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Article

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Posted Date: June 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10043461/v1>

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Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Scientific Reports on October 2nd, 2026. See the published version at <https://doi.org/10.1038/s41598-026-72547-2>.

Hour-scale response of low-Earth-orbit satellite altitude to extreme geomagnetic storms revealed by the NinjaSat CubeSat during the 2024 solar maximum

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Abstract

Extreme geomagnetic storms accelerate LEO satellite decay by inflating the thermosphere, yet the hour-scale pathway from solar-wind energy to atmospheric heating is poorly understood. Using the GNSS receiver of the NinjaSat X-ray CubeSat (~ 500 km, 97° sun-synchronous, 10-min cadence), we tracked orbital altitude through solar-maximum 2024. After removing the secular drag trend and EUV-driven background, we cross-correlated the storm-time altitude-change rate with geomagnetic indices during the two largest geomagnetic storms of 2024. The residual correlates with the polar-cap (PC) index at $r \gtrsim 0.8$, with PC leading the altitude response by ~ 2 h (combined 95 % CI $[-4.8, +0.4]$ h; October event: -3.2 ± 3.2 h), consistent with the Joule-heating transport timescale. It also correlates with the Dst index ($r \approx 0.82\text{--}0.84$), but the altitude drop *precedes* the Dst minimum by ~ 3 h, attributing the correlation to a common solar-wind driver rather than ring-current heating. Comparison with XRISM (31° , ~ 560 km) shows that in May 2024 heating extended to low latitudes (both satellites decayed), whereas in October 2024 only NinjaSat responded, indicating polar-localised heating. Polar Joule heating, indexed by PC, is thus the dominant storm-time drag driver, and the $\sim 2\text{--}3$ h PC lead provides

a natural operational window for drag forecasting.

Keywords: space weather; geomagnetic storm; PC index; Dst index; Joule heating; orbital decay.

1 Introduction

The population of satellites in low Earth orbit (LEO) has grown by more than an order of magnitude over the past decade, with small satellites and CubeSats now responsible for the majority of new launches. At altitudes below ~ 600 km the dominant non-gravitational perturbation on these spacecraft is atmospheric drag, whose magnitude is set by the mass density of the thermosphere^{1,2}. Accurate, short-latency prediction of the thermospheric density is therefore required both for operational collision avoidance and for the sustainability of the LEO environment as the number of resident space objects continues to rise³.

The thermospheric density is modulated primarily by two external energy inputs. Under geomagnetically quiet conditions the solar extreme-ultraviolet (EUV) irradiance is the dominant heat source, driving the slow solar-cycle and 27-day variations^{4,5}. The quantitative EUV response of the LEO altitude during the rising phase of cycle 25 has been reported in a companion study⁶. Superposed on this secular and quasi-periodic background, however, are impulsive density enhancements driven by the dissipation of solar-wind energy into the magnetosphere–ionosphere system during geomagnetic storms, which are the focus of the present work.

Tracking the thermospheric density during extreme storms with hour resolution requires a sampling cadence much finer than that available from conventional two-line element (TLE) catalogues, which typically update only a few times per day. Moreover, empirical thermospheric models such as NRLMSISE-00⁴ and DTM-2013⁷ rely on 3-hour Kp or Ap indices, while JB2008⁵ uses the hourly Dst index as its geomagnetic proxy; all three systematically underpredict the density enhancement during the largest storms^{1,3} because neither the 3-hour Kp/Ap window nor the Dst index can fully resolve the impulsive, polar-sourced heating described below. A key unresolved question is which geomagnetic observable is the most direct causal proxy of the storm-time thermospheric heating. Two widely used indices characterise complementary regions of the magnetosphere: the polar cap (PC) index, a one-minute-cadence proxy of the solar-wind electromagnetic energy input through the high-latitude ionosphere^{8,9}, and the ring-current-driven Dst index, which captures the global, low-latitude magnetospheric response¹⁰.

Here we exploit the onboard Global Navigation Satellite System (GNSS) receivers of two X-ray astronomy satellites that both operated throughout 2024. The 6U CubeSat NinjaSat¹¹ orbits in a sun-synchronous (97° inclination) orbit near 500 km, passing over all latitudes including the polar cap and auroral zone on every orbit. The X-ray Imaging and Spectroscopy Mission XRISM orbits at 31° inclination near 560 km, sampling exclusively the low-to-mid-latitude thermosphere. NinjaSat telemetres GNSS position solutions at 10-minute cadence, whereas XRISM does so at 30-second cadence, providing radial altitude measurements with sub-kilometre precision. Together, the two orbits sample complementary latitude regimes within the same storm

events, enabling a direct two-point test of the latitudinal extent of storm-time thermospheric heating. To extract the dynamic storm signal from the raw GNSS altitude, which is dominated by the secular orbital decay common to all LEO satellites, we construct for each spacecraft the altitude residual $\Delta a \equiv a_{\text{SGP4}} - a_{\text{GNSS}}$, where a_{GNSS} is the GNSS-derived altitude and a_{SGP4} is the altitude obtained by propagating NORAD two-line element sets (TLEs) with the SGP4 algorithm¹². Because the SGP4 model tracks the secular decay but does not resolve hour-scale density enhancements, a positive Δa indicates extra atmospheric drag beyond the background trend. By cross-correlating Δa with the PC and Dst indices during the May^{13,14} and October¹⁵ 2024 superstorms, we isolate the hour-scale atmospheric response from the slowly varying secular and periodic decay.

In this paper we quantify the storm-time thermospheric response during the May and October 2024 superstorms using GNSS data from both NinjaSat and XRISM, separate the geomagnetic impulsive component from the secular and periodic EUV-driven baseline, and identify the causal geomagnetic driver through cross-correlation analysis with the PC and Dst indices. Section 2 presents the altitude residuals, the correlations with the PC and Dst indices, and the latitude dependence revealed by the two-satellite comparison of NinjaSat and XRISM. Section 3 interprets these findings and discusses the implications for storm-time orbital prediction. Section 4 describes the NinjaSat GNSS data, the TLE propagation, the EUV baseline removal, the geomagnetic indices and the statistical procedures.

2 Results

2.1 Altitude residual between SGP4 and GNSS

The altitude time series is governed by three distinct physical components: (1) a *secular* term—a monotonically decreasing long-term trend caused by continuous atmospheric drag over months to years; (2) a *periodic* term—a quasi-periodic ~ 27 -day modulation driven by the solar-rotation cycle of EUV irradiance; and (3) an *impulsive* term—episodic enhancements during geomagnetic storms that are the primary focus of this study. Both the GNSS-derived and SGP4-propagated altitudes show a clear secular downward trend throughout 2024 due to the long-term atmospheric drag at ~ 500 km. Figure 1a shows a representative one-month comparison for July 2024; the two altitude time series track each other closely, reflecting the same secular decay, together with the residual $\Delta a(t) \equiv a_{\text{SGP4}} - a_{\text{GNSS}}$ (green, right axis). During this geomagnetically quiet interval the residual reflects the slowly varying, EUV-driven periodic component of thermospheric density; after the EUV baseline is removed (Sect. 4.5), the quiet-period scatter of Δa is small ($\lesssim 0.1$ km). Figure 1b shows the corresponding Savitzky–Golay-smoothed residual $\widetilde{\Delta a}$ and its time derivative $\dot{\widetilde{\Delta a}}$ for the same interval; the slowly oscillating $\dot{\widetilde{\Delta a}}$ reflects the ~ 27 -day *periodic* modulation of thermospheric density by the solar-rotation EUV cycle.

2.2 EUV baseline regression and subtraction

To separate the geomagnetic-storm signal from the background EUV forcing, we regress $\widetilde{\Delta a}$ (time-shifted by the optimal EUV response lag following Ref.⁶) against the GOES-18 EXIS EUV

irradiance at 140.5 nm during the geomagnetically quiet interval July–September 2024. Figure 2 shows the scatter plot for July 2024 (representative month); the linear fits yield correlation coefficients $r = 0.77$, 0.74 and 0.76 for July, August and September, respectively, confirming that solar EUV is the dominant driver of $\widetilde{\Delta a}$ during quiet intervals.

2.3 Case studies: the May and October 2024 superstorms

During the two largest geomagnetic storms of 2024—in May and October—large *impulsive* excursions of $\widetilde{\Delta a}$ appear on top of the *periodic* EUV baseline established in Sect. 2.2.

Figure 3a shows the smoothed altitude residual $\widetilde{\Delta a}$ and rate of change $\dot{\widetilde{\Delta a}}$ for the May 2024 “Gannon” superstorm¹³. Following the storm sudden commencement (SSC) at 17:05 UT on 10 May, the rate of change $\dot{\widetilde{\Delta a}}$ rises sharply and the cumulative residual $\widetilde{\Delta a}$ increases by ~ 0.3 km within two days, indicating that the spacecraft was decaying faster than the pre-storm secular trend. The October 2024 event¹⁵ (SSC at 15:04 UT on 10 October; Fig. 3b) shows a qualitatively similar but somewhat larger response, with $\widetilde{\Delta a}$ increasing by ~ 0.5 km within two days.

Applying the regression model to the storm intervals yields the EUV-estimated component $\widetilde{\Delta a}_{\text{EUV}}$ shown as the red dashed curves in Figs. 3c,d. In both storm intervals the EUV-estimated component tracks the pre-storm background but fails to reproduce the large positive spike that occurs at the time of the geomagnetic main phase, demonstrating that the storm-time enhancement of $\widetilde{\Delta a}$ is geomagnetically driven and cannot be attributed to elevated solar EUV output. The storm residual $\widetilde{\Delta a} - \widetilde{\Delta a}_{\text{EUV}}$ (black curves) is used in all subsequent cross-correlation analyses.

The visual co-variation between the geomagnetic drivers and the EUV-subtracted altitude rate is illustrated in Fig. 4. Figures 4a,b show that the PCN index and $\widetilde{\Delta a} - \widetilde{\Delta a}_{\text{EUV}}$ peak nearly simultaneously near 11 May and 11 October, with PCN reaching ≈ 12 mV m⁻¹ (May) and ≈ 13 mV m⁻¹ (October). Figures 4c,d show the corresponding comparisons with $|\text{Dst}|$; strikingly, in both events the altitude rate (black) peaks *before* $|\text{Dst}|$ (blue) reaches its maximum, a temporal ordering that is the opposite of what would be expected if the ring current were the causal driver of thermospheric heating. This ordering motivates the separate cross-correlation analyses presented below.

2.4 Response to the PC index

Figures 5a,b show the cross-correlation between the EUV-subtracted rate of change $\widetilde{\Delta a} - \widetilde{\Delta a}_{\text{EUV}}$ and the PCN index as a function of lag τ for the May and October storms, respectively. In both events the peak correlation is positive ($r \approx 0.81$ in May, $r \approx 0.85$ in October), consistent with enhanced polar Joule heating (large positive PCN) driving increased atmospheric drag (large positive $\widetilde{\Delta a}$). The peak lag in May is $\tau = 0$ h ($^{+3.2}_{-6.3}$ h, 95 % CI) and in October $\tau = -3.17$ h (± 3.17 h, 95 % CI), where the confidence intervals are derived from a Fisher z -transform applied at the peak correlation and span all shifts whose correlation is statistically indistinguishable from the peak value. The May event has a broader lag uncertainty than October, likely reflecting the more impulsive and shorter main phase of the Gannon storm, which limits the effective

window of distinguishable time lags. Taking the inverse-variance weighted mean over both events, the combined lag estimate is $\tau_{\text{combined}} = -2.2 \pm 2.6$ h (negative τ indicating PCN leads the altitude response), with the October event contributing 69% of the total weight. The 95% confidence interval of τ_{combined} formally includes zero (-4.8 to $+0.4$ h), so the data alone cannot exclude a simultaneous response; however, the October event individually constrains the lag to $-3.17^{+3.17}_{-3.17}$ h, consistent with polar energy input preceding the thermospheric density enhancement at ~ 500 km. The magnitude of this delay is consistent with the finite response time of the upper thermosphere to Joule heating localised in the polar ionosphere: electrodynamic heating deposited near 110–130 km altitude is redistributed to the 500 km level by a combination of vertical expansion and meridional transport on time-scales of a few hours^{2,16}.

2.5 Correlation with the $|\text{Dst}|$ index and its reversed temporal order

Figures 5c,d show the cross-correlation with $|\text{Dst}|$. The altitude rate is strongly positively correlated with $|\text{Dst}|$ —the deepest negative excursions of Dst accompany the largest positive rates of increase of Δa —with a peak coefficient of $r \approx 0.82$ in May and $r \approx 0.84$ in October. The magnitude is comparable to that found with PCN, but the temporal order is reversed: in both events the peak occurs at a *positive* lag $\tau_{\text{peak}} \approx +3$ h (95% CI $[0, +6]$ h for October; $[-4, +6]$ h for May, with the peak clearly on the positive side of zero), meaning that $|\text{Dst}|$ lags the altitude response by about three hours—or equivalently, the altitude drop precedes the Dst minimum. Taken together with the PC result, this implies a total separation of $\tau_{\text{Dst}} - \tau_{\text{combined}} \approx 5$ h between the onset of the polar energy input and the development of the ring-current signature at mid latitudes, in quantitative agreement with the equatorward propagation time of heated thermospheric air measured by the CHAMP accelerometer^{2,17}. The reversed temporal order makes the Dst–altitude correlation a *consequence* of a common solar-wind driver rather than a direct thermal coupling (Sect. 3).

2.6 Latitude dependence: NinjaSat versus XRISM

To probe the latitude dependence of the thermospheric response, we compare $\widetilde{\Delta a}$ for NinjaSat (~ 500 km altitude, 97° sun-synchronous orbit) with that derived from TLE and GNSS data for XRISM (~ 560 km, 31° inclination). Figure 6a shows that during the May “Gannon” event *both* satellites exhibit clear positive excursions of $\widetilde{\Delta a}$, peaking near 11 May. The NinjaSat peak ($\approx 0.04 \text{ km s}^{-1}$) is approximately twice the XRISM peak ($\approx 0.02 \text{ km s}^{-1}$); the fact that XRISM also responds, despite its low inclination orbit that samples only the mid-to-low latitude thermosphere, suggests that the auroral electrojet and associated Joule heating extended to latitudes below $\sim 30^\circ$ during the Gannon event. In contrast, during the October 2024 storm (Fig. 6b), only NinjaSat shows a clear storm response; the XRISM $\widetilde{\Delta a}$ remains near zero throughout the event. This contrast implies that the October thermospheric heating was confined to the polar cap and auroral zone, and did not extend to the lower-latitude thermosphere sampled by XRISM’s 31° -inclination orbit.

Table 1 summarises the storm responses of the two satellites for both events.

Table 1. Storm-time altitude-change rate response of NinjaSat and XRISM. Peak $\widetilde{\Delta a}$ values are in km s^{-1} . “Response” indicates a statistically significant positive excursion above the pre-storm baseline.

Event	Satellite	Inclination	Altitude (km)	Storm response (peak $\widetilde{\Delta a}$)
May 2024 (Gannon)	NinjaSat	97°	~ 500	Yes ($\approx 0.04 \text{ km s}^{-1}$)
May 2024 (Gannon)	XRISM	31°	~ 560	Yes ($\approx 0.02 \text{ km s}^{-1}$)
October 2024	NinjaSat	97°	~ 500	Yes ($\approx 0.05 \text{ km s}^{-1}$)
October 2024	XRISM	31°	~ 560	No ($\approx 0 \text{ km s}^{-1}$)

3 Discussion

The causal chain: polar Joule heating drives storm-time orbital decay.

Here we present our interpretation of the results in Sect. 2 that bear on the causal driver of the storm-time NinjaSat altitude drop in May and October 2024. Two lines of evidence point to polar ionospheric Joule heating, quantified by the PC index, as the primary driver. First, $\widetilde{\Delta a}$ correlates with PC at $r \gtrsim 0.8$ with $\tau_{\text{combined}} = -2.2 \pm 2.6 \text{ h}$ (PC leading or simultaneous with the altitude response), demonstrating that the polar energy input does not lag the orbital response (Sect. 2.4). Second, the PC-derived hemispheric Joule-heating power during both storms exceeds the concurrent EUV baseline by a factor of $\sim 2.5\text{--}3$ (see energetics analysis below), and exceeds the quiet-time Joule-heating rate by more than an order of magnitude, so Joule heating is energetically dominant.

The October-event lag of $\tau = -3.17 \pm 3.17 \text{ h}$ is our tightest single-event constraint and falls squarely within the 2–4 h window expected from vertical thermospheric transport. The PC index tracks the rate at which the solar-wind merging electric field deposits electromagnetic energy into the high-latitude ionosphere through cross-polar-cap convection and auroral electrojet currents^{8,9}; it responds within minutes of a southward interplanetary magnetic field (IMF) onset. Joule dissipation is concentrated primarily in the auroral electrojets at 110–130 km altitude, where the Pedersen conductivity is largest². The resulting heating raises the thermospheric temperature locally, initiating an upwelling that propagates to the $\sim 500 \text{ km}$ level of NinjaSat through a combination of vertical pressure-driven expansion and poleward-to-equatorward meridional wind transport over a timescale of two to four hours^{2,16}. The inverse-variance weighted mean lead time is $\tau_{\text{combined}} = -2.2 \pm 2.6 \text{ h}$. The 95 % confidence interval formally includes zero (-4.8 to $+0.4 \text{ h}$), so the composite estimate alone cannot rule out a simultaneous response. This breadth is dominated by the May event, whose peak lag of $\tau = 0 \text{ h}$ with 95 % CI ${}^{+3.2}_{-6.3} \text{ h}$ provides weak lag discrimination, likely because the exceptionally impulsive Gannon main phase compressed the window of distinguishable lags. The October event, which is less impulsive and better sampled ($n = 84$), yields the tighter constraint $\tau = -3.17 \pm 3.17 \text{ h}$ and contributes 69 % of the total inverse-variance weight; taken on its own, this event places the lead time within the 2–4 h range expected for vertical thermospheric transport, consistent with accelerometer-based estimates from the CHAMP and GRACE satellites during previous storm cycles^{2,16,17}.

The variation of Dst index is a consequence, not a cause.

The decisive evidence against a causal role for Dst is temporal. The cross-correlation analysis (Sect. 2.5) shows that the Dst index *lags* the altitude response by $\tau_{\text{peak}} \approx +3$ h (95 % CI: October $[0, +6]$ h; May $[-4, +6]$ h): the orbital altitude had already begun to drop before the ring-current signature reached its maximum. Although the $|\text{Dst}|$ -altitude correlation is as numerically strong as the PC-altitude correlation ($r \approx 0.82$ in May and 0.84 in October), this reversed temporal ordering—the altitude response *leading* Dst by ~ 3 h—rules out a direct causal link between the ring current and thermospheric heating.

The physical reason is straightforward. The Dst index measures the magnetic perturbation produced by the equatorial ring current, whose ion population is trapped on closed drift shells at geocentric distances of $L \approx 3\text{--}7 R_{\oplus}$ —hundreds of thousands of kilometres above the ~ 500 km thermosphere in which NinjaSat operates. There is no direct thermal pathway by which energetic ring-current ions ($\sim 10\text{--}100$ keV) can heat the neutral atmosphere on the hour timescale. The ring-current population is built up by the injection of energetic ions from the plasma sheet over several hours of enhanced magnetospheric convection driven by prolonged southward IMF; the Dst minimum therefore lags the onset of storm-time polar energy input by a comparable timescale^{2,10}. Consequently, the strong Dst-altitude correlation arises because both quantities respond to the same upstream solar-wind driver, not because Dst causally heats the thermosphere. The total temporal separation $\tau_{\text{Dst}} - \tau_{\text{combined}} \approx 5$ h is broadly consistent with the characteristic propagation time of storm-time thermospheric disturbances from high to mid latitudes inferred from CHAMP accelerometer measurements^{2,17}, further supporting the picture in which a single solar-wind perturbation sequentially drives polar Joule heating, thermospheric expansion, and ring-current injection on progressively longer timescales.

Storm-time energetics. The PC-derived hemispheric Joule-heating power Q_J (Eq. 5; Fig. 7) peaks at $\sim 1.3 \times 10^{12}$ W (1320 GW) during the May main phase and at $\sim 1.8 \times 10^{12}$ W (1760 GW) during the October main phase. These values exceed the contemporaneous average EUV heating baseline from the companion study⁶ by a factor of ~ 2.5 (May) and ~ 3 (October), and are more than an order of magnitude above the quiet-time Joule-heating rate of ~ 95 GW, establishing geomagnetically driven Joule heating as the dominant incremental thermospheric energy source during both storm intervals.

Comparison with empirical thermospheric models.

Operational thermospheric density models widely used for orbit determination and drag prediction have geomagnetic inputs that cannot fully capture the hour-scale response reported here. NRLMSISE-00⁴ and DTM-2013⁷ use 3-hour Kp or Ap indices, whose averaging window smooths out the impulsive storm-time heating. JB2008⁵ employs the hourly Dst index as its geomagnetic proxy; as demonstrated in Sect. 2.5, Dst itself lags the thermospheric response by ~ 3 h and therefore cannot serve as a timely predictor of storm-induced drag enhancement. This structural limitation produces a well-known tendency to underestimate thermospheric density enhancements during large storms^{1,3,14}, with direct operational consequences: collision-avoidance

screening overestimates the miss distance, post-event orbit reconstruction lags by hours, and mission-lifetime estimates carry large uncertainties during solar maximum.

Our results suggest a concrete, three-step path to improvement, using the PC index as a single physically motivated replacement for the Kp, Ap, or Dst proxies currently used in operational models. *Step 1:* The PC index is disseminated in real time at 1-minute cadence by DTU Space (PCN) and the Arctic and Antarctic Research Institute (PCS); the Knipp et al. empirical relation¹⁸ (Eq. 5) converts PC directly to hemispheric Joule-heating power Q_J . *Step 2:* Q_J is converted to a thermospheric temperature increment $\Delta T/T \propto \Delta \rho/\rho$ via a hydrostatic column model calibrated to the ambient NRLMSISE-00 profile⁴. *Step 3:* The resulting density increment yields an altitude-change rate enhancement $\Delta \dot{a} \propto \Delta \rho \cdot C_D A / (2m)$, providing a forward estimate of storm-time drag with a lead time of ~ 2 – 3 h relative to the peak altitude response. Replacing Kp or Ap with this PC-driven Joule-heating input in next-generation thermospheric models would capture both the rapid response to southward-IMF onset and the recovery following IMF northward turning—features that are averaged away in 3-hour geomagnetic indices.

Latitude and altitude dependence.

The comparison of NinjaSat (sun-synchronous, 97° , ~ 500 km) with JAXA’s X-ray Imaging and Spectroscopy Mission (XRISM; 31° , ~ 560 km), which also carries an onboard GNSS receiver, provides a first constraint on the latitude and altitude dependence of the storm-time thermospheric response. In May 2024, both satellites exhibited a clear altitude drop peaking near 11 May, indicating that the storm-induced density enhancement was not confined to polar latitudes but extended to the low-inclination orbit of XRISM. This is consistent with an exceptionally strong Gannon-storm auroral electrojet that expanded equatorward beyond the XRISM ground track¹³. In October 2024, by contrast, only NinjaSat showed a significant altitude response while XRISM remained near its secular trend, pointing to a polar-localised heating pattern despite a comparable Dst minimum. This storm-to-storm difference in the latitudinal extent of thermospheric heating is a further illustration that the PC index — which integrates the polar energy input globally — is a more reliable predictor of orbital impact than Dst, which gives no direct information about the spatial distribution of the magnetospheric energy deposition.

Limitations.

Here we discuss limitations of the current study. First, the analysis is based on a single satellite whose orbital altitude declined from ~ 500 km at the start of 2024 to ~ 450 km by year end. The thermospheric density response varies with altitude (the fractional enhancement $\Delta \rho/\rho$ grows with altitude because the scale height increases with temperature) and with local time (because the Joule-heating pattern rotates with the convection zone relative to the satellite ground track); quantitative conclusions about the lag and the amplitude may differ for significantly different orbital regimes.

Second, the PC index is known to saturate at very large cross-polar-cap potentials ($\gtrsim 200$ kV), which are approached during the May 2024 storm peak^{8,9}. PC saturation would cause the Knipp et al. formula¹⁸ to underestimate the true Joule-heating power at storm maximum, so

the energetics estimates above should be regarded as lower bounds during the most extreme phase of the May event.

Finally, the statistical conclusions rest on two storm events, which, while among the largest of the modern space era, do not constitute a sufficient ensemble to quantify the dependence of the PC-lead lag (October event: -3.17 h; combined: -2.2 ± 2.6 h) on storm intensity, season, solar-cycle phase, or orbital altitude. A multi-storm analysis spanning the descending phase of solar cycle 25 will be required to establish the universality of the results reported here.

Implications and outlook.

From a scientific standpoint, this work provides the first quantitative, in-orbit demonstration that the high-latitude ionosphere is the decisive coupling channel between the magnetosphere and the drag-relevant thermosphere during extreme geomagnetic storms. The result supports the view, drawn from ground-based radar² and empirical modelling¹, that electrojet-scale Joule heating at auroral latitudes dominates the storm-time thermospheric energy budget, and it constrains the characteristic coupling timescale to the 2–4 h range independently of storm intensity.

Looking ahead, extending this approach to a constellation of GNSS-equipped LEO satellites would enable three-dimensional mapping of the thermospheric density response as a function of altitude, latitude, and local time within a single storm event—a dataset of the kind needed to validate next-generation ionosphere–thermosphere general circulation models. Driving such models with the PC index as their geomagnetic forcing, rather than Kp or Ap, represents a natural next step towards physics-based, hour-scale orbital decay forecasting for the rapidly growing LEO population.

From a practical standpoint, the identification of PC as the most direct proxy for storm-time LEO orbital decay provides an immediately actionable forecast tool. A real-time PC-based drag enhancement predictor—requiring only the publicly available 1-minute PC index, the Knipp et al. conversion¹⁸, and a hydrostatic column model calibrated to the ambient NRLMSISE-00 profile⁴—could alert operators of satellites at ~ 500 km altitude to an impending density surge approximately three hours before its peak effect on the orbit. This lead time is sufficient to recompute revised conjunction assessments and, for manoeuvrable spacecraft, to plan corrective Δv burns before the density maximum arrives.

4 Methods

4.1 The NinjaSat mission and onboard GNSS

NinjaSat is a 6U ($10 \times 20 \times 30$ cm³) CubeSat developed for soft-X-ray monitoring of bright compact objects¹¹. It was launched into a sun-synchronous orbit at an initial altitude of ≈ 530 km on 11 November 2023 by the SpaceX Transporter-9 mission, and had decayed to ~ 500 km by mid-2024. The spacecraft carries a GNSS receiver that provides position, velocity and time fixes in a body-fixed frame at a telemetry cadence of 10 minutes throughout the period of the present analysis (1 January–31 December 2024). Positions are transformed into an Earth-centred frame

using standard IAU 2000/2006 precession–nutation and polar-motion models, and the orbital altitude is defined as the radial distance from the Earth’s centre minus an assumed mean Earth radius of 6371 km (spherical Earth approximation). Because the raw altitude is dominated by the $\sim 2\pi/\omega_{\text{orb}} \simeq 95$ -minute orbital oscillation about the mean radius, we fit a two-orbit sinusoidal model to the 10-minute samples and retain the smooth mean-altitude component $a_{\text{GNSS}}(t)$ sampled at an effective cadence of 3 h, identical to that used in the companion study⁶.

4.2 The XRISM mission and onboard GNSS

XRISM is a JAXA/NASA X-ray astronomy satellite launched on 7 September 2023 into a 31° -inclination orbit near ~ 560 km altitude. It carries an onboard GNSS receiver with a 30-second telemetry cadence. The same data-reduction procedure described in Sect. 4.1 is applied to the XRISM GNSS time series: positions are transformed into an Earth-centred frame, the orbital altitude is extracted as the mean-radius component via a two-orbit sinusoidal fit, and a_{GNSS} is sampled at a 3-h effective cadence. The altitude residual $\Delta a = a_{\text{SGP4}} - a_{\text{GNSS}}$ and its time derivative $\dot{\Delta a}$ are computed identically for XRISM and NinjaSat, allowing a direct quantitative comparison of the storm-time thermospheric response at two latitude regimes within the same events.

4.3 TLE propagation

The altitude baseline against which the dynamic response is measured is derived from NORAD two-line element sets (TLEs), retrieved from space-track.org, using the Simplified General Perturbations 4 (SGP4) semi-analytic model¹². For each calendar month we select a single representative TLE whose epoch falls near the middle of that month, then propagate the orbit ± 15 days from that epoch to cover the full month. The SGP4-propagated position is computed at each epoch recorded by the onboard GNSS receiver, and the radial distance from the Earth’s centre minus the mean Earth radius of 6371 km gives the propagated altitude a_{SGP4} on the same time grid as a_{GNSS} . The same two-orbit sinusoidal fit applied to the GNSS time series is applied here, yielding the mean altitude $a_{\text{SGP4}}(t)$ at an effective cadence of 3 h. Because the effective drag coefficient B^* embedded in the TLE is fitted to the *past* orbit, a_{SGP4} follows the secular long-term decay but does not capture the hour-scale response to storm-time density enhancements.

4.4 SGP4–GNSS altitude residual and its rate of change

Adopting the sign convention of the companion paper⁶, the quantity analysed in this work is the altitude residual

$$\Delta a(t) \equiv a_{\text{SGP4}}(t) - a_{\text{GNSS}}(t), \quad (1)$$

so that $\Delta a > 0$ corresponds to the satellite being *lower* than predicted by SGP4 and therefore experiencing extra atmospheric drag. Forming the residual removes the secular drag baseline common to both time series and leaves the short-term, storm-driven perturbation. The 3-h-sampled $\Delta a(t)$ is then smoothed with a Savitzky–Golay filter¹⁹ of polynomial order $p = 1$ and window length $N = 9$ points (covering ≈ 27 h). The window length was chosen to balance two

competing requirements: it must be long enough to suppress high-frequency orbital perturbations (e.g. atmospheric tides, J_2 precession artefacts, and GNSS positioning noise) yet short enough to preserve the multi-hour rise-and-fall structure of the storm-time altitude response, which develops on a timescale of one to two days. A window of $N = 9$ satisfies both criteria for the large-amplitude ($\gtrsim 0.3$ km) altitude excursions observed during the May and October 2024 superstorms; longer windows risk smoothing away the sharp onset and recovery of the storm signal. This yields the smoothed residual $\widetilde{\Delta a}(t)$. To remove the small residual long-term trend imprinted by the solar-EUV-driven quiet-time density variation, a low-frequency baseline obtained by a running-median filter of length one week is subtracted from $\widetilde{\Delta a}$ before the correlation analysis. One data point in the October 2024 interval (2024-10-13 09:14 UT) was absent from the onboard GNSS telemetry; it was replaced by linear interpolation between the two adjacent 3-h samples before smoothing. For the correlation analyses we use the rate of change

$$\dot{\widetilde{\Delta a}}(t) = \frac{d\widetilde{\Delta a}(t)}{dt}, \quad (2)$$

estimated by centred finite differences on the 3-h grid. Working in $\dot{\widetilde{\Delta a}}$ rather than $\widetilde{\Delta a}$ emphasises the impulsive response that is characteristic of storm-time Joule heating.

4.5 EUV baseline removal

The altitude residual $\widetilde{\Delta a}(t)$ contains a slowly varying component driven by solar extreme-ultraviolet (EUV) heating in addition to the impulsive geomagnetic signal of interest. To separate these contributions, we exploit the geomagnetically quiet period July–September 2024, during which the orbital decay is dominated by EUV forcing. Following the companion study⁶, we perform a linear regression of $\dot{\widetilde{\Delta a}}$ (time-shifted by the optimal EUV response lag) against the GOES-18 EUV and X-ray Irradiance Sensors (EXIS) irradiance at 140.5 nm over this quiet interval, yielding an EUV-driven altitude-change-rate model $\dot{\widetilde{\Delta a}}^{\text{EUV}}(t)$. This model is then subtracted from the storm-interval derivative (7–17 May and 6–17 October), leaving a geomagnetic-storm component $\dot{\widetilde{\Delta a}}^{\text{storm}}(t) = \dot{\widetilde{\Delta a}}(t) - \dot{\widetilde{\Delta a}}^{\text{EUV}}(t)$ that is used in all subsequent cross-correlation analyses.

4.6 Geomagnetic indices

Two geomagnetic indices are used. (i) The *polar cap* index PC is computed from the deviation of the magnetic horizontal component at near-polar observatories, normalised so that it is approximately linearly proportional to the solar-wind merging electric field^{8,9}. We use both the northern (PCN, Thule) and the southern (PCS, Vostok) indices provided by the International Service of Geomagnetic Indices at a native cadence of 1 minute, and average them to the 3-h cadence of the altitude time series. (ii) The *disturbance storm-time* index Dst is the hourly average deviation of the horizontal magnetic component at four mid-latitude observatories (Hermanus, Kakioka, Honolulu and San Juan), from the World Data Center for Geomagnetism, Kyoto¹⁰, obtained via the NASA/OMNI2 service. Dst is linearly interpolated onto the 3-h time grid. The analysis focuses on two intervals that bracket the two largest geomagnetic storms of 2024:

396 7–17 May (“Gannon” storm) and 6–17 October.

397 4.7 Statistical analysis

398 The time-delay response of the altitude residual to each index $X(t) \in \{\text{PCN}, \text{PCS}, \text{Dst}\}$ is
 399 quantified by the Pearson linear correlation coefficient $r(\tau)$ between the rate of change of the
 400 altitude residual $\dot{\Delta}a(t)$ and the index evaluated at a shifted time, $X(t + \tau)$, for τ scanned from
 401 -24 to $+24$ h in steps of the 3-h sampling cadence. The peak of $r(\tau)$ defines the characteristic
 402 lag τ_{peak} ; a negative τ_{peak} means that the index leads the altitude response (the index was earlier
 403 in time), whereas a positive τ_{peak} means that the index lags the altitude response (the index
 404 came later).

405 The 95 % confidence interval on r_{peak} is obtained from the Fisher z transformation

$$z = \text{arctanh}(r) = \frac{1}{2} \ln \left(\frac{1+r}{1-r} \right), \quad (3)$$

406 whose standard error for a sample of n paired observations is $\text{SE}(z) = (n - 3)^{-1/2}$. The 95 % CI
 407 on r is obtained by computing $z_{\text{peak}} \pm 1.960 \text{SE}(z)$ and back-transforming via $r = \tanh(z)$. The
 408 95 % CI on τ_{peak} is then defined as the range of lags for which $r(\tau)$ falls within the confidence
 409 bounds on r_{peak} , i.e. all τ satisfying $r_{\text{lower}} \leq r(\tau) \leq r_{\text{upper}}$. This yields an asymmetric uncertainty
 410 interval $\tau_{\text{peak}}^{+(\tau_{\text{max}}^{\text{CI}} - \tau_{\text{peak}})}_{-(\tau_{\text{peak}} - \tau_{\text{min}}^{\text{CI}})}$.

411 The combined lag estimate from two independent storm events is computed as the inverse-variance
 412 weighted mean

$$\tau_{\text{combined}} = \frac{\sum_i w_i \tau_{\text{peak},i}}{\sum_i w_i}, \quad w_i = \sigma_i^{-2}, \quad (4)$$

413 where $\sigma_i = (\tau_{\text{max},i}^{\text{CI}} - \tau_{\text{min},i}^{\text{CI}})/2$ is the symmetric half-width of the 95 % CI for event i . The
 414 associated combined uncertainty is $\sigma_{\text{combined}} = (\sum_i w_i)^{-1/2}$.

415 4.8 Energetics estimate from the PC index

416 We convert the PC-inferred hemispheric Joule-heating power Q_J through the empirical relation
 417 of Ref. ¹⁸, which expresses Q_J as a quadratic function of PC:

$$Q_J [\text{GW}] = 24.89 \text{PC} + 3.41 \text{PC}^2 + 0.41 \text{Dst} + 0.0015 \text{Dst}^2. \quad (5)$$

418 The resulting Joule-heating power time series is compared with the EUV heating baseline obtained
 419 from the companion study⁶ to evaluate the relative importance of geomagnetic and radiative
 420 energy inputs during the storm main phases.

421 4.9 Code and data availability

422 The analysis pipeline, implemented in Python 3.11 with SGP4, SPICEPY and ASTROPY, is
 423 available from the corresponding author on reasonable request and will be released in a public

repository upon acceptance. Access to the NinjaSat GNSS time series is described in the Data availability section.

Data availability

The NinjaSat GNSS data used in this study are available from the NinjaSat team at RIKEN (Tamagawa–Enoto group) upon reasonable request. TLE data are publicly available from NORAD (<https://www.space-track.org>). The PC index is publicly available from DTU Space (<https://pcindex.org>). The Dst index is publicly available from the World Data Center for Geomagnetism, Kyoto (<https://wdc.kugi.kyoto-u.ac.jp>). The custom analysis code that supports the findings of this study is available from the corresponding author on reasonable request and will be released in a public repository upon acceptance.

References

- [1] J. T. Emmert. Thermospheric mass density: A review. *Adv. Space Res.*, 56:773–824, 2015. doi: 10.1016/j.asr.2015.05.038.
- [2] G. W. Prölss. Density perturbations in the upper atmosphere caused by the dissipation of solar wind energy. *Surv. Geophys.*, 32:101–195, 2011. doi: 10.1007/s10712-010-9104-0.
- [3] D. M. Oliveira and E. Zesta. Satellite orbital drag during magnetic storms. *Space Weather*, 17(11):1510–1533, 2019. doi: 10.1029/2019SW002287.
- [4] J. M. Picone, A. E. Hedin, D. P. Drob, and A. C. Aikin. NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues. *J. Geophys. Res.*, 107(A12): 1468, 2002. doi: 10.1029/2002JA009430.
- [5] B. R. Bowman, W. K. Tobiska, F. A. Marcos, C. Y. Huang, C. S. Lin, and W. J. Burke. A new empirical thermospheric density model JB2008 using new solar and geomagnetic indices. In *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, 2008. doi: 10.2514/6.2008-6438. AIAA 2008-6438.
- [6] H. Tanaka, T. Nakagawa, S. Nozawa, T. Tamagawa, T. Enoto, T. Kitaguchi, W. Iwakiri, T. Mihara, T. Takeda, N. Ota, S. Aoyama, N. Iwata, H. Takahashi, and T. Yamasaki. Thermospheric expansion driven by solar EUV variability: impacts on the orbit of a LEO CubeSat. *Earth Planets Space*, 2026. submitted; companion paper.
- [7] S. Bruinsma. The DTM-2013 thermosphere model. *J. Space Weather Space Clim.*, 5:A1, 2015. doi: 10.1051/swsc/2015001.
- [8] O. A. Troshichev, A. S. Janzhura, and P. Stauning. Unified PCN and PCS indices: Method of calculation, physical sense, and dependence on the IMF azimuthal and northward components. *J. Geophys. Res.*, 111:A05208, 2006. doi: 10.1029/2005JA011402.
- [9] P. Stauning. The Polar Cap index: A critical review of methods and a new approach. *J. Geophys. Res. Space Phys.*, 118:5021–5038, 2013. doi: 10.1002/jgra.50462.

- [10] M. Sugiura and T. Kamei. Equatorial Dst index 1957–1986. *IAGA Bulletins*, 40, 1991. available from the World Data Center for Geomagnetism, Kyoto.
- [11] T. Tamagawa, T. Enoto, T. Kitaguchi, W. Iwakiri, T. Mihara, H. Takahashi, T. Takeda, M. Numazawa, Y. Kato, H. Uchiyama, C.-P. Hu, H. Odaka, Y. Yoshida, H. Sato, K. Uchiyama, J. Toeda, Y. Kojima, Y. Nambu, Y. Itoh, et al. NinjaSat: an astronomical X-ray CubeSat observatory. *Publ. Astron. Soc. Japan*, 77(3):466–479, 2025. doi: 10.1093/pasj/psaf014.
- [12] D. A. Vallado, P. Crawford, R. Hujsak, and T. S. Kelso. Revisiting spacetrack report #3. In *AIAA/AAS Astrodyn. Spec. Conf.*, 2006. doi: 10.2514/6.2006-6753. AIAA 2006-6753.
- [13] H. Hayakawa, Y. Ebihara, A. Mishev, S. Koldobskiy, K. Kusano, S. Bechet, S. Yashiro, K. Iwai, A. Shinbori, K. Mursula, Y. Miyoshi, R. Kataoka, T. Asikainen, H. Miyahara, and M. Lockwood. The solar and geomagnetic storms in 2024 May: A flash data report. *Astrophys. J.*, 979:49, 2025. doi: 10.3847/1538-4357/ad9335.
- [14] W. E. Parker and R. Linares. Satellite drag analysis during the May 2024 Gannon geomagnetic storm. *J. Spacecr. Rockets*, 61(5):1412–1416, 2024. doi: 10.2514/1.A36164.
- [15] D. M. Oliveira, E. Zesta, and D. Nandy. The 10 October 2024 geomagnetic storm may have caused the premature reentry of a Starlink satellite. *Front. Astron. Space Sci.*, 11:1522139, 2025. doi: 10.3389/fspas.2024.1522139.
- [16] E. K. Sutton, J. M. Forbes, and D. J. Knipp. Rapid response of the thermosphere to variations in Joule heating. *J. Geophys. Res. Space Phys.*, 114:A04319, 2009. doi: 10.1029/2008JA013667.
- [17] E. K. Sutton, J. M. Forbes, and R. S. Nerem. Global thermospheric neutral density and wind response to the severe 2003 geomagnetic storms from CHAMP accelerometer data. *J. Geophys. Res. Space Phys.*, 110:A09S40, 2005. doi: 10.1029/2004JA010985.
- [18] D. J. Knipp, W. K. Tobiska, and B. A. Emery. Direct and indirect thermospheric heating sources for solar cycles 21–23. *Sol. Phys.*, 224:495–505, 2004. doi: 10.1007/s11207-005-6393-4.
- [19] A. Savitzky and M. J. E. Golay. Smoothing and differentiation of data by simplified least squares procedures. *Anal. Chem.*, 36(8):1627–1639, 1964. doi: 10.1021/ac60214a047.

Funding

This research was supported by the Science Tokyo Support Program for Doctoral Students, funded by the Universities for International Research Excellence. T.N. acknowledges the financial support by the JSPS KAKENHI Grant Numbers 23H00130, 23H05441, 24H00249, and 25K24561.

Author contributions

H.T. conceived the analysis, processed the GNSS and TLE data, carried out the statistical analysis and wrote the manuscript. T.N. and S.N. supervised the research and contributed to the interpretation of the results. T.T. (Tamagawa), T.E. (Enoto), T.K., W.I., T.M., T.T. (Takeda), N.O., A.A., S.I., T.T. (Takahashi) and K.Y. are members of the NinjaSat team; they planned, built and operated the satellite and provided the onboard GNSS telemetry and the calibration information required for this analysis. All authors discussed the results, reviewed the manuscript and approved the final version.

Additional information

Competing interests. The authors declare no competing interests.

Figure legends

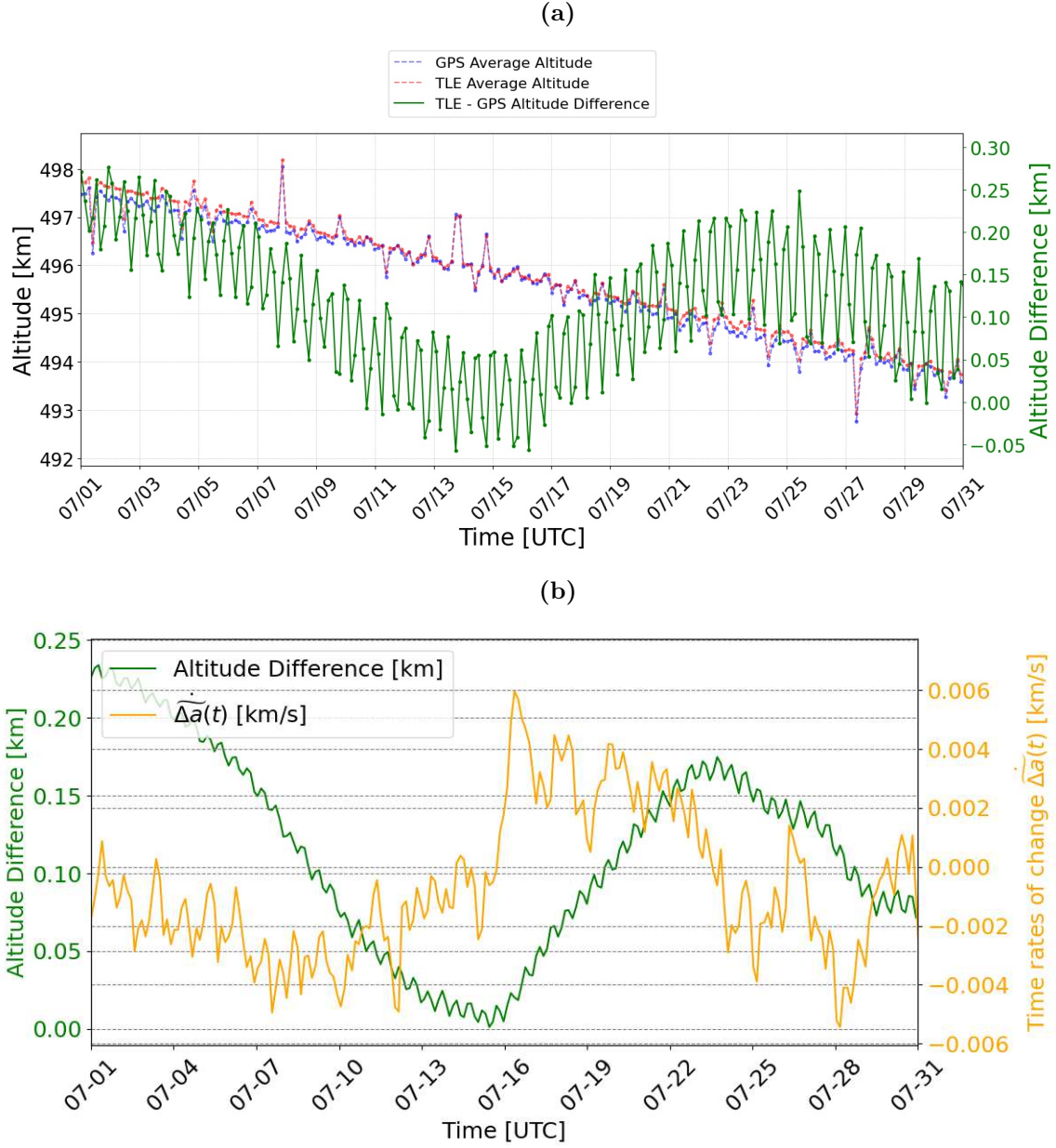


Figure 1. Representative one-month comparison of NinjaSat orbital altitude and its smoothed residual (July 2024). (a) Left y -axis: orbital altitude derived from the onboard GNSS receiver (blue dashed) and from a single mid-month TLE propagated with SGP4 (red dashed). Right y -axis: altitude residual $\Delta a \equiv a_{\text{SGP4}} - a_{\text{GNSS}}$ (green solid). Positive Δa indicates the spacecraft is below the SGP4 prediction, reflecting enhanced atmospheric drag. (b) Green (left y -axis): Savitzky–Golay-smoothed residual $\widetilde{\Delta a}(t)$. Orange (right y -axis): rate of change $\dot{\Delta a}(t)$, estimated by centred finite differences on the 3-h grid. The slowly oscillating pattern reflects the quiet-time EUV-driven thermospheric response; the EUV baseline is subtracted before the storm-period correlation analyses (Sect. 4.5).

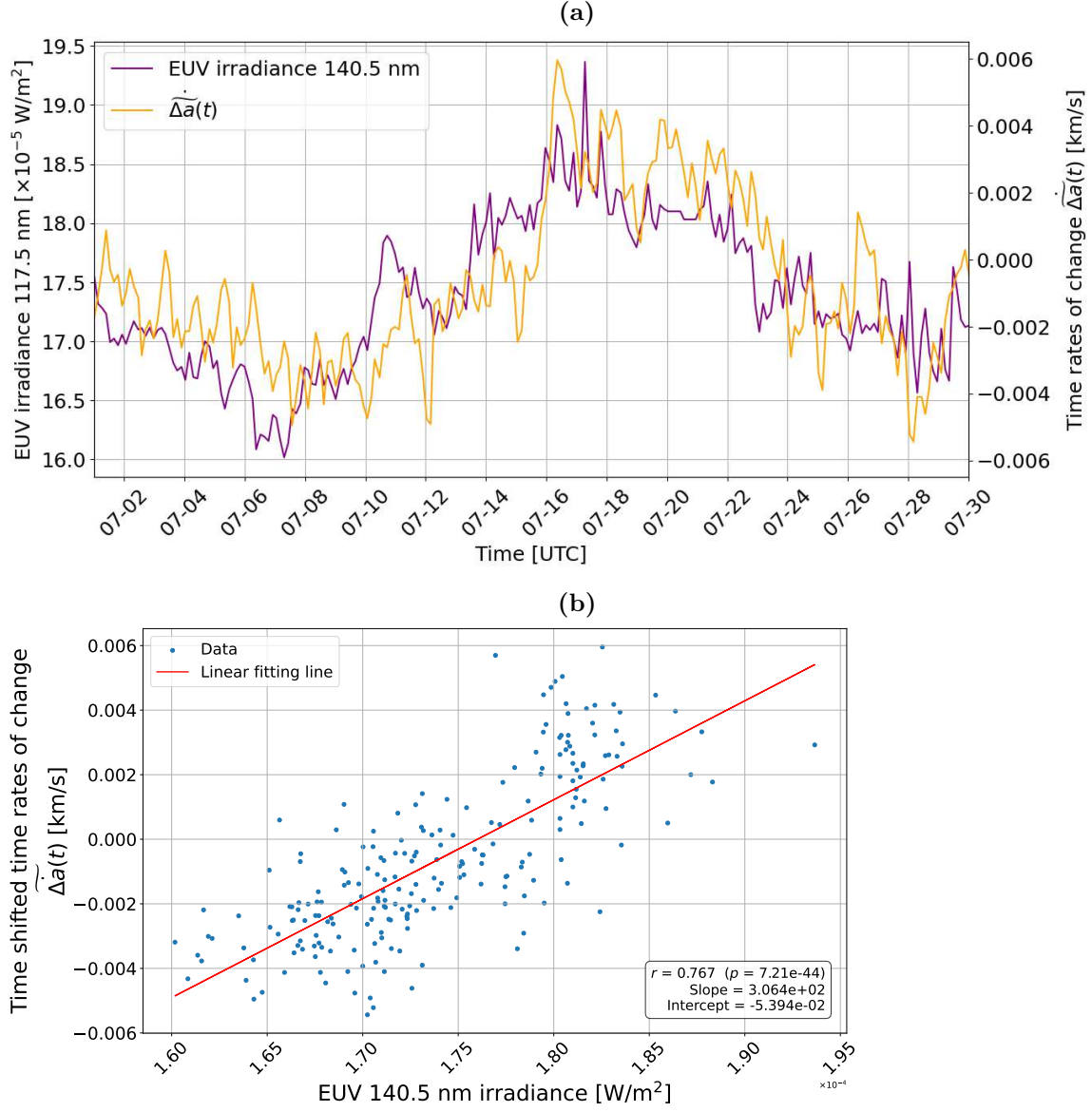


Figure 2. EUV baseline regression: July 2024 (representative month). (a) Time series of the GOES-18 EXIS EUV irradiance at 140.5 nm (purple, left y -axis) and the smoothed altitude rate of change $\widetilde{\Delta a}$ (orange, right y -axis) during the geomagnetically quiet month of July 2024. The two quantities track each other closely on the ~ 27 -day solar-rotation timescale, demonstrating that EUV is the dominant driver of $\widetilde{\Delta a}$ during quiet intervals. (b) Scatter plot of the time-shifted $\widetilde{\Delta a}$ versus EUV irradiance at 140.5 nm for the same interval. The red line shows the least-squares linear fit ($r = 0.767$, $p = 7.2 \times 10^{-44}$). Equivalent regressions for August ($r = 0.741$) and September 2024 ($r = 0.759$) yield similar coefficients. This regression model is subsequently applied to the storm intervals to estimate and remove the EUV-driven component of $\widetilde{\Delta a}$.

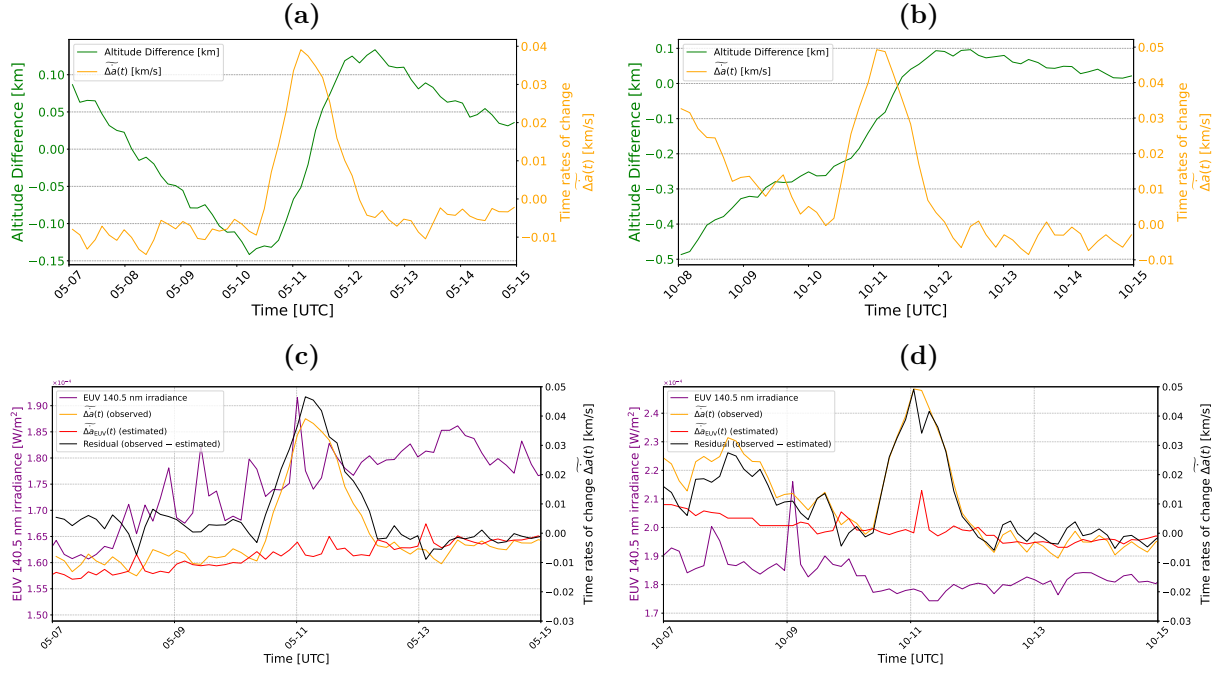


Figure 3. Storm-time altitude residual and EUV baseline subtraction for the two 2024 superstorms. *Upper panels:* smoothed altitude residual $\Delta a(t)$ (green, left y -axis) and its rate of change $\Delta a'(t)$ (orange, right y -axis) for (a) May 2024 “Gannon” storm (SSC at 17:05 UT on 10 May) and (b) October 2024 storm (SSC at 15:04 UT on 10 October). In both events Δa peaks sharply during the main phase and the cumulative residual Δa increases by ~ 0.3 km (May) and ~ 0.5 km (October) within two days of the SSC. *Lower panels:* EUV baseline subtraction for (c) May 2024 and (d) October 2024 (140.5 nm channel). Purple (left y -axis): GOES-18 EUV irradiance at 140.5 nm. Orange: observed Δa . Red dashed: EUV-estimated Δa_{EUV} from the quiet-period regression model. Black: storm residual $\Delta a - \Delta a_{\text{EUV}}$, which isolates the geomagnetic component used in all subsequent correlation analyses. The large positive spike near 11 May and 11 October is not reproduced by the EUV model, confirming its geomagnetic origin.

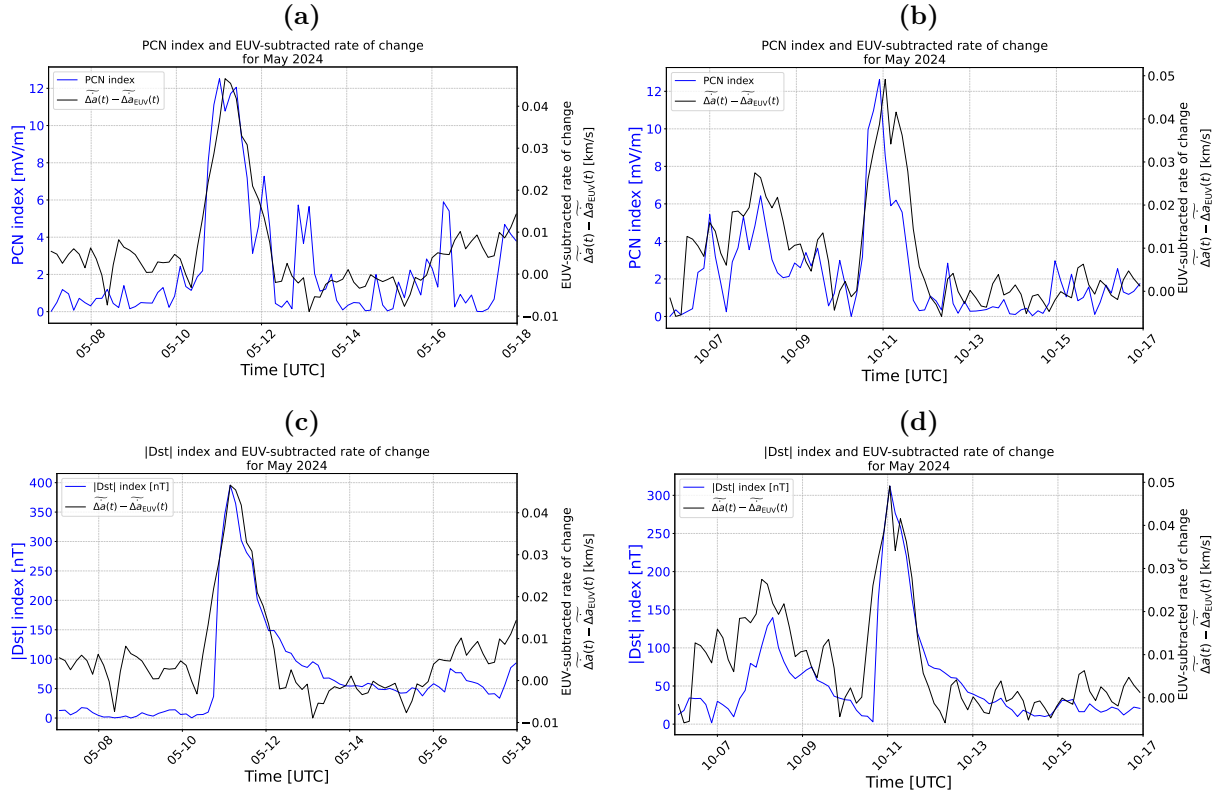


Figure 4. Visual co-variation of geomagnetic indices and the EUV-subtracted altitude rate.

Top row: PCN index (blue, left y -axis) and $\hat{\Delta}a - \hat{\Delta}a_{\text{EUV}}$ (black, right y -axis) for (a) May 2024 and (b) October 2024. Both quantities peak simultaneously near 11 May and 11 October, with PCN reaching $\approx 12 \text{ mV m}^{-1}$ (May) and $\approx 13 \text{ mV m}^{-1}$ (October). Bottom row: corresponding panels for the |Dst| index (c) May 2024 and (d) October 2024. In both events the altitude rate (black) peaks *before* |Dst| (blue) reaches its maximum, a temporal reversal that motivates the cross-correlation analysis (Sect. 2.5).

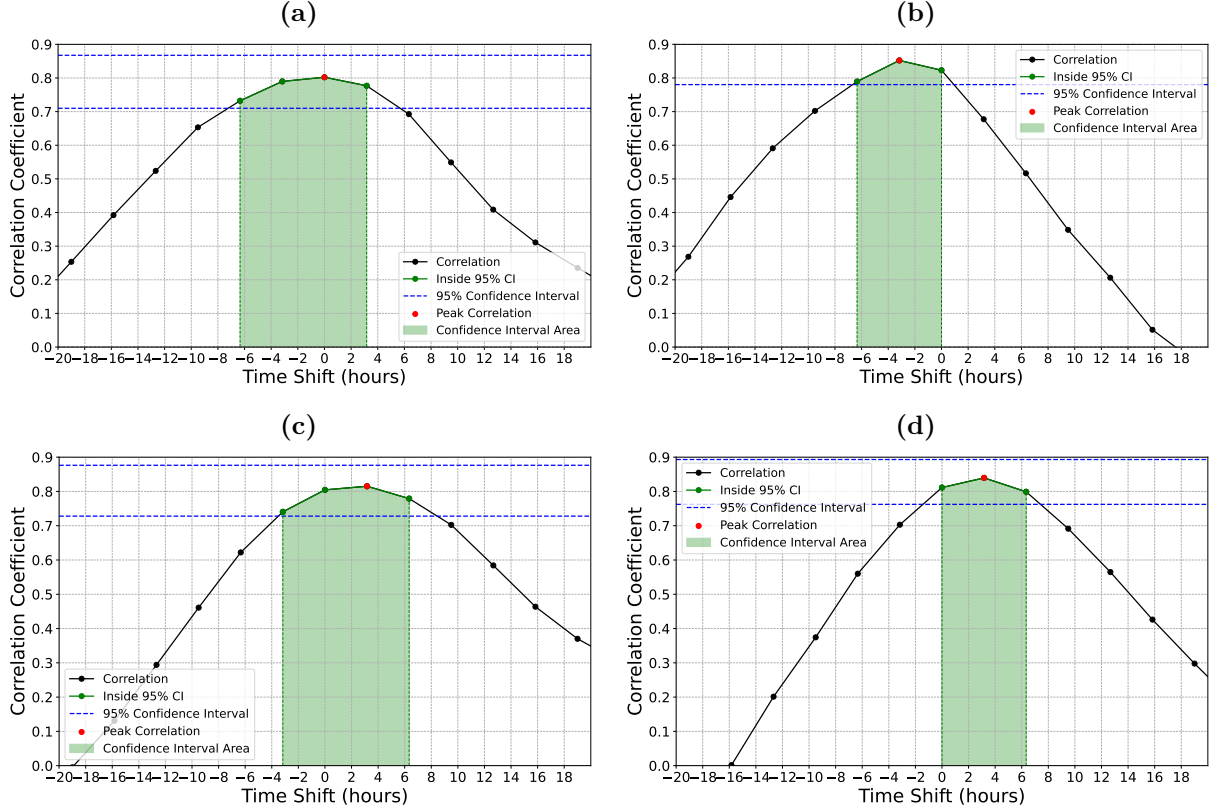


Figure 5. Cross-correlation of $\tilde{\Delta a}$ with the PCN index and $|\text{Dst}|$. Top row: cross-correlation with PCN for (a) May 2024 and (b) October 2024. Bottom row: cross-correlation with $|\text{Dst}|$ for (c) May 2024 and (d) October 2024. In all panels: black curve = Pearson $r(\tau)$; green segment = lags within the 95 % confidence interval; red dot = peak correlation; blue dashed lines = 95 % confidence bounds on r_{peak} ; negative τ = index leads. PCN peaks at $\tau = 0$ h (May) and $\tau = -3.17$ h (October), indicating that the index leads or is simultaneous with the altitude response; $|\text{Dst}|$ peaks near $\tau \approx +3$ h (altitude leads the index).

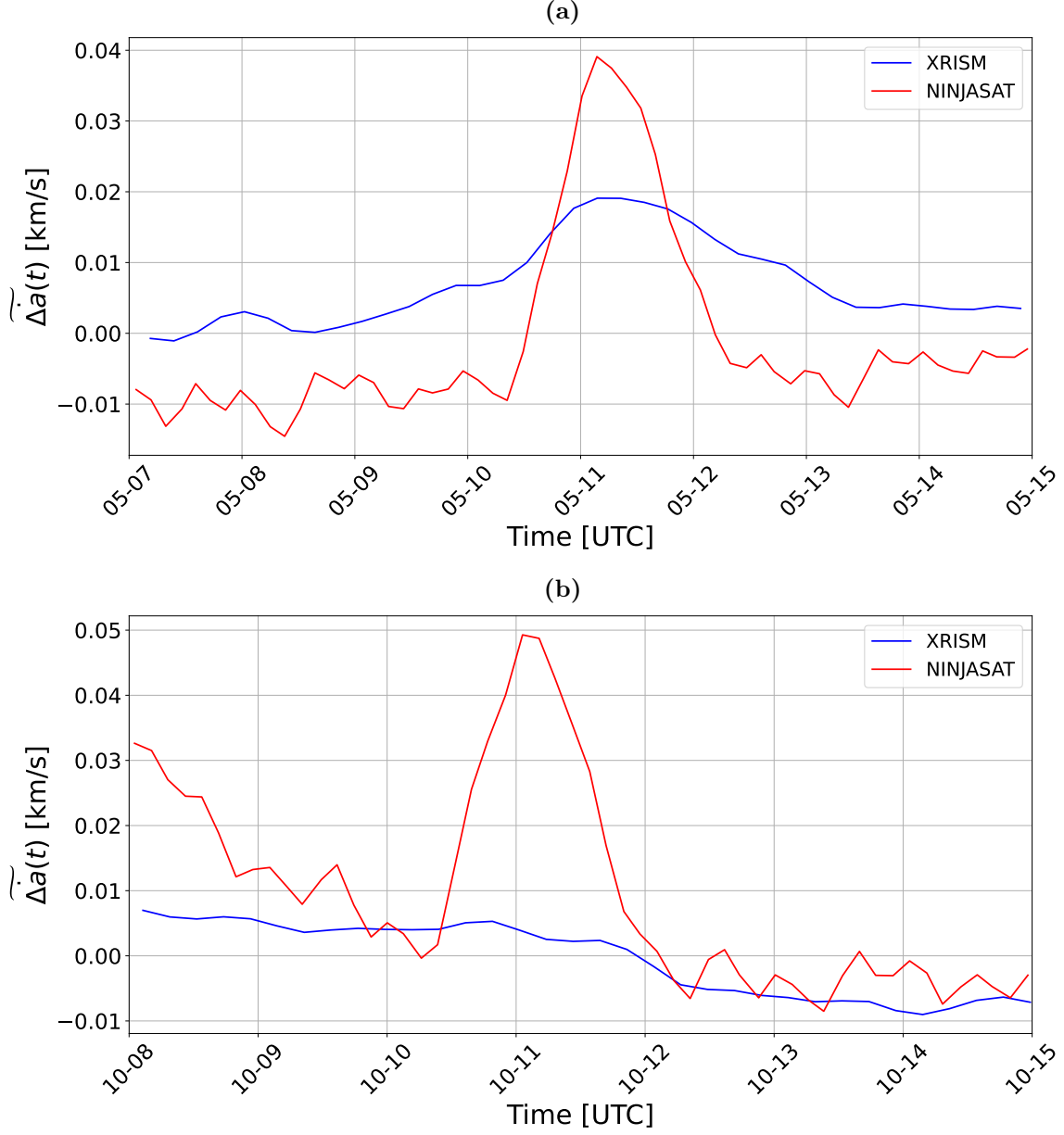


Figure 6. Altitude-change rate comparison between NinjaSat and XRISM. (a) May 2024; (b) October 2024. Red: Δa for NinjaSat (~ 500 km, 97° inclination). Blue: Δa for XRISM (~ 560 km, 31° inclination). In May both satellites show a clear positive excursion, with the NinjaSat peak (≈ 0.04 km s $^{-1}$) approximately twice the XRISM peak (≈ 0.02 km s $^{-1}$), indicating that heating extended to low latitudes. In October NinjaSat peaks at ≈ 0.05 km s $^{-1}$ while XRISM remains near zero, indicating polar-localised heating.

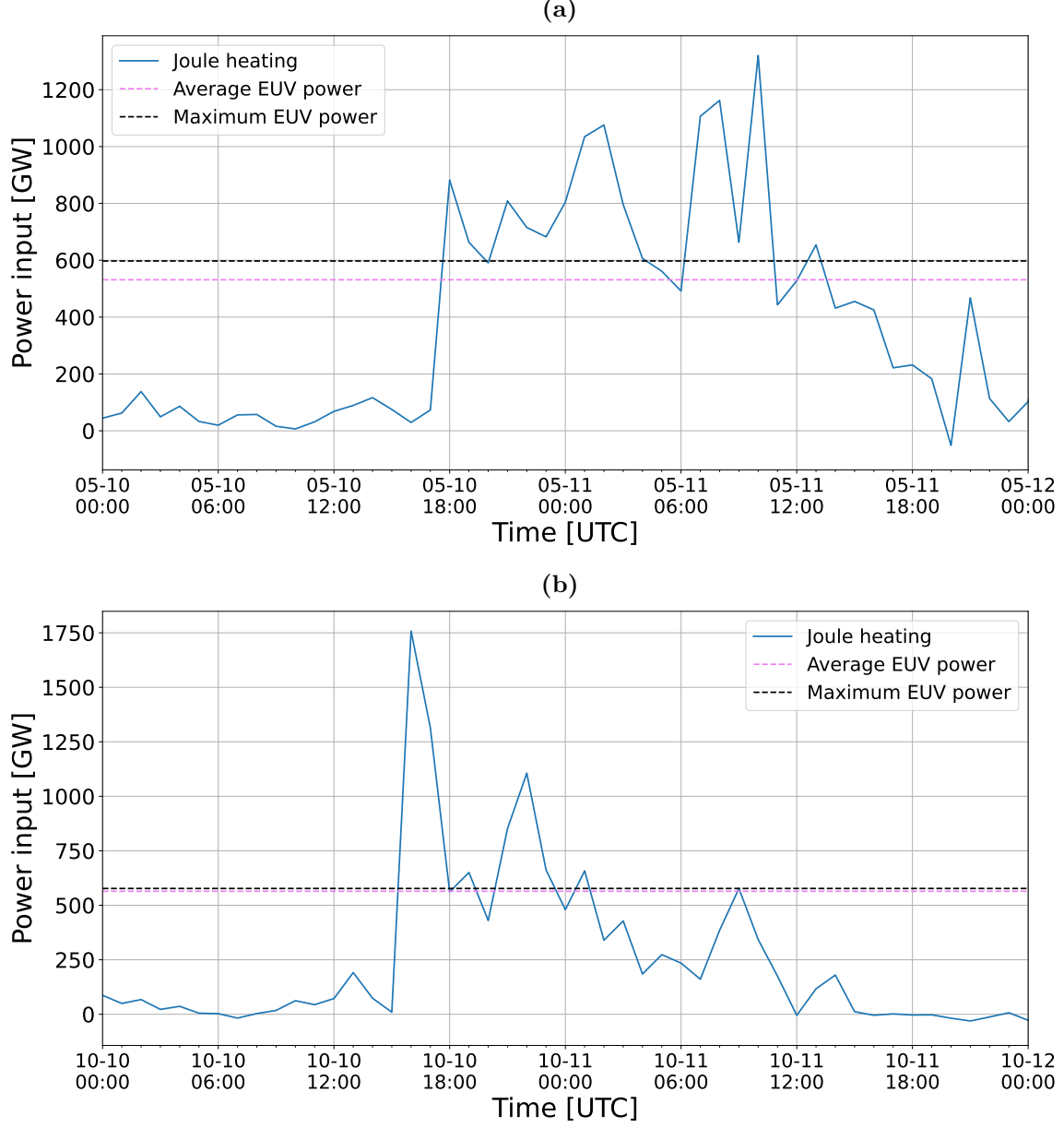


Figure 7. Storm-time energetics. (a) May 2024; (b) October 2024. Blue solid: hemispheric Joule-heating power Q_J derived from the PCN index via the empirical relation of Ref.¹⁸ (Eq. 5). Pink dashed: average EUV heating power during the storm interval, from the companion study⁶ (≈ 530 GW in May; ≈ 565 GW in October). Black dashed: maximum EUV heating power (≈ 600 GW in May; ≈ 577 GW in October). Q_J peaks at ~ 1320 GW (May) and ~ 1760 GW (October), a factor of ~ 2.5 – 3 above the EUV baseline and more than an order of magnitude above the quiet-time Joule-heating rate (~ 95 GW).