The effect of South Atlantic Anomaly on ring current electron dynamics

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Abstract

The South Atlantic Anomaly (SAA) affects particle evolution and loss processes in the inner magnetosphere. However, the impact of the SAA on ring current particles and the energy dependence of precipitation remain unclear. Using the Storm-Time Ring Current Model (STRIM) that accounts for the SAA effect, we simulate a storm event to demonstrate the effect of the SAA on electron precipitation. Results show that electron precipitation near the SAA is significantly greater than in other regions around L = 4. Furthermore, wave-particle interactions can further promote high-energy (tens and hundreds of keV) electron precipitation near the SAA, leading to decay into the ionosphere. Comparisons with in-situ observations indicate that simulations incorporating the SAA effect better capture the intensity and variations of electron precipitation. This study emphasizes the necessity of including the SAA effect in models for accurately interpreting ring current electron dynamics and the north-south asymmetry of electron precipitation.

Storm Time Ring Current Model (STRIM)

$$\frac{\partial Q}{\partial t} + \frac{1}{L^2}\frac{\partial}{\partial L}\left(L^2\left\langle\frac{dL}{dt}\right\rangle Q\right) + \frac{\partial}{\partial \phi}\left(\left\langle\frac{d\phi}{dt}\right\rangle Q\right) + \frac{1}{\gamma p}\frac{\partial}{\partial E}\left(\gamma p\left\langle\frac{dE}{dt}\right\rangle Q\right) + \frac{1}{h(\mu_0)\,\mu_0}\frac{\partial}{\partial \mu_0}\left(h(\mu_0)\,\mu_0\left\langle\frac{d\mu_0}{dt}\right\rangle Q\right) = \left\langle\frac{\delta Q}{\delta t}\right\rangle_{loss} + \left\langle\frac{\delta Q}{\delta t}\right\rangle_{lc}$$

- Solves bounce-averaged ring current electron distribution $Q\ (L,\phi,E,\mu,t)$ in the equatorial plane
- Loss process:
  - **Chorus and Hiss** wave interactions
  - Atmospheric losses
  - **SAA**: $\left\langle\frac{\partial Q}{\partial t}\right\rangle_{lc} = -\frac{Q}{\tau_{lc}}$ $\quad \tau_{lc} = \frac{1}{2}\tau_B$

(1) **Average** method

$$\tau_B = \frac{2}{v}\int_b^a \frac{ds}{\sqrt{1-\frac{B(s)}{B_m}}}$$

(2) **Separate** method

$$\tau_B = \frac{4}{v}\int_0^a \frac{ds}{\sqrt{1-\frac{B(s)}{B_m}}}$$

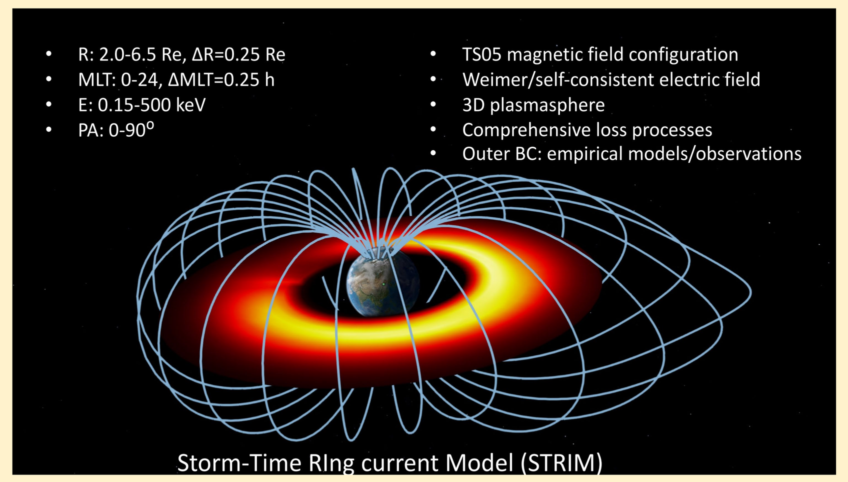


Figure 1. An illustration of STRIM

- where τ_{lc} and τ_B represent the loss and bounce periods, a and b represent the mirror points.

Fengyun-3E (FY-3E)

Electron precipitating observation from the Medium Energy Electron Detector (MEED) onboard FY-3E spacecraft. The FY-3E satellite is a Chinese near-polar meteorological satellite in a sun-synchronous orbit at an altitude of ~ 836 km, with an orbital inclination of 98.75°. Its orbital period is about 100 minutes, completing 14 full orbits per day.

MEED is capable of providing the energy spectrum of **30–600 keV** electrons and **full pitch angle** distribution in LEO orbits, with a time resolution of 2 seconds.

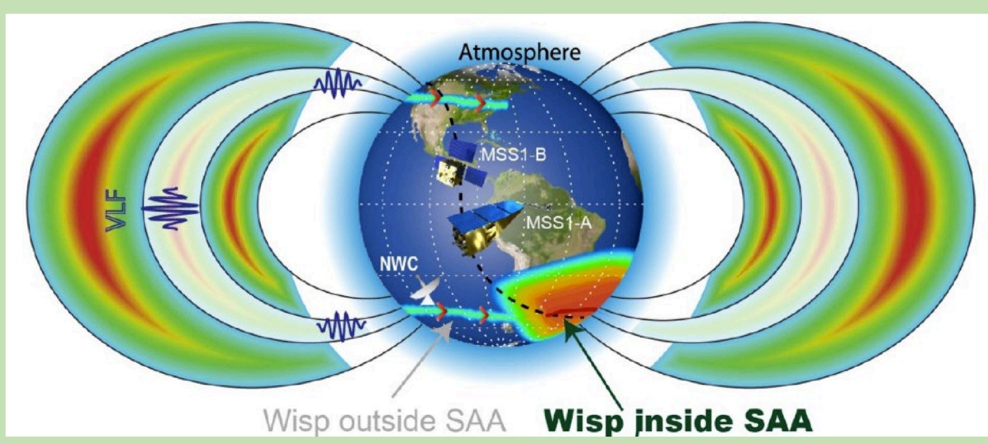


Figure 2. Schematic diagram of the FY-3 satellite orbit (from Sun et al. (2024) Figure 7)

♦ STRIM results (April 10, 2022, Dst_{min} = - 65)

The Dst index rapidly dropped to its minimum of -65 nT around 07:00 UT before entering the recovery phase. Compared to the Average method, the Separate method results in a lower Dst during the main phase, yielding a better match with the observation.

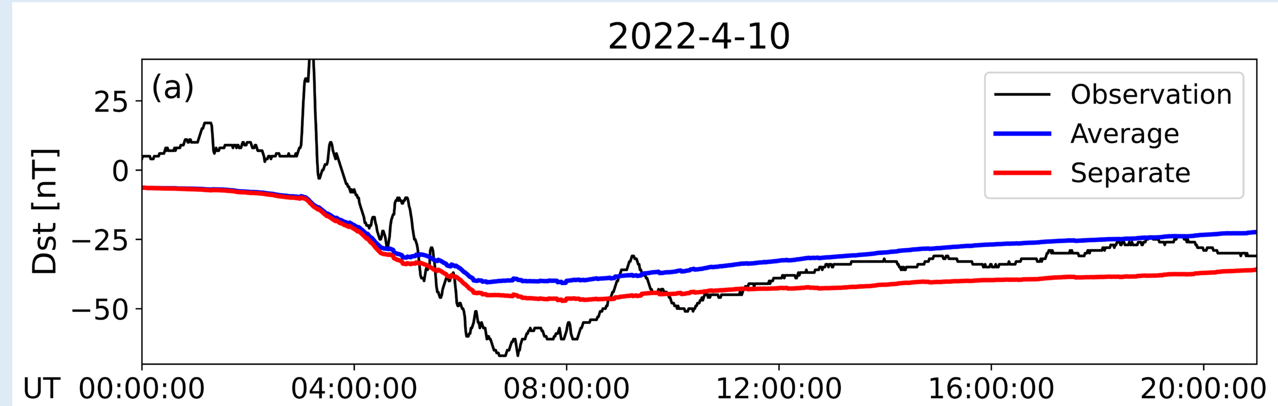
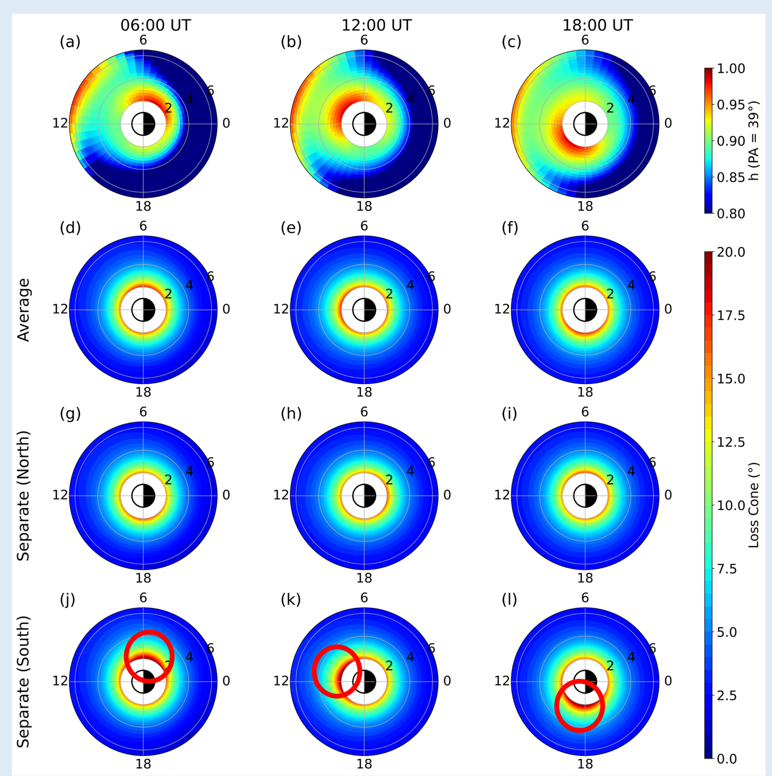


Figure 3. The simulated Dst index derived by Average (blue) and Separate (red) methods and the observed Dst index (black).

♦ SAA features: h parameter and loss cone



The h is proportional to the particle's bounce period and defined as:

$$h(\mu_0, R_0) = \frac{1}{2R_0}\int_b^a \frac{ds}{\sqrt{(1-B(s)/B_m)}}$$

The weakened magnetic field surrounding the SAA region enlarges the loss cone, enhancing the loss of ring current particles.

Figure 4. (a-c): The h of 40° electrons at 06:00 (a), 12:00 (b) and 18:00 UT (c). (d-l): Loss cones derived by the Average (d-f) and Separate (g-l) methods.

♦ SAA effects on the distribution of ring current electrons

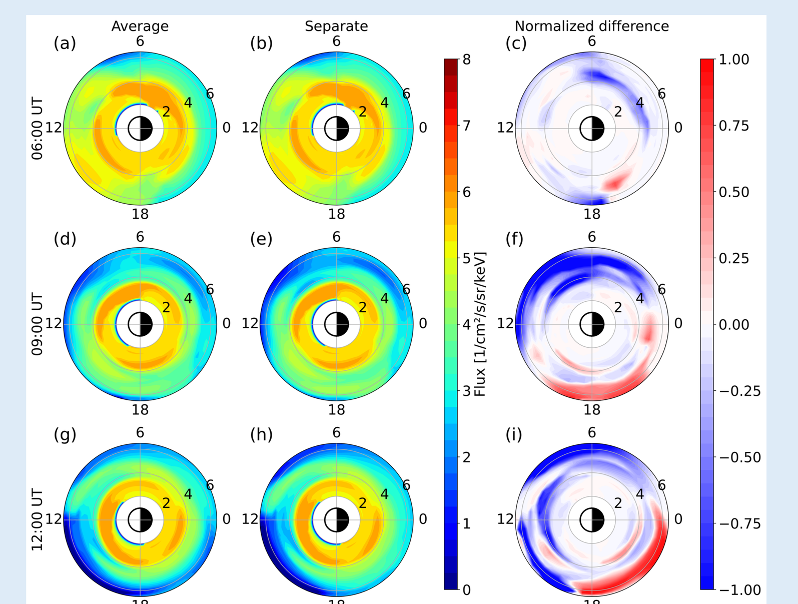


Figure 5. Flux of 5 keV electrons with 45° pitch angle calculated by Average (a, d, g) and Separate (b, e, h) methods at 06:00 UT, 12:00 UT and 18:00 UT. The normalized difference between the two methods.

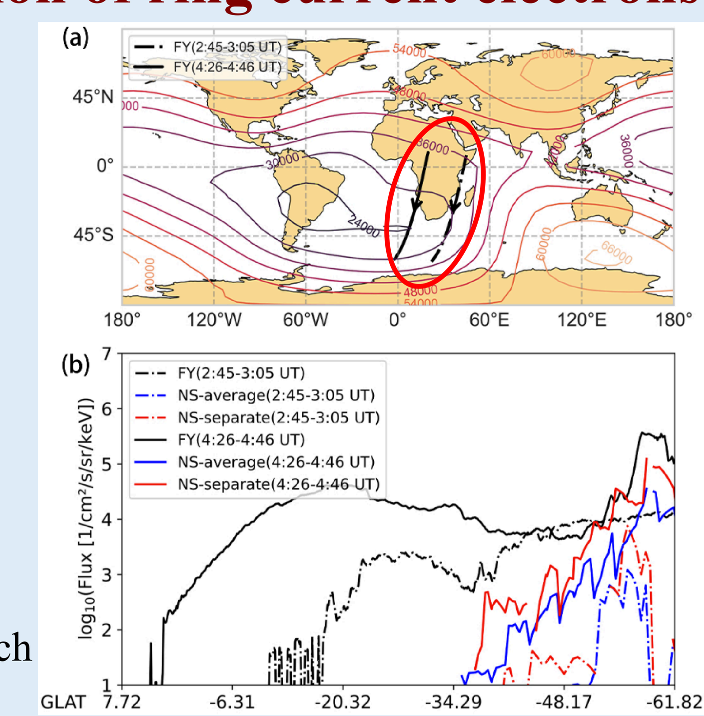
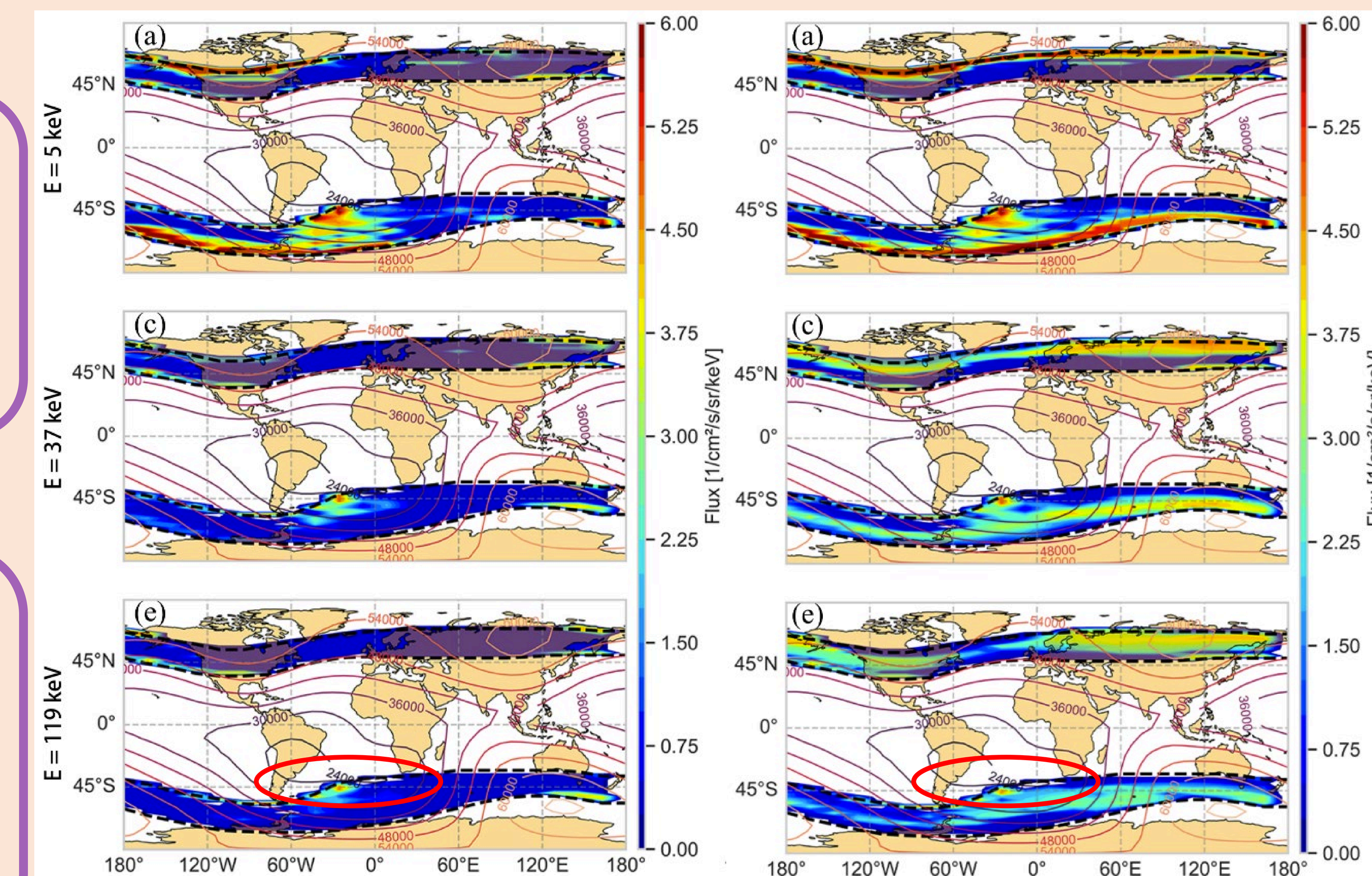


Figure 6. Comparison between simulated electron precipitation and FY-3E observation.

♦ The energy dependence of electron precipitation near SAA

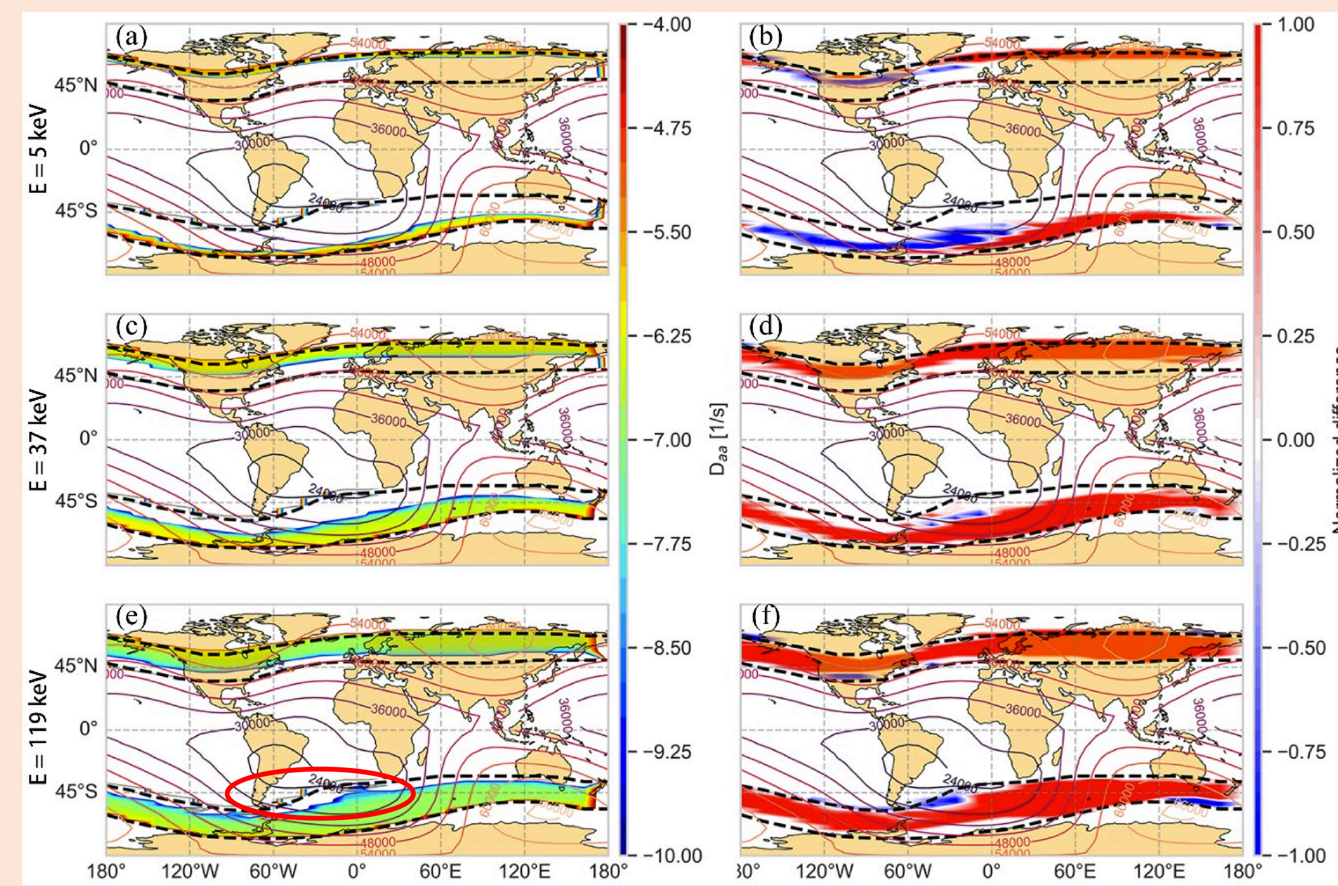


SAA significantly promotes low-energy (several keV) electron precipitation compared to high-energy (hundreds of keV) electrons.

Considering wave-particle interactions, the precipitation of low-energy electrons changes little, while that of high-energy electrons enhances significantly.

Regions of increased high-energy electron precipitation correlate well with $D_{\alpha\alpha}$.

Wave-particle interaction can promote energetic electron decay due to SAA, accounting for the energy dependence of precipitation.



Summary

- The SAA significantly affects the ring current electron **transport** and promotes electron **precipitation**.
- **Wave-particle interaction** can promote energetic electron decay due to SAA, accounting for the **energy dependence** of precipitation.
- Considering the realistic effect of SAA is essential for accurately interpreting the **north-south asymmetry** in electron precipitation.