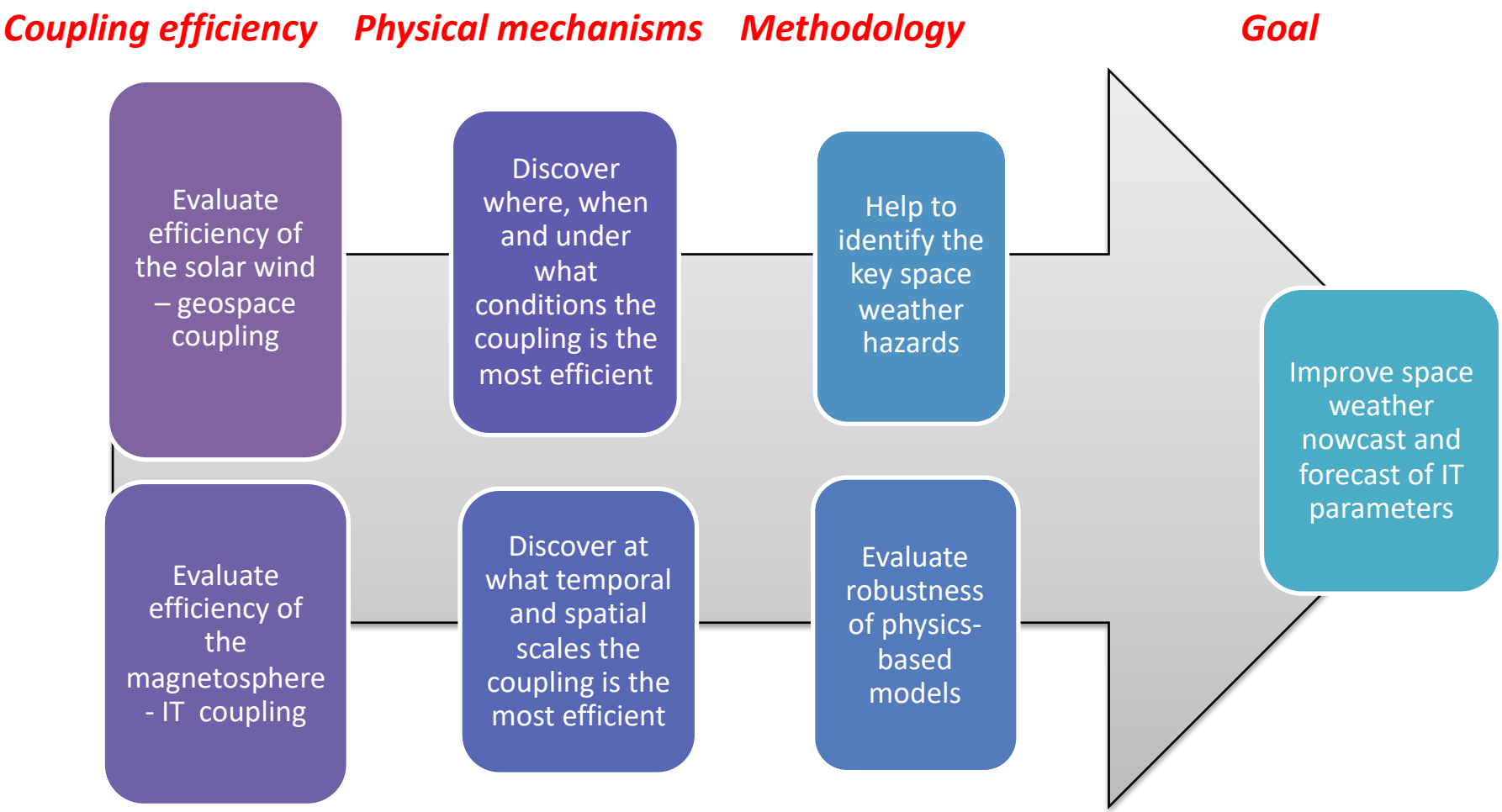
Hatch et al., 2017

Estimations of the e/m IT energy budget

source	Spatial scales			Temporal scales		
	Large >500km	Meso 150-500	Small <150km	Large >15min	Meso 1-10 min	Small ~min – 10s sec
Measurements and data assimilation: AMIE+ (Lu et al;, 1995; McHarg et al., 2005; +), radars (Thayer et al., 1998; Cosgrove et al., 2009; Sojka et al., 2009), sounding rockets (Sangalli et al., 2009)			coverage		campaigns	
Empirical models (JH_N, Weimer05-based JH, Cosgrove et al., 2011, …)					statistical	
Global Circulation Models or physics-based modeling (TIEGCM, GITM, …)			drivers?		event-based	dynamic effects?

- *Scale range definitions can vary for different physical parameters (in reference to particles, fields, currents)*

Importance of understanding energy budget for space weather



Global view ***Regional view***

Why the IT is affected? ***How?***

Electromagnetic energy impact:
Joule heating of IT potentially accounts for ~70 % of the input energy during storms (Turner at al., 2009)