EVALUATION OF THE EMPIRICAL SCALING OF JOULE HEATING RATES IN PHYSICS-BASED ATMOSPHERE-IONOSPHERE MODELS

6. NATIONALER WELTRAUMWETTERWORKSHOP

25 SEPTEMBER 2024

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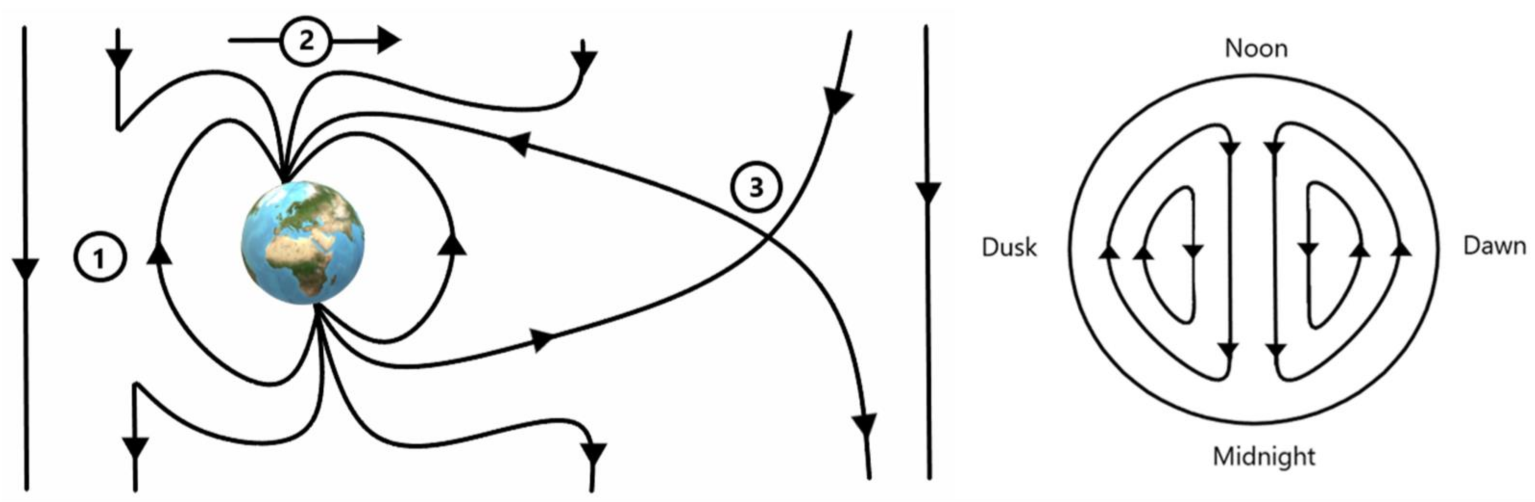
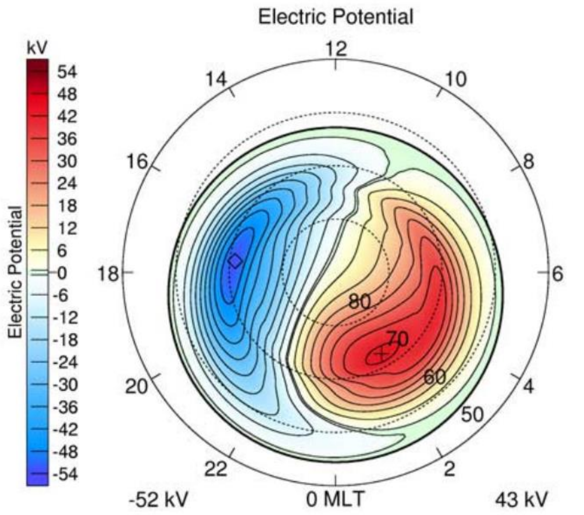
DLR

High-Latitude Joule heating in models



[Günzkofer, *PhD thesis*, LMU München, 2024]



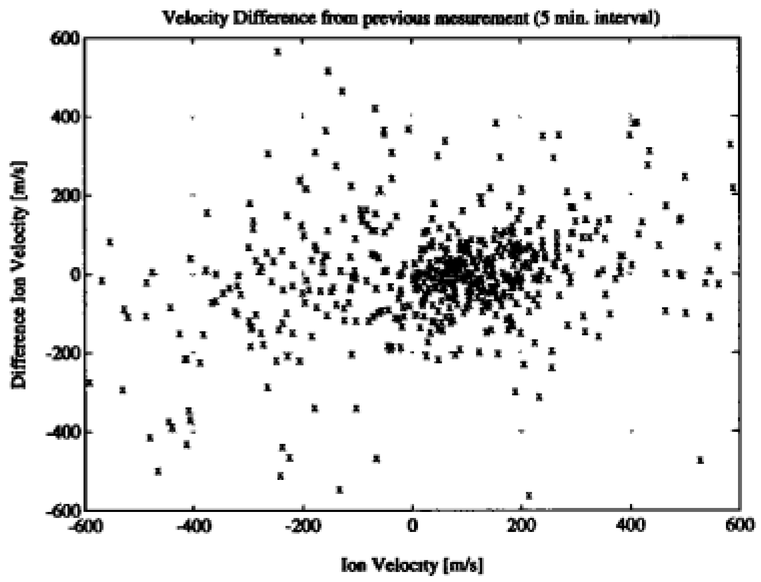
[Weimer, *J. of Geophys. Res.*, **110**, A05306, 2005]

- interaction of Earth‘s and interplanetary magnetic field lines leads to large-scale polar plasma convection
- electric fields propagate down along magnetic field lines into the ionospheric dynamo region
- resulting currents cause Joule heating (Pedersen currents) and geomagnetic disturbances (Hall currents)

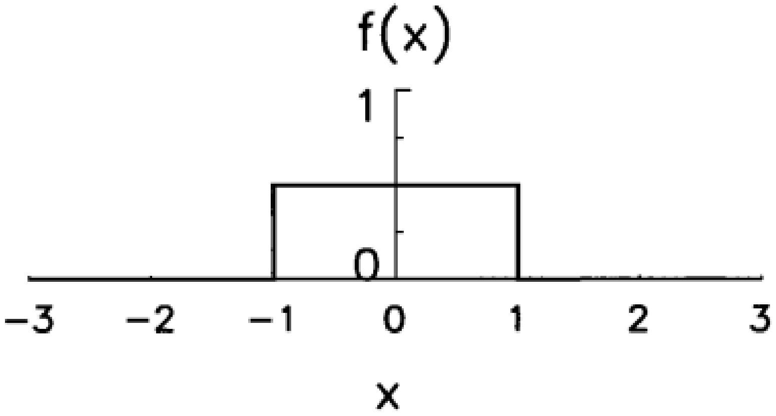
! Empirical plasma convection is commonly applied in ionosphere models !

convection model	parameter(s)
Heelis	*Kp*
Weimer	$B_y, B_z, v_{SW}, \rho_{SW}$
AMGeO (assimilative)	SuperDARN, SuperMAG, +

Empirical scaling factor (Codrescu *et al.*, 1995)



[Codrescu *et al.*, *Geophys. Res. Lett.*, **22**, 2393-2396, 1995]



$$\frac{|v_i - v_{i+5min}|}{v_i} \sim 1.5 \longrightarrow E = e_m + x \cdot e_v \quad (e_v \sim 1.5 e_m)$$

$$Q_J \propto \bar{E}^2 = \int_{-1}^{+1} (e_m + x \cdot e_v) \cdot f(x)\, \mathrm{d}x = e_m^2 + \frac{e_v^2}{3} \sim 1.5 e_m^2$$

$$\boldsymbol{Q_J \sim 1.5 \cdot Q_{J,m}}$$

JOULEFAC

Joule heating factor. This factor is multiplied by the joule heating calculation (see subroutine qjoule_tn in qjoule.F).

Data type: real

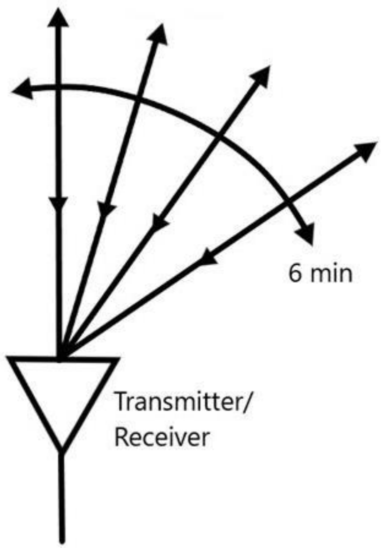
Default: 1.5

[from TIE-GCM userguide]

! BUT: JOULEFAC is based on a 6-hour, geomagnetically disturbed measurement period !

- geomagnetic activity
- local time
- latitude
- season (Emery *et al.*, 1999)

EISCAT electric field measurements (69°N, 19°E)



- 3D ion velocity measurements with EISCAT beam-swing campaigns
- two TIE-GCM runs with Heelis/Weimer convection

$$\boldsymbol{q_{J,E} = \sigma_P(N_{e,E}) \cdot E_E^2}$$

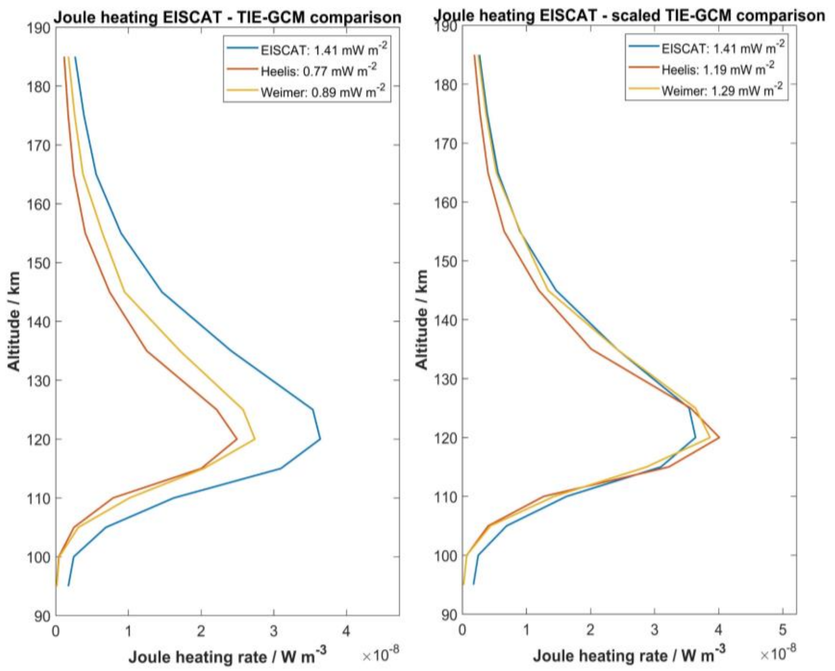
$$\boldsymbol{q_{J,m} = \sigma_P(N_{e,m}) \cdot E_m^2}$$

22-day campaign September 2005

$$\boldsymbol{Kp > 2}$$

Heelis: $\boldsymbol{f = 1.60}$

Weimer: $\boldsymbol{f = 1.41}$



Stochastic inversion, following Nygren *et al.*, (2011):

$$\boldsymbol{M} = \mathbf{A} \cdot \boldsymbol{x} + \epsilon \qquad \hat{\boldsymbol{x}} = \mathbf{Q}^{-1} \cdot (\mathbf{A}^T \cdot \mathbf{\Sigma}^{-1}) \cdot \boldsymbol{M}$$

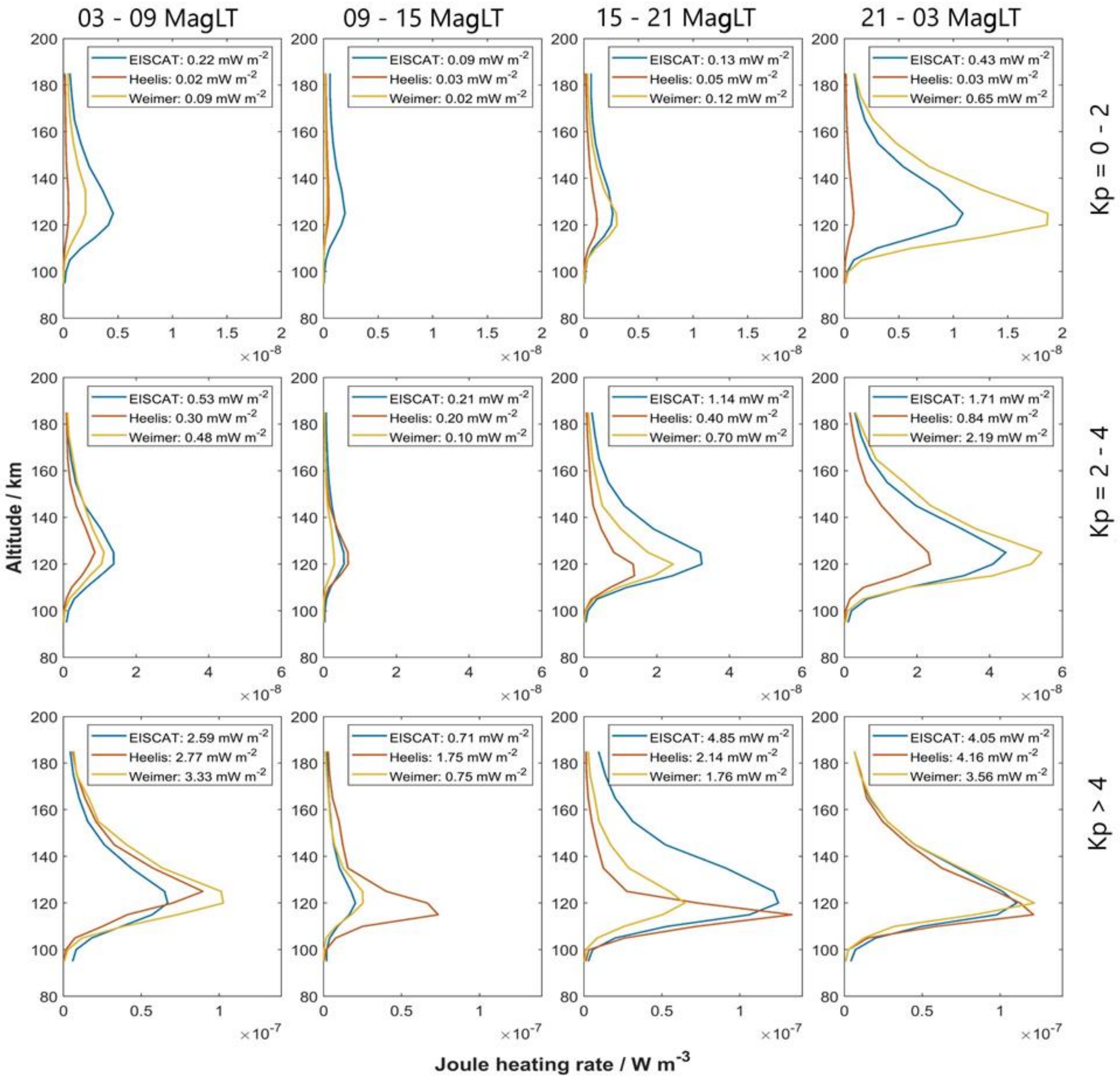
$\boldsymbol{M}$: measurement vector
$\mathbf{A}$: theory matrix
$\boldsymbol{x}$: unknow variables ($\boldsymbol{v}^F$)
ϵ: measurement uncertainties

$\hat{\boldsymbol{x}}$: most probable solution
$\mathbf{Q}$: Fisher information matrix
$\mathbf{\Sigma}$: covariance matrix of ϵ

$$\boldsymbol{E}_\perp = -\boldsymbol{v}^F \times \boldsymbol{B}$$

[Günzkofer *et al.*, *Earth Space Sci.*, **11**, e2023EA003447, 2024]

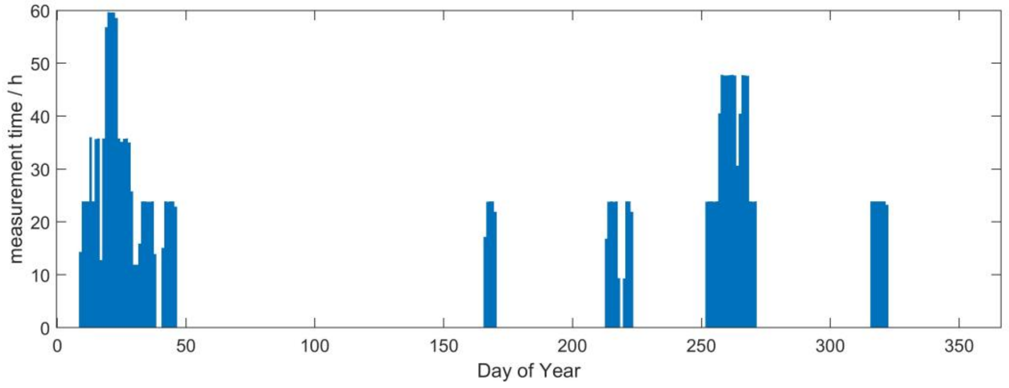
EISCAT CP2 database and method



[Günzkofer *et al.*, *Earth Space Sci.*, **11**, e2023EA003447, 2024]

total: ~ 2220 hours

2003 - 2017



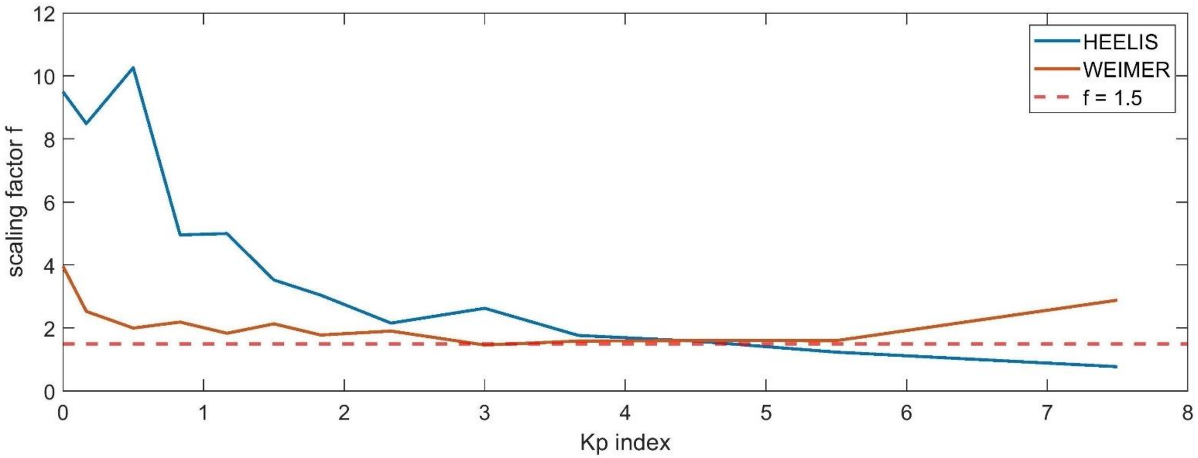
bin measurement/model q_J profiles with respect to

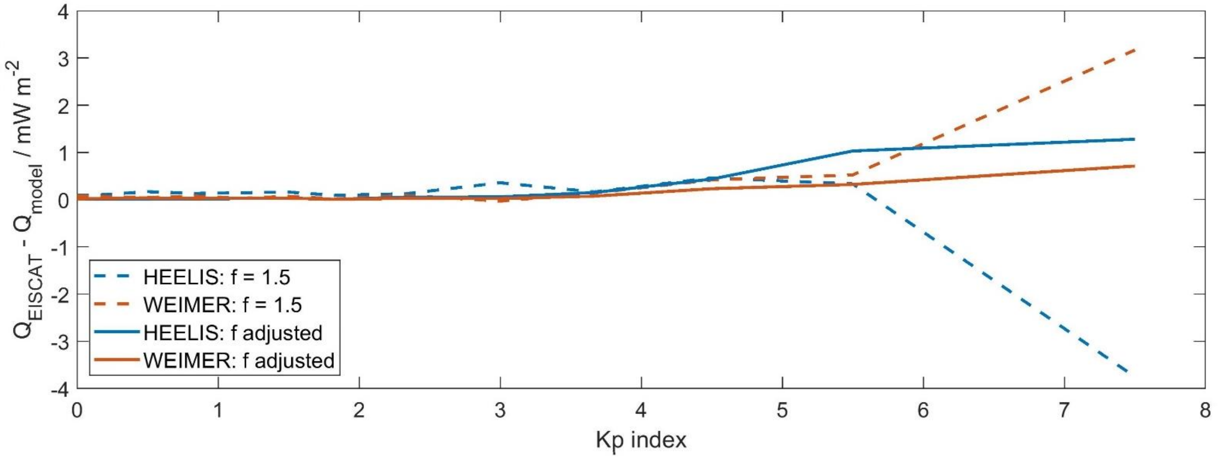
- Kp index
- Kan-Lee merging electric field (solar wind and IMF parameters)
- magnetic local time

determine scaling factor with non-linear least-square fit of Joule heating rate profiles:

$$q_{J,E}(h) = f \cdot q_{J,m}(h)$$

Required scaling factor - Kp





[Günzkofer *et al.*, *Earth Space Sci.*, **11**, e2023EA003447, 2024]

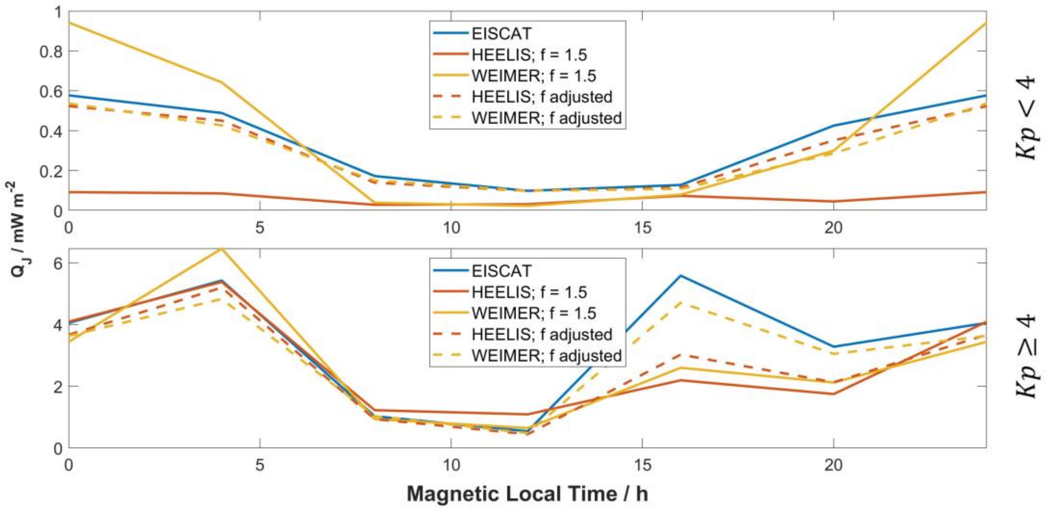
Table 4
Adjusted Scaling Factors f_H and f_W for Heelis- and Weimer-Driven Model Runs With Respect to Kp Index and E_{KL}

Kp	f_H	f_W	E_{KL} (mVm^{-1})	f_H	f_W
0	9.50	3.97	**0–0.1**	4.76	2.09
0.333	8.49	2.53	**0.1–0.2**	10.44	2.72
0.667	10.26	2.00	**0.2–0.35**	12.11	4.21
1	4.96	2.19	**0.35–0.5**	8.44	1.82
1.333	5.00	1.84	**0.5–0.7**	5.44	1.45
1.667	3.53	2.14	**0.7–0.9**	3.35	1.44
2	3.05	1.78	**0.9–1.15**	1.40	1.21
2.333–2.667	2.16	1.91	**1.15–1.6**	2.19	0.93
3–3.333	2.63	1.46	**>1.6**	1.38	0.67
3.667–4	1.77	1.59			
4.333–5	1.59	1.61			
5.333–6	1.24	1.60			
>6	0.77	2.89			

! **strong deviations from default $f = 1.5$ found** !

- low *Kp*: no major impact on absolute q_J/Q_J
- medium *Kp*: $f = 1.5$ works considerably well
- high *Kp*: low occurence

Required scaling factor – magnetic local time



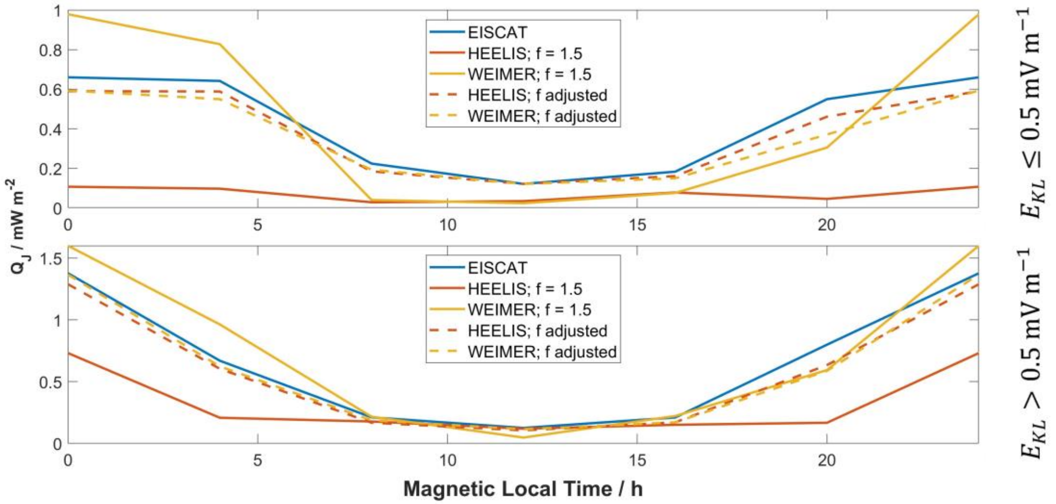


Table 5
Adjusted Scaling Factor f_H and f_W for Heelis- and Weimer-Driven Model Runs With Respect to the Kp Index and MagLT

Kp/MagLT	03–09	09–15	15–21	21–03
0–2	$f_H = 13.32$	$f_H = 5.59$	$f_H = 3.45$	$f_H = 18.91$
	$f_W = 3.16$	$f_W = 8.31$	$f_W = 1.40$	$f_W = 0.87$
2–4	$f_H = 2.68$	$f_H = 1.32$	$f_H = 3.57$	$f_H = 2.89$
	$f_W = 1.88$	$f_W = 2.90$	$f_W = 2.20$	$f_W = 1.24$
4–9	$f_H = 1.31$	$f_H = 0.46$	$f_H = 1.64$	$f_H = 1.43$
	$f_W = 1.04$	$f_W = 1.23$	$f_W = 3.28$	$f_W = 1.49$

Table 6
Adjusted Scaling Factor f_H and f_W for Heelis- and Weimer-Driven Model Runs With Respect to E_{KL} and MagLT

E_{KL} (mVm^{-1})/MagLT	03–09	09–15	15–21	21–03
0–0.2	$f_H = 8.90$	$f_H = 4.49$	$f_H = 5.61$	$f_H = 9.27$
	$f_W = 2.52$	$f_W = 6.62$	$f_W = 2.86$	$f_W = 1.00$
0.2–0.5	$f_H = 13.00$	$f_H = 7.62$	$f_H = 6.25$	$f_H = 21.15$
	$f_W = 3.42$	$f_W = 10.63$	$f_W = 1.18$	$f_W = 1.27$
>0.5	$f_H = 3.04$	$f_H = 1.28$	$f_H = 4.47$	$f_H = 2.92$
	$f_W = 1.51$	$f_W = 2.61$	$f_W = 1.30$	$f_W = 1.14$

[Günzkofer *et al.*, *Earth Space Sci.*, **11**, e2023EA003447, 2024]

- day-night variation:
  - Weimer-driven ↑
  - Heelis-driven ↓
- daytime Q_J underestimated for low Kp/E_{KL}
- afternoon Q_J underestimated for high Kp

Summary

1. Default Joule heating scaling factor $f = 1.5$ works considerably well as the general average

2. Distinct variations of the required scaling factor with **geomagnetic activity**, **magnetic local time**, and **plasma convection model**

3. Look-up tables with **corrected scaling factors** provided in **Günzkofer *et al.*, (2024)**

Outlook

1. Measurements:
   - Problem: single-point measurements
     ➔ no latitudinal or longitudinal variations
     ➔ including **PFISR (Fairbanks, Alaska)**
   - Problem: low time resolution for 3D ion velocity/electric field measurements
     ➔ apply **phased-array ISRs** (PFISR, EISCAT_3D)

2. Modelling:
   - do assimilative convection models perform better?
     ➔ **AMGeO convection model**
   - what impact has a higher time resolution on the model Joule heating rates?
     ➔ **high-res WACCM-X**

References:
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