Thermospheric density variation and its response to Joule heating during geomagnetic storms

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Background

- The neutral mass density variation associated with the induced satellite drag force plays an important role in the LEO spacecraft operations in the thermosphere, such as orbit maintenance, lifetime, and collision avoidance.

Re-enter the atmosphere

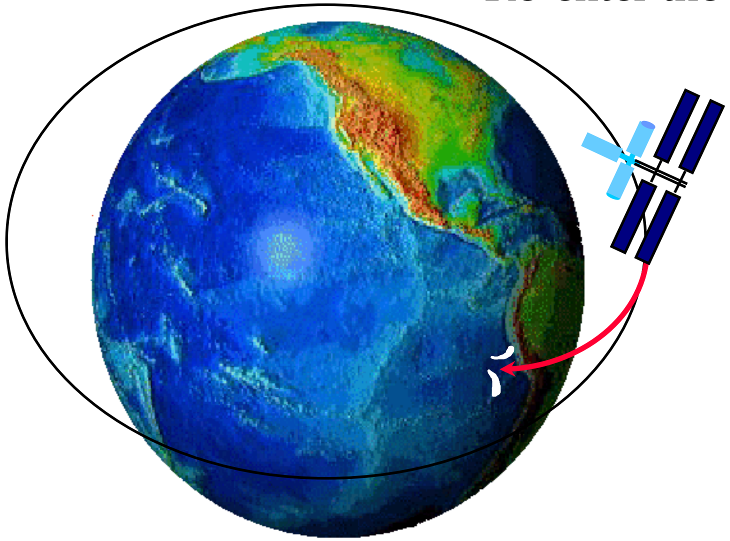
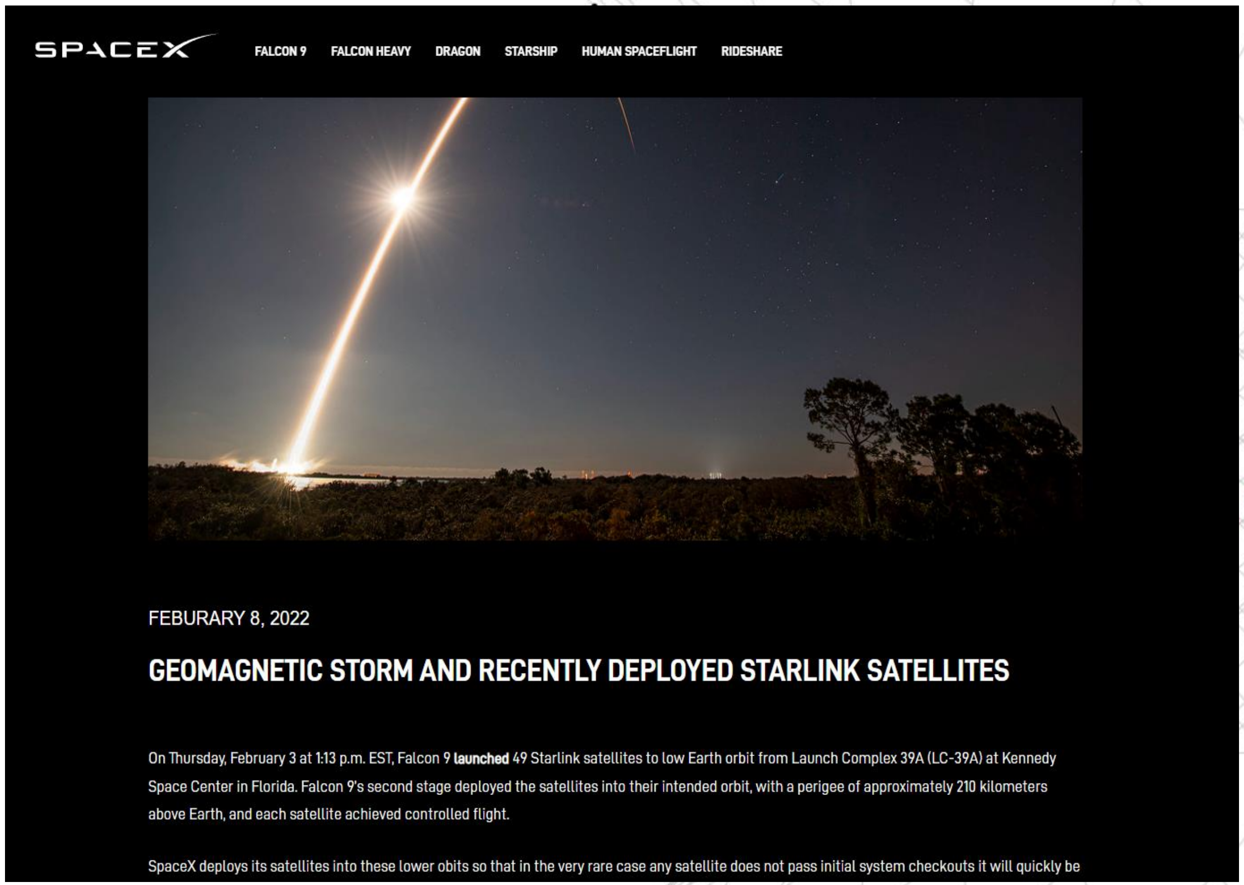


Figure 1. Early landing of spacecraft

- Example ---- February 03, 2022



SpaceX company launched 49 Starlink networking satellites. However, due to the strong impact of the subsequent Storm, the neutral mass density of the atmosphere in LEO increased. The air drag increased at about 200 km sharply by 50%, causing satellites in normal condition to quickly re-enter the atmosphere before they could raise their orbits.

Thermospheric Density

- Data Sources： Neutral Mass Density from **CHAMP** and **GRACE** satellites at **400 km** during **2002-2008**; **NRLMSISE-00** Model

- Storm Levels (Classify)： **Dst Indices**; Weak, Moderate and Intense Geomagnetic storms (**265**) (Srivastava and Venkatakrishnan, 2004) and (Gonzalez et al., 1999)

Table 1 Geomagnetic storm list

	Weak geomagnetic storm	Moderate geomagnetic storm	Intense geomagnetic storm
Dst	-49 nT < Dst≤ -30 nT	-99 nT < Dst≤ - 50 nT	Dst≤ -100 nT
Spring	40	30	12
Summer	28	17	12
Autumn	26	28	12
Winter	29	28	3
Total Number	123	103	39

Joule heating

During geomagnetic storms, the energy input mainly comes from Joule heating, which can take up to **two-thirds of the energy** being deposited into the thermosphere.

(Knipp et al., 2004; Lu et al., 2016; Wilson et al., 2006).

Joule heating $Q_J = \sigma_P (\mathbf{E} + \mathbf{u} \times \mathbf{B})^2$ (Aikio et al., 2012; Fuller-Rowell et al., 2013)

where σ_P is Pedersen conductivity, **E** is the electric field, **u** is the neutral wind velocity, and **B** is the geomagnetic field.

Height-integrated Joule heating $\Sigma_Q = \Sigma_p \boldsymbol{E}^2$ (Lu et al., 1995)

where Σ_p is the height-integrated Pedersen conductance and **E** is the convection electric field.

Height-integrated Pedersen conductance (Hardy et al., 1987; Robinson et al., 1987)

$$\Sigma_{p(solar)} = 0.88\sqrt{s_a \cos\theta}$$ (Robinson and Vondrak, 1984)

$$\Sigma_{p(elec)} = \frac{40E_0}{16+E_0^2}\sqrt{I}$$ (Hardy et al., 1987)

Storm-----November 20-21, 2003

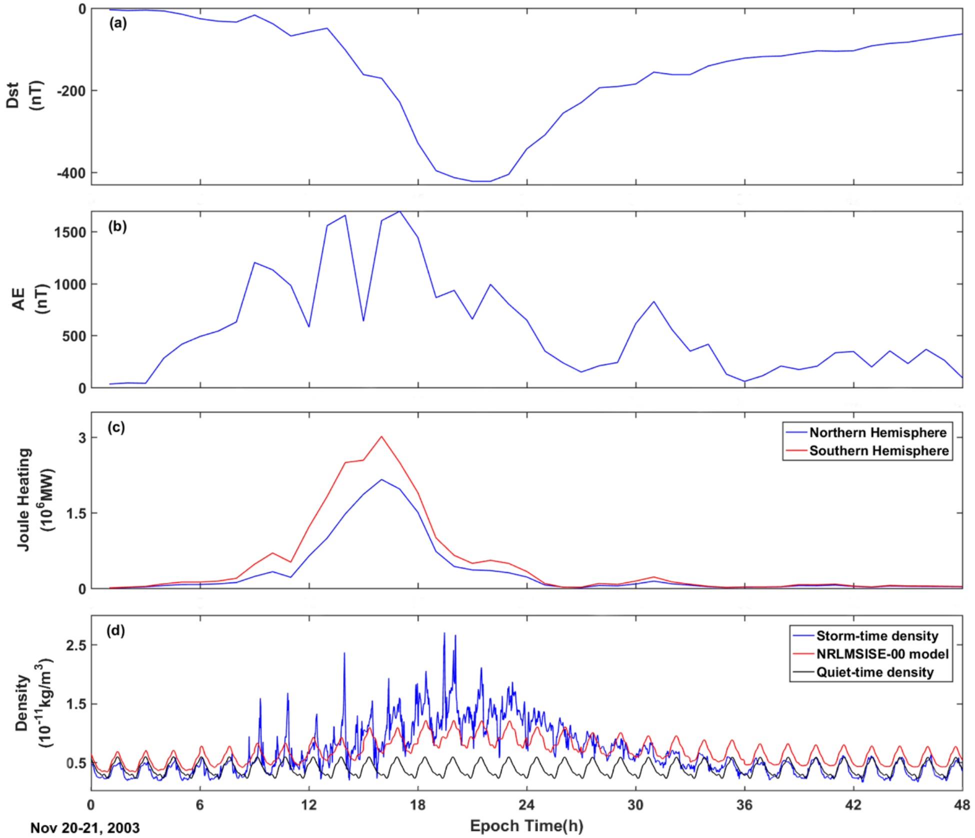


Figure 1. The temporal variations of different parameters under the intense geomagnetic storm event on November 20-21, 2003. (a) Dst index, (b) AE index, (c) total integrated Joule heating for northern (blue line) and southern hemisphere (red line), (d) thermospheric density observed from the CHAMP satellite (blue line) measurement, NRLMSISE-00 model (red line) simulation, compared with the prediction of the NRLMSISE-00 in the quiet time (black line)

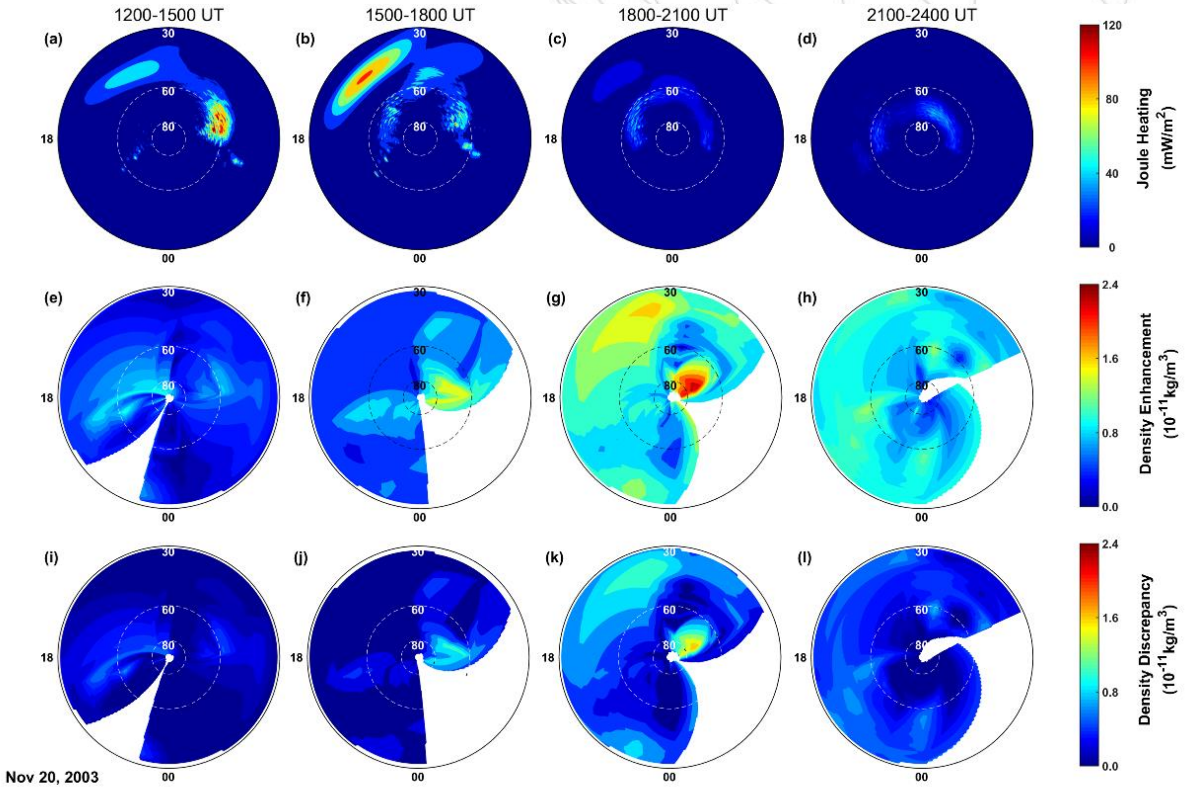


Figure 3. Intense geomagnetic storm event of November 20, 2003. (a-d) 3-hour averaged height-integrated Joule heating, (e-h) thermospheric density enhancement, and (i-l) thermospheric density discrepancy, at 1200UT-1500UT, 1500-1800UT, 1800-2100UT, and 2100-2400UT, respectively. The patterns are plotted in latitude versus local time coordinates, with the center of the pattern corresponding to the North Pole and the outer circle corresponding to 30° N.

(Wang et al., 2021)

Time relationship

The delay time of density

- Weak, 61% storms at 0 ~ 1 hour
- Moderate, 60% storms at 1 ~ 2 hours
- Intense, 54% storms at 3 ~ 5 hours
- As storms intensify, density delays Joule heating for longer time.

The peak duration of Joule heating

- Weak and Moderate, 0 ~ 2 hours.
- Intense, 1 ~ 3 hours, longer than weak and moderate.

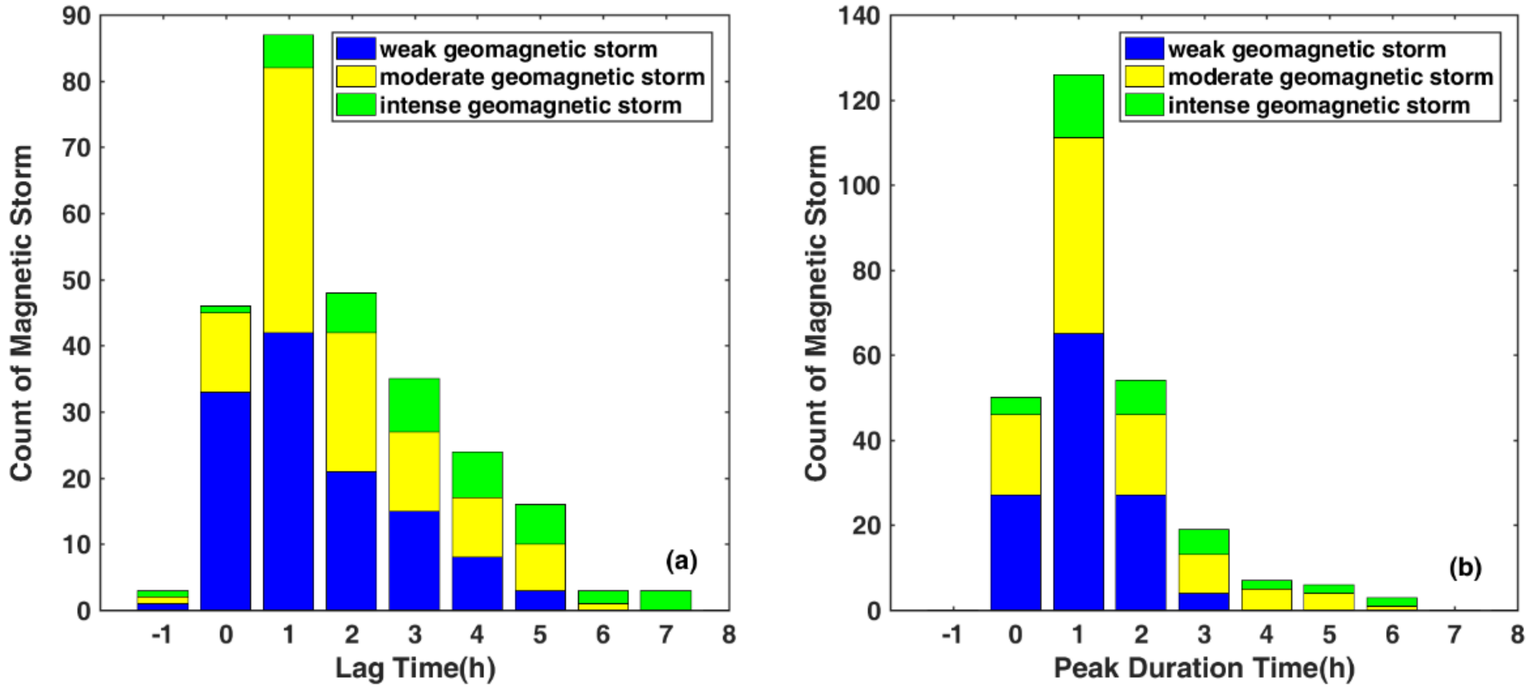


Figure 4. (a) Lag time of thermospheric density and (b) peak duration time of Joule heating during weak, moderate, and intense geomagnetic storms. The results for weak, moderate, and intense geomagnetic storms are shown in blue, red and black, respectively.

(Wang et al., 2020)

Latitude difference

Latitude Difference

- Weak, 50% storms at 0°-5°
- Moderate, 45% storms at 5°-10°
- Intense, 50% storms at 10°-20°
- As storms intensify, Joule heating enhances thermospheric density at remote poleward (higher) latitudes.

LT (local time) Difference

- Weak and Moderate, 87% storms at -8 ~ 8 LT
- Intense, 79% storms at -4 ~ 4 LT
- Thus, the density is closer to Joule heating with LT as storms intensify.

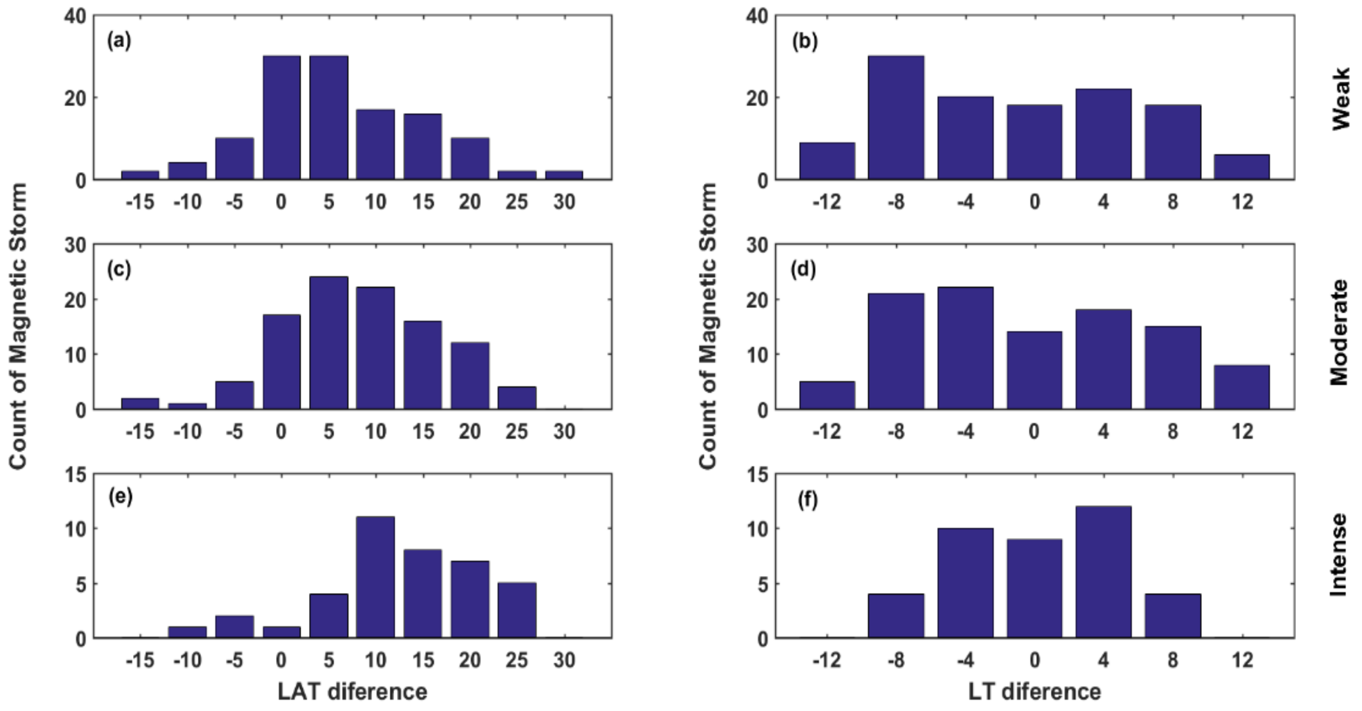


Figure 4. Latitude difference (left column), and LT difference (right column) between peak Joule heating and peak thermospheric density enhancement during weak (a-b), moderate (c-d), and intense geomagnetic storms (e-f) from 265 geomagnetic storm cases. Positive latitude and LT differences mean that density enhancement occurs at higher latitude and later local time than Joule heating.

(Wang et al., 2021)

Statistics for Time Difference (Dst with AE, Denisty with Joule heating)

Dst and AE

Dst lag AE:

- Weak: 1 hour
- Moderate: 1-2 hours
- Intense: 3-5 hours
- As storms intensify, Dst delays AE for longer time.

Density and Joule heating

Density lag JH:

- Weak: 0-1 hour
- Moderate: 1-2 hours
- Intense: 3-5 hours

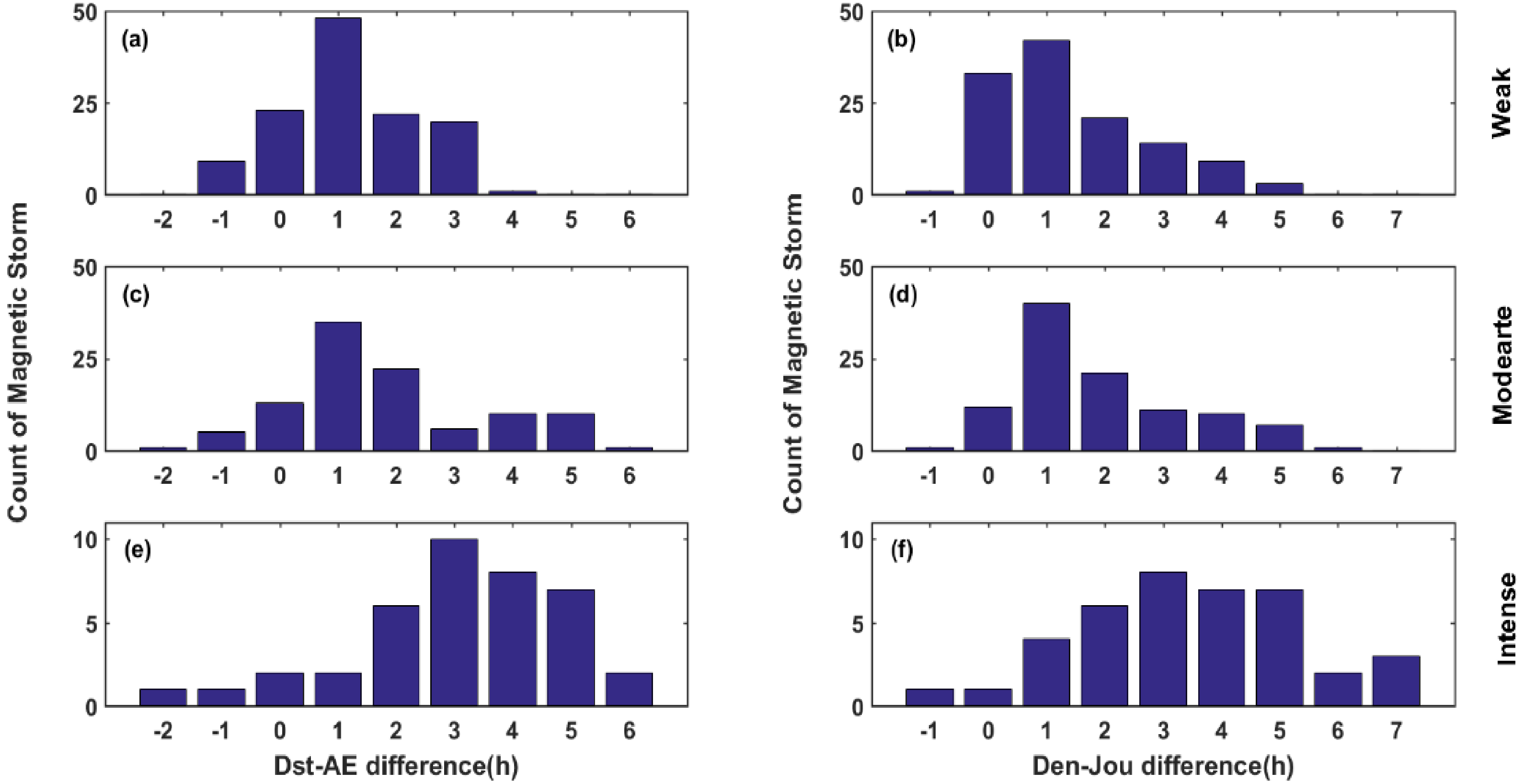


Figure 3. (Left column) Time difference between peak Dst and peak AE, and (right column) between peak thermospheric density and peak Joule heating during (a, b) weak, (c, d) moderate, and (e, f) intense geomagnetic storms from 265 geomagnetic storm cases.

Statistics for Time Difference (Density with Dst and AE)

Density and Dst

Dst lag Density:

- Weak and Moderate: 0-1 hour
- Intense: 0-2 hours
- Dst indices delay
- The time difference is about 1 hour during storms.

Density and AE

Density lag AE:

- Weak: 0-1 hour
- Moderate: 0-2 hours
- Intense: 2-4 hours
- The time difference increases as geomagnetic storm intensifies.

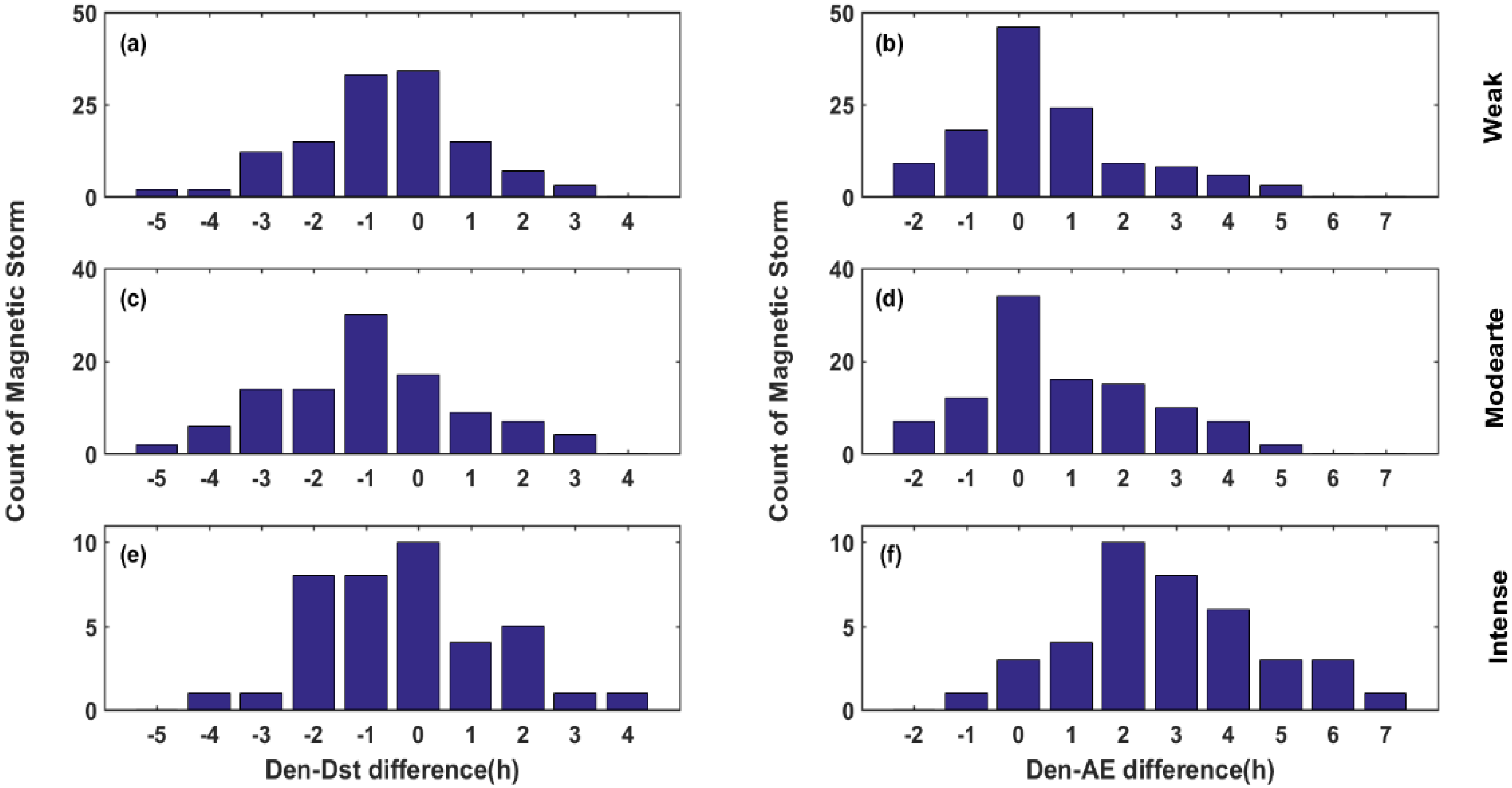


Figure 2. (Left column) Time difference between peak thermospheric density and peak Dst, and (right column) between peak density and peak AE during (a, b) weak, (c, d) moderate, and (e, f) intense geomagnetic storms from 265 geomagnetic storm cases.

Statistics to calculate correlation

- **Density enhancement:** storm-time - quiet-time
- **Density discrepancy:** observation - model

The correlation coefficient (r) of density enhancement with

- Dst (0.77),
- AE (0.64),
- Joule heating (0.70)
- density discrepancy (0.97)

- The positive correlation is well established during geomagnetic storms.

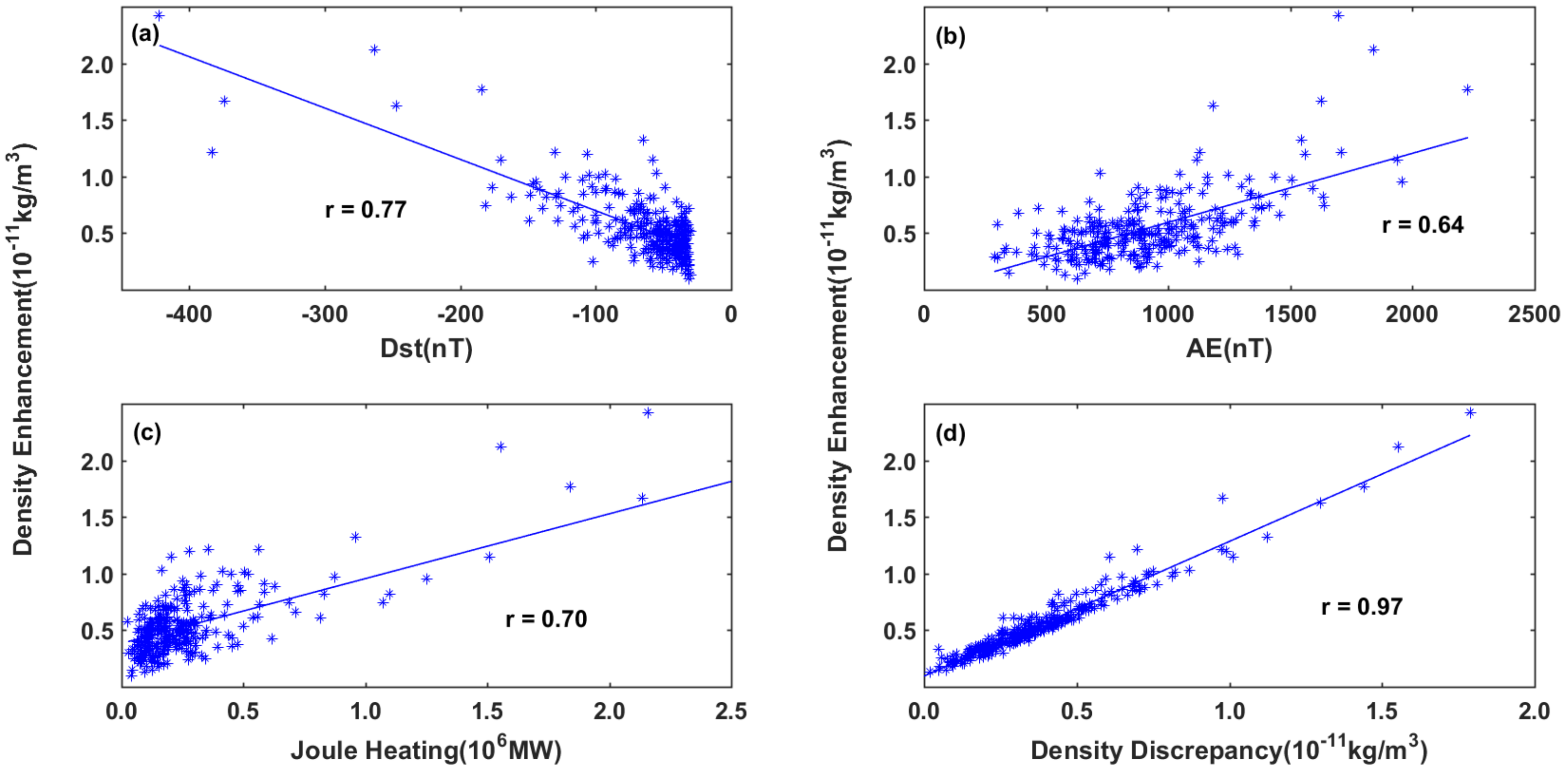


Figure 4. Distribution of peak thermospheric density enhancement and (a) Dst, (b) AE, (c) peak Joule heating and (d) peak density discrepancy for 265 geomagnetic storms cases.

Statistics to test calibration results

- The original NRLMSISE-00 model underestimate the peak density observation during geomagnetic storms
- The calibration results simulate thermospheric density better than the NRLMSISE-00 model.
- MRE(Mean Relative Error) decrease from 40% to 10%.

$$\text{MRE} = \frac{observation - model}{observation}$$

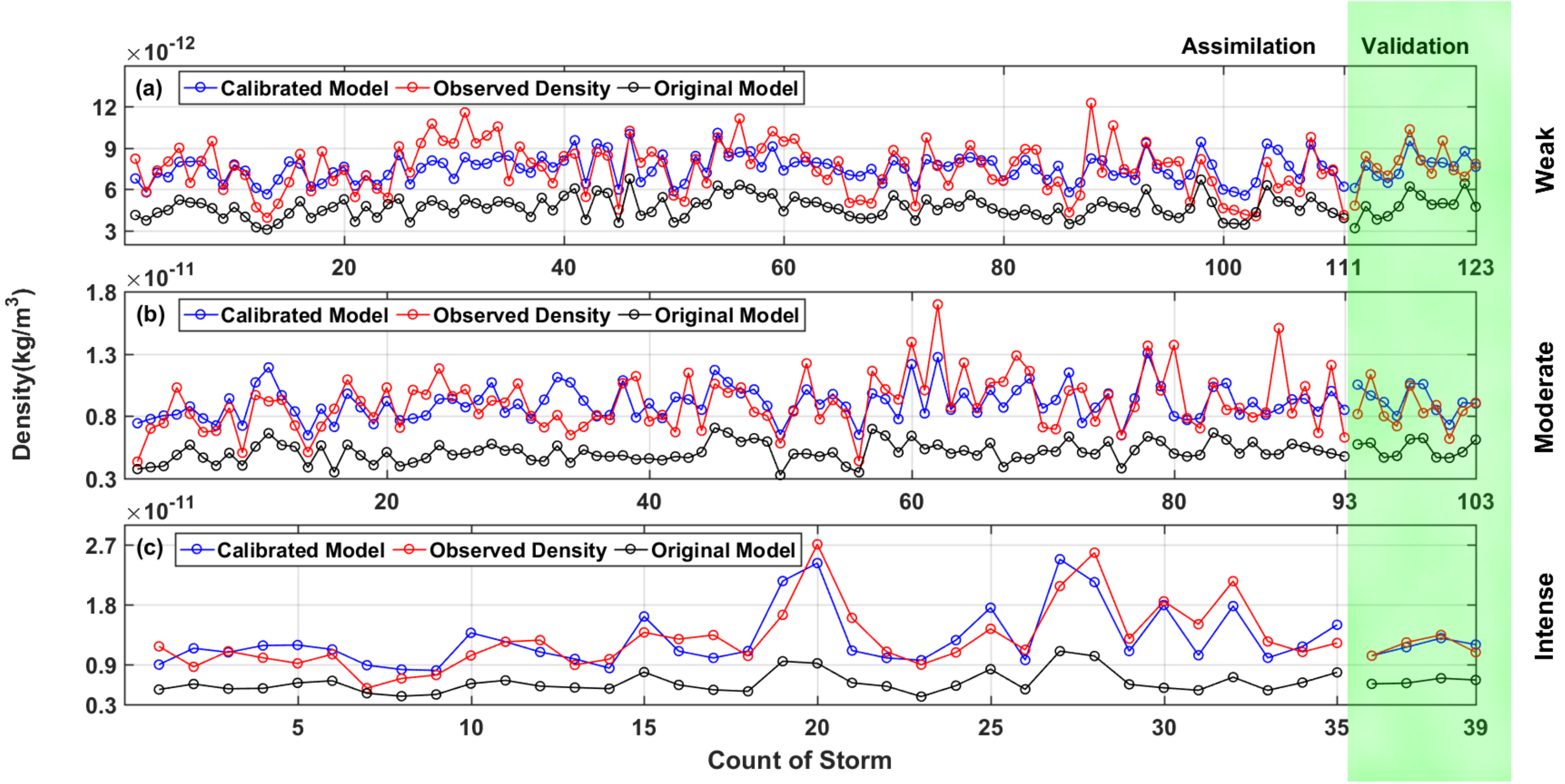


Figure 6. The calibrated density (blue line), the observed density (red line), and the density from original NRLMSISE-00 (black line) during (a) weak, (b) moderate, and (c) intense geomagnetic storms. The density with white background is assimilation on the left of the Figure and validation is shown on the right with green background.

Summary:

1. Thermospheric density delays Joule heating during geomagnetic storms. The time lag is about 0-2 hrs during weak and moderate storms, while it is 3-5 hrs for intense storms.

2. The peak duration of Joule heating increases for more intense geomagnetic storms..

3. Joule heating can affect the density enhancement at higher latitude regions. The latitudinal difference between thermospheric density and Joule heating is about 0° -10° during weak and moderate geomagnetic storms, while it increases to 10° -15° for intense storms.

4. Joule heating, Dst, AE indices can be used to assimilate thermospheric density model NRLMSISE-00 during geomagnetic storms. The calibrated NRLMSISE-00 model results can better simulate the storm-time thermospheric density, with the MRE between observation and model decreasing from 40% to 10%.

More details can be found:

1. **Wang, X.,** Miao, J., Aa, E., Ren, T., Wang, Y., & Liu, J., et al. (2020). Statistical analysis of Joule heating and thermosphere response during geomagnetic storms of different magnitudes. Journal of Geophysical Research: Space Physics, 125, e2020JA027966. https://doi.org/10.1029/2020JA027966

2. **Wang, X**., Miao, J., Lu, X., Aa, E., Liu, J., Wang, Y., & Liu, S. (2021). Latitudinal impacts of Joule heating on the high-latitude thermospheric density enhancement during geomagnetic storms. Journal of Geophysical Research: Space Physics, 126, e2020JA028747. https://doi.org/10.1029/2020JA028747.

3. **Wang, X.,** Miao, J., Lu, X., Aa, E., Luo, B., Liu, J., et al. (2022). Using temporal relationship of thermospheric density with geomagnetic activity indices and Joule heating as calibration for NRLMSISE-00 during geomagnetic storms. Space Weather, 20, e2021SW003017. https://doi.org/10.1029/2021SW003

Thank you