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Nighttime Westward Equatorial Electrojet Observed During the January 2026 Geomagnetic Storm

Key Points:

- The equatorial electrojet (EEJ) response to the January 2026 geomagnetic storm is examined using magnetometer data
- EEJ strengths estimated using the conventional two-station method suggest the presence of nighttime westward EEJ currents
- A chain of low-latitude magnetometers provides additional evidence for nighttime westward EEJ currents

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Abstract The equatorial electrojet (EEJ) is a narrow band of zonal electric current flowing in the E-region ionosphere within approximately $\pm 2^\circ$ latitude of the magnetic equator. At night, the EEJ is generally considered very weak because of low ionospheric conductivity. However, evidence in the literature suggests that strong EEJ currents might occur on the night side during geomagnetic storms. This paper presents observations of the nighttime EEJ during the January 2026 geomagnetic storm. During the storm main phase, the EEJ strengths estimated using the conventional two-station method indicate the presence of intense westward EEJ currents (150–200 mA/m) in the Thailand and Philippine sectors during pre-sunrise hours. Observations from a chain of low-latitude magnetometers distributed across the Thailand sector further reveal the latitudinal structure of the ground magnetic field signatures associated with the nighttime westward EEJ, providing additional evidence for the presence of nighttime westward EEJ currents. The nighttime westward EEJ in the Thailand and Philippine sectors coincides with strong eastward EEJ (~ 250 mA/m) in the Peruvian sector on the dayside, consistent with the influence of prompt penetration electric fields from high latitudes. Intensifications of the nighttime westward and daytime eastward EEJ are accompanied by enhanced asymmetric geomagnetic field disturbances at mid latitudes and equatorward expansion of auroral electrojet signatures.

1. Introduction

The Pedersen and Hall conductivities of the mid- and low-latitude ionosphere are largest in the dayside *E* region at altitudes of approximately 95–150 km (e.g., Richmond, 2011). Tidal winds at these altitudes are on the order of several tens of meters per second in the horizontal component and are an effective driver of daytime ionospheric dynamo currents on the order of milliamperes per meter during geomagnetically quiet periods (e.g., Forbes & Lindzen, 1976; Richmond et al., 1976; Richmond & Roble, 1987). These currents, often referred to as solar quiet (Sq) currents, are largely confined to the dayside (e.g., Chulliat et al., 2025; Matsushita & Maeda, 1965; Takeda, 2002), as the ionospheric conductivities are substantially larger during day than night. The presence of Sq currents during day and their absence during night leads to regular daily Sq variations of the geomagnetic field on the order of a few tens of nanoteslas observed at ground observatories over mid and low latitudes.

The magnitude of geomagnetic Sq variation in the horizontal (H) component is enhanced near the magnetic equator (e.g., Egedal, 1947; Soares et al., 2020). At the magnetic equator, the background magnetic field is purely horizontal, and this unique configuration of the geomagnetic field allows a vertical electric field of the order of millivolts per meter to be maintained (e.g., Raghavarao & Anandarao, 1987; Richmond, 1973; Untiedt, 1967). The vertical electric field leads to an enhancement of the effective zonal ionospheric conductivity (Baker & Martyn, 1953; Hirono, 1952). The enhanced zonal conductivity, in turn, enables a strong zonal ionospheric current to flow along the dayside magnetic equator, explaining anomalously large Sq variations near the magnetic equator.

Under the assumption that the ionosphere is an electrically conducting thin shell, the ionospheric current can be expressed as follows (Tsunomura, 1999, and references therein):

$$\mathbf{J} = \mathbf{\Sigma} \cdot \mathbf{E}, \quad (1)$$

or in a matrix-vector form:

$$\begin{bmatrix} J_{\theta} \\ J_{\varphi} \end{bmatrix} = \begin{bmatrix} \int \sigma_{\theta\theta} dz & \int \sigma_{\theta\varphi} dz \\ -\int \sigma_{\theta\varphi} dz & \int \sigma_{\varphi\varphi} dz \end{bmatrix} \begin{bmatrix} E_{\theta} \\ E_{\varphi} \end{bmatrix}, \quad (2)$$

where $\mathbf{J}$ is height-integrated current density, $\mathbf{\Sigma}$ is height-integrated conductivity tensor, and $\mathbf{E}$ is electric field. z , θ , and φ are height, colatitude, and longitude in an orthogonal magnetic coordinate system, respectively. The components of the conductivity tensor are height-integrated values of $\sigma_{\theta\theta}$, $\sigma_{\theta\varphi}$, and $\sigma_{\varphi\varphi}$, which are given by:

$$\sigma_{\theta\theta} = \frac{\sigma_{\parallel} \sigma_P}{\sigma_{\parallel} \sin^2 I + \sigma_P \cos^2 I}, \quad (3)$$

$$\sigma_{\theta\varphi} = \frac{\sigma_{\parallel} \sigma_H \sin I}{\sigma_{\parallel} \sin^2 I + \sigma_P \cos^2 I}, \quad (4)$$

and

$$\sigma_{\varphi\varphi} = \sigma_P + \frac{\sigma_H^2 \cos^2 I}{\sigma_{\parallel} \sin^2 I + \sigma_P \cos^2 I}. \quad (5)$$

Here $\sigma_{\parallel}$, σ_P , and σ_H are parallel, Pedersen, and Hall conductivities, respectively, and I is magnetic inclination. At the magnetic equator, $E_{\theta} = 0$ and $I = 0$, and thus using Equations 2 and 5, the zonal current intensity is:

$$J_{\varphi} = \int \sigma_{\varphi\varphi} dz E_{\varphi} = \int \left(\sigma_P + \frac{\sigma_H^2}{\sigma_P} \right) dz E_{\varphi} = \int \sigma_C dz E_{\varphi}. \quad (6)$$

σ_C is the so-called Cowling conductivity (e.g., Chapman, 1956) and is much larger than $\sigma_{\varphi\varphi}$ outside the magnetic equator ($|I| > 0$), resulting in an enhanced zonal current confined near the magnetic equator.

Chapman (1951) introduced the concept of the equatorial electrojet (EEJ), a narrow band of zonal ionospheric current flowing along the dayside magnetic equator that is superimposed upon background Sq currents. Sounding rocket measurements have confirmed the presence of EEJ, with its peak current intensity at an altitude of 105–110 km (e.g., Davis et al., 1967; Pfaff Jr et al., 1997; Sampath & Sastry, 1979). Characteristics of EEJ, such as intensity and width, have been studied using north-south chains of ground-based magnetometers across the magnetic equator in different longitude sectors (e.g., Doumouya et al., 1998; Fambitakoye & Mayaud, 1976; Forbush, 1961; Onwumechilli, 1959; Rabiou et al., 2013; Yacob, 1966).

The “two-station” method is a simple and widely used technique for estimating the EEJ strength from ground-based magnetometer data (e.g., Anderson et al., 2002, 2004; Archana et al., 2018; Fang et al., 2008;

Rastogi, 1989; Sharma et al., 2026; Stolle et al., 2008; Tulasi Ram et al., 2024; Yizengaw et al., 2014). It uses H-component magnetic field perturbations measured at a pair of ground stations: one located near the magnetic equator and the other in the same longitude sector but outside the EEJ belt. The EEJ-related enhancement in H at the magnetic equator is obtained by subtracting the H variation observed outside the EEJ belt from that measured near the magnetic equator.

The EEJ has also been studied using satellite-borne magnetometer data (e.g., Alken et al., 2015; Cain & Sweeney, 1972; Y. Huang et al., 2025; G. Jadhav et al., 2002; Lühr et al., 2004). As a low-Earth-orbit satellite flies over the magnetic equator, the magnetic effect of the EEJ is observed as a localized change in the magnetic field centered at the magnetic equator. EEJ intensities observed by ground-based and satellite-borne magnetometers are generally in good agreement (e.g., Ayebare et al., 2023; Benaissa et al., 2017; Manoj et al., 2006; Soares et al., 2022).

The zonal electric field in the low-latitude *E* region is usually eastward during day under quiet geomagnetic conditions (e.g., Alken et al., 2013; Richmond et al., 1980; Scherliess & Fejer, 1999), and accordingly, the average daytime EEJ is directed eastward. However, the direction of the EEJ is occasionally observed to reverse to the westward direction, the phenomenon known as counter-electrojet, or CEJ (Amory-Mazaudier et al., 2017; Gouin, 1962; Mayaud, 1977). The CEJ results from the reversal of the zonal electric field (e.g., Pandey, Sekar, et al., 2018). Various factors can contribute to the westward reversal of the daytime zonal electric field under geomagnetically quiet conditions, including tidal waves (Hanuise et al., 1983; Singh et al., 2018), equatorial Kelvin waves (A. P. Jadhav et al., 2025), and vertical winds (Raghavarao & Anandarao, 1980). Occurrence characteristics of the quiet-time CEJ have been extensively studied by both ground-based measurements (e.g., Marriott et al., 1979; Rabiou et al., 2017; Rastogi, 1974; Soares et al., 2019) and satellite observations (Sreelakshmi & Vichare, 2025; Zhou et al., 2018).

The quiet-time EEJ exhibits substantial spatial and temporal variability. In the spatial domain, the daytime EEJ intensity varies with longitude, mainly due to longitudinal differences in the background magnetic field (Doumouya et al., 2003; Rastogi, 1962) and tidal winds (England et al., 2006; Lühr et al., 2008; Soares et al., 2018; H. Wang et al., 2020). In the temporal domain, the EEJ intensity exhibits an 11-year solar-cycle variation, reflecting enhanced Cowling conductivity during solar maximum periods (e.g., Alken & Maus, 2007; Matzka et al., 2017; Rastogi & Iyer, 1976). In addition, the EEJ shows seasonal and day-to-day variability. Numerical studies suggest that these variations arise primarily from changes in neutral winds at *E*-region altitudes (Kawano-Sasaki & Miyahara, 2008; Yamazaki, Richmond, Maute, Liu, et al., 2014; Yamazaki, Richmond, Maute, Wu, et al., 2014). Simultaneous observations of the daytime EEJ and *E*-region winds have revealed a strong correlation between EEJ intensity and equatorial zonal wind velocity during geomagnetically quiet periods (Yamazaki et al., 2021, 2024).

Little is known about the behavior of the EEJ at night. The characteristic decay time of the post-sunset equatorial *E*-region plasma is of the order of 10^2 s (Farley, 2009), and thus plasma densities in the *E* region rapidly decrease after sunset to levels one to two orders of magnitude lower than during daytime. Accordingly, the *E*-region conductivity is considered very low throughout the night. The local-time variation of the height-integrated Cowling conductivity is shown in Figure 1a. It was calculated using Equation 6, with Pedersen and Hall conductivities obtained from the ionospheric conductivity model at the World Data Center (WDC) for Geomagnetism, Kyoto (see Maeda, 1977, for formula), which is based on the International Reference Ionosphere (IRI; Bilitza et al., 2017) and the neutral atmospheric model NRLMSISE-00 (Picone et al., 2002). The conductivities were integrated over altitudes from 90 to 150 km. The nighttime height-integrated Cowling conductivity is ~ 1 S at 02:00–05:00 local time (LT), about two orders of magnitude smaller than its daytime value near noon (~ 100 S). These values are consistent with previously reported estimates (e.g., Richmond & Roble, 1987; Takeda & Araki, 1985).

The quiet-time equatorial zonal electric field is predominantly westward at night (e.g., Fejer et al., 2008). Although its magnitude is comparable to that of the daytime eastward electric field, the nighttime EEJ is expected to be very weak in the *E* region because of the low ionospheric conductivity and may not be readily detectable. Onwumechili (1992) compiled historical sounding rocket measurements conducted at night over mid- and low-latitude regions. He identified three measurements at mid latitudes and six near the magnetic equator. No evidence of nighttime ionospheric currents was found in any of these measurements, except for one observation by Davis

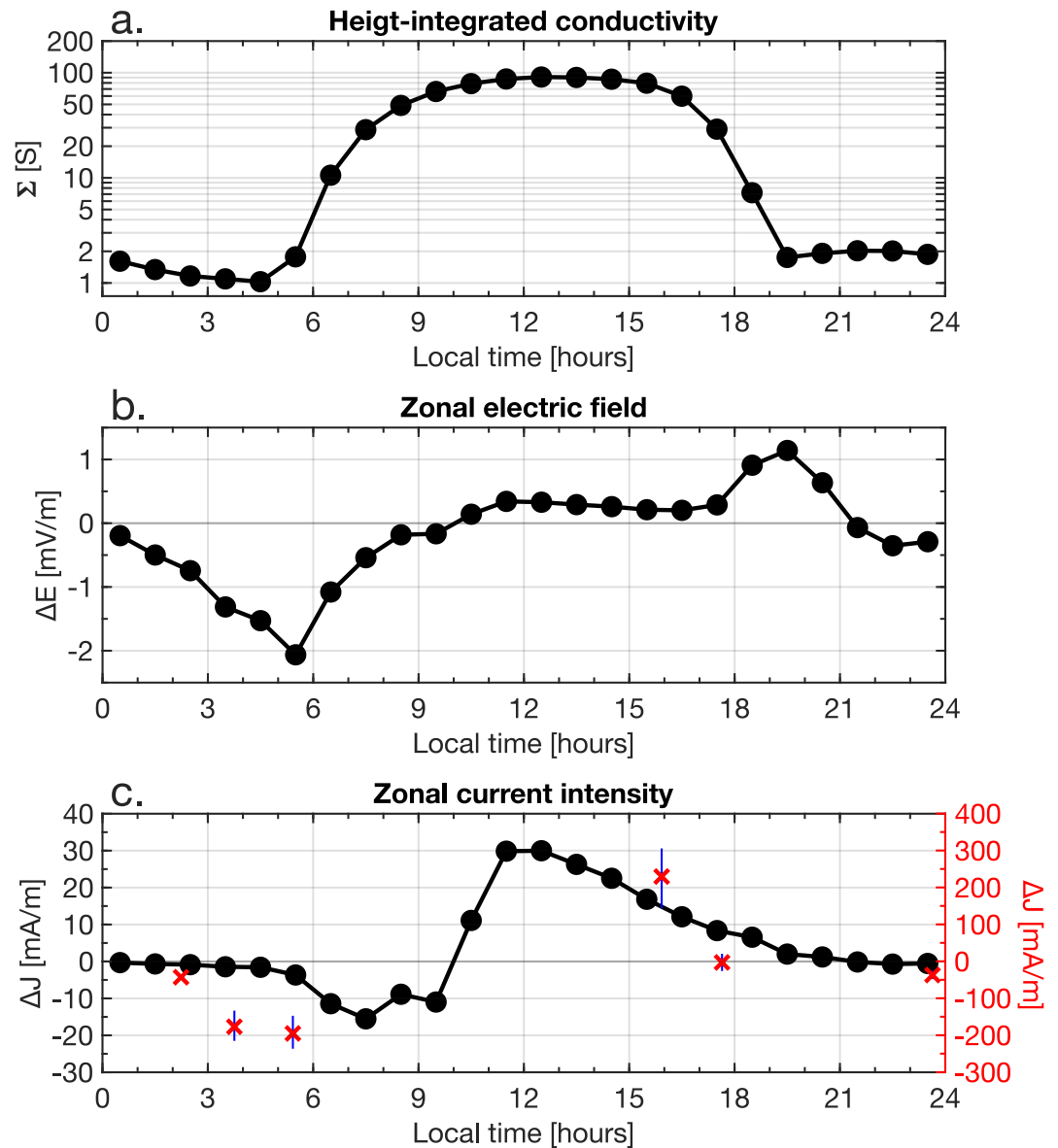


Figure 1. Local-time variations of (a) height-integrated Cowling conductivity, (b) zonal electric field perturbation associated with prompt penetration, and (c) the corresponding zonal current intensity perturbation. Red crosses in panel (c) denote equatorial electrojet (EEJ) current perturbations inferred from ground-based ΔH_{EEJ} measurements in six longitude sectors at 21:00 UT on 19 January 2026. The Cowling conductivity was computed along the magnetic equator using Equation 6 and Pedersen and Hall conductivities integrated over 90–150 km from the world data center Kyoto ionospheric conductivity model for 21:00 UT on 19 January 2026. The zonal electric field perturbation was estimated from the average storm-time equatorial vertical plasma drift perturbation reported by C.-S. Huang (2015). The zonal current intensity perturbation was calculated as the product of the height-integrated Cowling conductivity and the zonal electric field perturbation. Because the height-integrated Cowling conductivity and the zonal current intensity perturbation were derived for a fixed time of 21:00 UT on 19 January 2026, their local-time variations may also be affected by longitudinal variations.

et al. (1967) near the magnetic equator, in which a small magnetic fluctuation detected around midnight at an altitude of ~ 100 km was attributed to a very weak westward EEJ current.

In a more recent study, Zhou et al. (2020) investigated the existence of the nighttime EEJ using magnetic field measurements from the CHAMP satellite during 2001–2009. They found that nighttime data occasionally exhibit localized magnetic signatures near the magnetic equator, consistent with a westward EEJ. Their statistical analysis of these signatures showed that the intensity of the nighttime westward EEJ is ~ 3 mA/m at 03:00 LT under geomagnetically quiet and moderately active conditions and increases toward later local times reaching

~9 mA/m at 06:00 LT. Since they used only the data containing clear EEJ signatures, the mean intensity of the nighttime EEJ may in fact be even smaller.

The nighttime westward EEJ of 3–9 mA/m reported by Zhou et al. (2020) would produce ground magnetic field variations of only a few nT. However, observational evidence in the literature suggests that the nighttime westward EEJ might be substantially stronger during geomagnetic storms. For instance, Abdu et al. (2007), using the two-station method, reported a magnetic field variation of ~30 nT in the difference between H perturbations at Yap (YAP, 9.3°N, 138.5°E) and at Guam (GUA, 13.6°N, 144.9°E) during pre-sunrise hours (04:00–05:00 LT) of the October 2003 geomagnetic storm. Fejer et al. (2007) observed a large variation ~100 nT in the H difference between at YAP and Okinawa (OKI, 26.8°N, 128.2°E) around sunrise (~05:00 LT) during the November 2004 geomagnetic storm. Tsuji et al. (2012), also using the YAP–OKI pair, reported an H difference of ~35 nT during 02:30–03:30 LT in the September 2002 geomagnetic storm. Similar magnetic effects were also reported by Shinbori et al. (2013) for the May 2002 geomagnetic storm and by Hashimoto et al. (2017) for several substorm events. More recently, during the May 2024 geomagnetic storm, Y. Huang et al. (2026) observed a variation of ~70 nT in the H difference between Colombo (CMB, 7.0°N, 80.1°E) and Gan International Airport (GAN, 0.7°S, 73.2°E) around 04:00 LT. In all cases, H variations near the magnetic equator showed negative deviations relative to those outside the EEJ belt, indicating a nighttime westward EEJ prior to sunrise. However, it is still unclear whether the H difference obtained from the two-station method reliably represents nighttime EEJ strength in the presence of extreme geomagnetic disturbances during geomagnetic storms, because no study has shown that nighttime EEJ magnetic signatures are confined near the magnetic equator in the same manner as those of the daytime EEJ.

A majority of previous studies on the storm impact on the EEJ are concerned with the daytime response (e.g., Kikuchi et al., 1996, 2008; Le Huy & Amory-Mazaudier, 2005; Le et al., 2024; Rastogi, 1977; Veenadhari et al., 2010; K. Zhang et al., 2024). Two drivers have been identified to cause daytime EEJ disturbances during geomagnetically active periods. One is prompt penetration electric field from the polar regions (e.g., Manoj et al., 2008; Nishida, 1968), and the other is disturbance dynamo electric field driven by storm-time thermospheric winds (e.g., Blanc & Richmond, 1980). Their effects on the EEJ have distinct response times. That is, the effect of prompt penetration electric field is observed immediately after a rapid increase or decrease in solar wind energy input into the polar regions (Kikuchi & Hashimoto, 2016), while the disturbance dynamo effect develops at low latitudes a few hours after storm onset because of the slow response of thermospheric winds and can persist for hours after the solar wind energy input has ceased (Fuller-Rowell et al., 2002; C.-M. Huang et al., 2005). Accordingly, the prompt penetration electric field effect is often prominent during the storm main phase (e.g., C.-S. Huang et al., 2005; C.-S. Huang, 2015), while the disturbance dynamo effect tends to be observed during the storm recovery phase (e.g., Pandey, Chakrabarty, & Sekar, 2018; Yamazaki & Kosch, 2015). The previous reports on the nighttime EEJ during geomagnetic storms found its maximum effect during the main phase of geomagnetic storms, suggesting the involvement of prompt penetration electric field.

The LT dependence of the prompt penetration electric field at low latitudes is known from previous observations (e.g., Fejer & Scherliess, 1995; Fejer & Scherliess, 1997; C.-S. Huang, 2015). A sudden increase in the solar wind energy input at the beginning of a geomagnetic storm or substorm leads to an increase in the eastward daytime electric field and the westward nighttime electric field. This pattern is robust across events with some minor seasonal and longitudinal dependence (e.g., Fejer et al., 2008; C. Xiong et al., 2016). C.-S. Huang (2015) derived the average LT variation in the equatorial vertical plasma drift velocity perturbation using C/NOFS satellite observations during the main phase of five geomagnetic storms in 2012. Figure 1b shows the results derived by C.-S. Huang (2015) but expressed in terms of the equatorial zonal electric field perturbation. The nighttime westward electric field is strongest during 05:00–06:00 LT. Figure 1c (black dots and connecting line) displays the corresponding EEJ perturbation; that is, the height-integrated Cowling conductivity (Figure 1a) multiplied by the zonal electric field perturbation (Figure 1b). The calculated EEJ perturbation is small throughout the night, despite the strong zonal electric field perturbation during pre-sunrise hours.

The present study is motivated by this apparent discrepancy between previous observations and theoretical expectations. That is, while nighttime EEJ currents are predicted to be weak (Figure 1), several studies have suggested the occurrence of strong nighttime EEJ currents during geomagnetic storms. The primary question we would like to address in this study is whether the nighttime EEJ magnetic signatures derived using the two-station method during geomagnetic storms are indeed associated with the EEJ. We focus on the recent geomagnetic storm

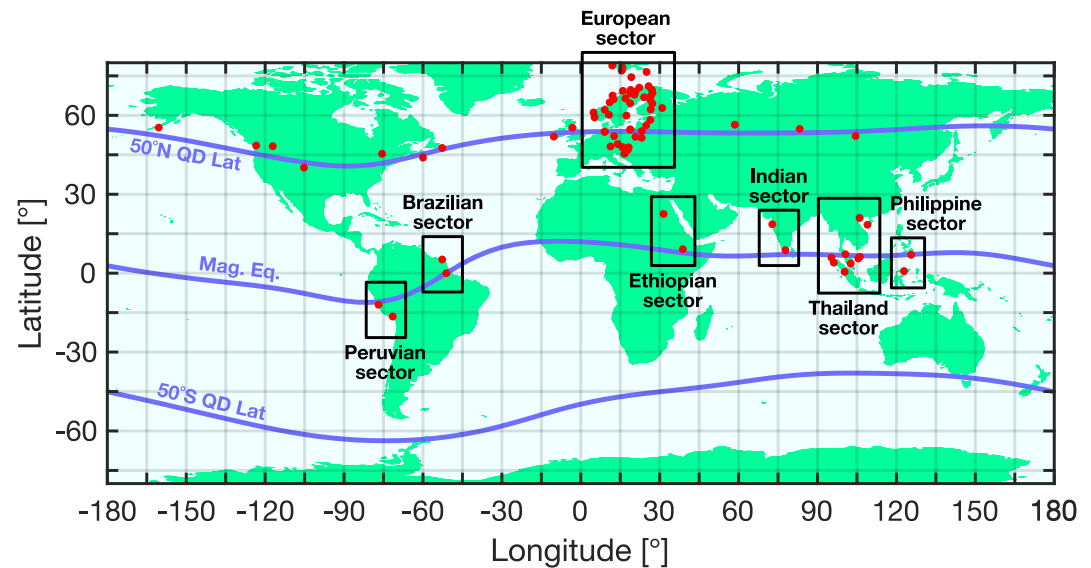


Figure 2. Map of the ground-based magnetometer stations used in this study.

event in January 2026. We first demonstrate that the H difference obtained from the conventional two-station method suggests the presence of strong nighttime westward EEJ currents during the storm main phase. Then, we examine H -component perturbations from a chain of low-latitude magnetometers distributed across the magnetic equator to determine whether the associated magnetic signatures are confined to the vicinity of the magnetic equator. This analysis helps clarify whether the H difference obtained from the two-station method can reliably identify the nighttime EEJ during the geomagnetic storm. Finally, we examine geomagnetic field perturbations at higher latitudes to provide insight into global electrodynamic coupling between the polar and equatorial regions.

2. Data and Analysis Method

2.1. Ground-Based Magnetometer Data

The main data set used in this study consists of ground-based magnetometer observations with a one-minute time resolution collected from multiple sources. The geographical locations of the stations are shown in Figure 2. Also, their geographical latitude and longitude, as well as Quasi-Dipole (QD) latitude and longitude (Laundal & Richmond, 2017), are listed in Tables 1–3.

2.1.1. Equatorial Regions

The EEJ strength is evaluated using the two-station method (e.g., Rastogi, 1989). As mentioned earlier, this technique involves geomagnetic field perturbations observed at a pair of stations: one station near the magnetic equator and the other station outside the EEJ belt, typically $5\text{--}10^\circ$ away from the magnetic equator, in the same longitude sector. We examine the EEJ in six longitude sectors (see Table 1) using the following pairs of the stations: JIC–ARE for the Peruvian sector ($\sim 75^\circ\text{W}$), MAA–KOU for the Brazilian sector ($\sim 50^\circ\text{W}$); ENT–ABS for the Ethiopian sector ($\sim 35^\circ\text{E}$), TIR–ABG for the Indian sector ($\sim 75^\circ\text{E}$); SKL–SCN for the Thailand sector ($\sim 100^\circ\text{E}$); DAV–LWK for the Philippine sector ($\sim 125^\circ\text{E}$). Note that data coverage in the latter two sectors relies particularly on magnetometers in Eastern and Western Indonesia.

JIC and ARE are part of the Low-Latitude Ionospheric Sensor Network (LISN; Valladares & Chau, 2012) and their data are provided by the Radio Observatorio de Jicamarca, Peru. MAA data (Mendel Martins et al., 2024) are provided by the Observatório Nacional and Federal University of Para (UFPA), Brazil, and GFZ Helmholtz Center for Geosciences (GFZ), Germany. KOU is provided by IPGP, France. ENT data (Nel et al., 2025) are provided by GFZ, Germany; South African National Space Agency, South Africa; and Space Science and Geospatial Institute (SSGI), Ethiopia, while ABS data are provided by National Research Institute of Astronomy and Geophysics, Egypt. TIR and ABG data are provided by the Indian Institute of Geomagnetism, India. SKL is

Table 1
Coordinates of Stations in Equatorial Regions Used in the Study

	Station name	Code	Lat	Lon	QD lat	QD lon
Peruvian sector	Jicamarca	JIC	12.0°S	76.9°W	1.0°S	4.0°W
	Arequipa	ARE	16.5°S	71.5°W	6.0°S	0.4°E
Brazilian sector	Macapa	MAA	0.0°S	51.1°W	0.3°S	22.0°E
	Kourou	KOU	5.2°N	52.7°W	5.4°N	22.1°E
Ethiopian sector	Entoto	ENT	9.1°N	38.8°E	1.5°N	112.6°E
	Abu Simbel	ABS	22.5°N	31.5°E	15.5°N	104.8°E
Indian sector	Tirunelveli	TIR	8.7°N	77.8°E	1.7°N	150.9°E
	Alibag	ABG	18.6°N	72.8°E	12.9°N	146.1°E
Thailand sector	Phu Thuy	PHU	21.0°N	106.0°E	15.6°N	179.1°E
	Ledong	LDN	18.4°N	109.0°E	12.8°N	178 °W
	Songkhla	SKL	7.2°N	100.6°E	0.5°N	173.5°E
	Sabang	SBG	5.9°N	95.3°E	1.2°S	168.3°E
	Meulaboh	MLB	4.0°N	96.2°E	3.1°S	169.2°E
	Sicincin	SCN	0.5°S	100.3°E	8.0°S	173.1°E
	Kepahyang	KPY	3.7°S	102.6°E	11.4°S	175.6°E
	Lampung Selatan	LPS	5.6°S	105.5°E	13.4°S	178.3°E
	Serang	SRG	6.2°S	106.1°E	14.0°S	178.8°E
	Davao	DAV	7.0°N	125.6°E	0.0°N	161.8°W
Philippine sector	Luwuk	LWK	0.8°S	122.9°E	8.2°S	164.5°W

part of the Southeast Asia Low-latitude Ionospheric Network (SEALION; Maruyama et al., 2007) and its data are provided by the National Institute of Information and Communications Technology (NICT), Japan, and the Geo-Informatics and Space Technology Development Agency, Thailand. SCN data are provided by the Meteorology, Climatology, and Geophysical Agency (BMKG), Indonesia. DAV is part of the Magnetic Data Acquisition System (MAGDAS; Yumoto & the MAGDAS Group, 2006; Yumoto & the MAGDAS Group, 2007; Uozumi et al., 2008) and its data are provided by the International Research Center for Space and Planetary Environmental

Table 2
Coordinates of Stations in Mid-Latitude Regions Used in the Study

Station name	Code	Lat	Lon	QD lat	QD lon
Shumagin	SHU	55.4°N	160.5°W	53.2°N	98.3°W
Victoria	VIC	48.5°N	123.4°W	53.1°N	60.4°W
Newport	NEW	48.3°N	117.1°W	54.1°N	53.1°W
Boulder	BOU	40.1°N	105.2°W	48.1°N	37.3°W
Ottawa	OTT	45.4°N	75.6°W	53.4°N	3.3°E
Sable Island	SBL	43.9°N	60.0°W	48.5°N	22.6°E
St John's	STJ	47.6°N	52.7°W	50.5°N	30.8°E
Valentia	VAL	51.9°N	10.3°W	48.4°N	68.6°E
Eskdalemuir	ESK	55.3°N	3.2°W	52.0°N	75.3°E
Wingst	WNG	53.7°N	9.1°E	49.8°N	85.2°E
Hel	HLP	54.6°N	18.8°E	50.8°N	93.9°E
Arti	ARS	56.4°N	58.6°E	53.3°N	132.0°E
Novosibirsk	NVS	54.8°N	83.2°E	51.6°N	157.0°E
Irkutsk	IRT	52.3°N	104.3°E	48.5°N	178.8°E

Science (i-SPES), Kyushu University, Japan. KOU and ABG are also part of the International Real-time Magnetic Observatory Network (INTERMAGNET; Love & Chulliat, 2013).

The magnetic field variation due to the EEJ is retrieved using the H-component magnetic field data. For each station, the quiet-nighttime baseline is determined as the average value of H over periods corresponding to 22:00–02:00 LT and $Hp30 < 3$ using the available data within the month of January 2026. Here, $Hp30$ is the geomagnetic activity index introduced by Yamazaki et al. (2022), which is an open-end high-cadence (30 min) alternative for the widely used three-hourly Kp index (Matzka et al., 2021). The baseline value is then subtracted from the corresponding H time series, which removes the magnetic effects of the core and crustal fields. Finally, the baseline-corrected H , denoted here as ΔH , outside the EEJ belt is subtracted from ΔH near the magnetic equator. This removes the magnetic effects of large-scale magnetospheric currents such as the ring current, partial ring current, and tail current as well as global-scale ionospheric Sq currents, isolating the magnetic effect of the EEJ. The residual magnetic field is denoted as ΔH_{EEJ} .

For the EEJ in the Thailand sector, we also use ΔH from other low-latitude stations in the same longitude sector to examine the meridional structure of the EEJ. These stations include PHU (15.6°N QD latitude), LDN (12.8°N QD latitude), SKL (0.5°N QD latitude), SBG (1.2°S QD latitude), MLB (3.2°S QD latitude), SCN (8.0°S QD latitude), KPY (11.4°S QD latitude), LPS (13.4°S QD latitude), and SRG (14.0°S QD latitude); see also Table 1. PHU is part of INTERMAGNET, while LDN belongs to the Chinese Meridian Project (C. Wang et al., 2024). SBG, MLB, KPY, LPS, and SRG data are provided by BMKG, Indonesia.

2.1.2. Mid-Latitude Region

The SYM and ASY indices (Iyemori, 1990) with a one minute time resolution, as provided by WDC, Kyoto, are used to monitor mid-latitude geomagnetic field disturbances during the January 2026 geomagnetic storm. The SYM-H index quantifies the zonally symmetric part of mid-latitude geomagnetic field disturbances in the H component and serves as a measure of magnetospheric ring current intensity. The ASY-H and ASY-D indices quantify the zonally asymmetric part of mid-latitude geomagnetic field disturbances in the geomagnetic northward and eastward directions, respectively.

In addition, magnetometer data from 14 mid-latitude stations located near $\sim 50^\circ$ N QD latitude (see Table 2) are analyzed to complement the interpretation of the ASY-H and ASY-D indices. All stations are part of INTERMAGNET. For each station, one-minute data in the H component were corrected for the symmetric ring current contribution by subtracting the SYM-H index multiplied by $\cos \theta_{QD}$, where θ_{QD} denotes the QD latitude. The magnetic northward (N) and eastward (E) components were then obtained through vector rotation as described in Chen et al. (2024), using the declination angle from the CHAOS-7 geomagnetic field model (Finlay et al., 2020). The Sq variation was estimated by fitting 24-, 12-, 8-, and 6-hr Fourier harmonics to quiet-time ($Hp30 < 3$) data of the same month and subsequently subtracted, together with its mean value, from the N and E components. The resulting magnetic field perturbations (ΔN and ΔE) represent the effect of magnetospheric and ionospheric currents but excluding contributions from the symmetric ring current and Sq currents.

2.1.3. Auroral and Subauroral Regions

The auroral electrojet indices (AE, AU, and AL; Davis & Sugiura, 1966) with a 1 minute time resolution, as provided by WDC, Kyoto, are used to monitor auroral electrojet activity. In addition, ground-based magnetometer data from stations at auroral and subauroral latitudes in the European sector (see Table 3) are also analyzed to provide more detailed information about the latitudinal extent of the auroral electrojet. This additional data set consists of 30 stations from the IMAGE magnetometer network (Tanskanen, 2009) and 14 stations from INTERMAGNET, with some stations belonging to both. The residual magnetic field perturbations ΔN and ΔE were derived in the same way as described above for the analysis of mid-latitude data.

2.2. Swarm Magnetic Field Data

Swarm is an Earth Explorer mission of the European Space Agency (ESA), dedicated to monitoring the Earth's magnetic field and near-Earth plasma environment (Friis-Christensen et al., 2006). Swarm consists of three identical satellites (Swarm A, B, and C) flying in near-polar orbits with inclination angles of approximately 87° .

Table 3

Coordinates of Stations in Auroral- and Subauroral Regions Used in the Study

Station name	Code	Lat	Lon	QD lat	QD lon
Ny Ålesund	NAL	78.9°N	11.9°E	76.8°N	105.2°E
Longyearbyen	LYR	78.2°N	15.8°E	75.9°N	106.7°E
Hornsund	HRN	77.0°N	15.6°E	74.7°N	104.6°E
Hopen Island	HOP	76.5°N	25.0°E	73.8°N	111.1°E
Bear Island	BJN	74.5°N	19.2°E	72.0°N	104.3°E
Nordkapp	NOR	71.1°N	25.8°E	68.3°N	106.7°E
Sørøya	SOR	70.5°N	22.2°E	67.8°N	103.4°E
Tromsø	TRO	69.7°N	18.9°E	67.0°N	100.1°E
Kevo	KEV	69.8°N	27.0°E	66.9°N	106.9°E
Andenes	AND	69.3°N	16.0°E	66.8°N	97.4°E
Kilpisjärvi	KIL	69.0°N	20.8°E	66.3°N	101.2°E
Abisko	ABK	68.4°N	18.8°E	65.7°N	99.1°E
Ivalo	IVA	68.6°N	27.3°E	65.7°N	106.4°E
Kiruna	KIR	67.8°N	20.4°E	65.1°N	100.2°E
Røst	RST	67.5°N	12.1°E	65.0°N	93.1°E
Sodankylä	SOD	67.4°N	26.6°E	64.5°N	105.2°E
Pello	PEL	66.9°N	24.1°E	64.0°N	102.8°E
Jäckvik	JCK	66.4°N	17.0°E	63.7°N	96.5°E
Dønna	DON	66.1°N	12.5°E	63.5°N	92.6°E
Ranua	RAN	65.9°N	26.4°E	62.9°N	104.3°E
Rørvik	RVK	65.0°N	11.0°E	62.3°N	90.7°E
Lycksele	LYC	64.6°N	18.7°E	61.7°N	97.1°E
Oulujärvi	OUJ	64.5°N	27.2°E	61.5°N	104.4°E
Mekrijärvi	MEK	62.8°N	31.0°E	59.6°N	107.1°E
Dombås	DOB	62.1°N	9.1°E	59.2°N	87.9°E
Hankasalmi	HAN	62.2°N	26.6°E	59.1°N	103.0°E
Solund	SOL	61.1°N	4.8°E	58.3°N	83.9°E
Harestua	HAR	60.2°N	10.7°E	57.1°N	88.5°E
Uppsala	UPS	59.9°N	17.4°E	56.7°N	94.1°E
Karmøy	KAR	59.2°N	5.2°E	56.2°N	83.6°E
Tartu	TAR	58.3°N	26.5°E	54.9°N	101.7°E
Birzai	BRZ	56.2°N	24.9°E	52.6°N	99.7°E
Hel	HLP	54.6°N	18.8°E	50.8°N	93.9°E
Suwałki	SUW	54.0°N	23.2°E	50.2°N	97.7°E
Wingst	WNG	53.7°N	9.1°E	49.8°N	85.2°E
Niemegk	NGK	52.1°N	12.7°E	47.9°N	88.0°E
Belsk	BEL	51.8°N	20.8°E	47.8°N	95.2°E
Polesie	PPN	51.5°N	23.1°E	47.4°N	97.2°E
Budkov	BDV	49.1°N	14.0°E	44.5°N	88.7°E
Furstenfeldbruck	FUR	48.2°N	11.3°E	43.4°N	86.1°E
Hurbanovo	HRB	47.9°N	18.2°E	43.2°N	92.2°E
Conrad Observatory	WIC	47.9°N	15.9°E	43.2°N	90.1°E

Table 3
Continued

Station name	Code	Lat	Lon	QD lat	QD lon
Tihany	THY	46.9°N	17.9°E	42.1°N	91.8°E
Lonjsko Polje	LON	45.4°N	16.7°E	40.3°N	90.6°E

To examine the magnetic effect of the EEJ, we analyze the 1-Hz vector magnetometer data, given as the Swarm Level 1b product MAGx_LR_1B (Olsen et al., 2013). The magnetic effect of the EEJ is separated from magnetic signatures of other sources. That is, the core, lithospheric, and magnetospheric fields are evaluated using the CHAOS-7 model and subtracted from the data in the North-East-Center (NEC) reference frame. Moreover, large-scale Sq fields are represented by polynomials of degree six fitted to the data outside $\pm 12^\circ$ QD latitude following Alken (2019), and are subtracted from the data. The residual fields in the north and center components (ΔB_{north} and ΔB_{center}) are inspected for possible EEJ-related signatures. Since Swarm A and C fly side by side, ΔB_{north} and ΔB_{center} obtained from the two satellites are largely similar, and thus, we discuss only the Swarm A and B results.

When magnetic effects of the EEJ can be clearly identified in ΔB_{north} and ΔB_{center} near the magnetic equator, the corresponding EEJ intensity is obtained from the Swarm Level 2 product EEfxTMS_2F (Alken et al., 2015). We first inspect the Swarm magnetic field residuals ΔB_{north} and ΔB_{center} , rather than relying solely on the Swarm EEJ product. This initial inspection is necessary to identify and exclude EEJ estimates that may be unreliable because of contamination by storm-time geomagnetic field disturbances. Such contamination can occur because the derivation of the Swarm EEJ product assumes that the residual magnetic fields, after removal of the core, lithospheric, magnetospheric, and large-scale Sq field contributions, represent spatial variations associated with the EEJ. During geomagnetic storms, however, the residual fields may also contain temporal variations that are not adequately captured by the magnetospheric field model, leading to erroneous EEJ estimates.

Apart from the EEJ analysis, Swarm data are also used to track equatorial boundaries of high-latitude field-aligned currents (FACs). Estimates of FAC intensities are given as the Swarm Level 2 product FACxTMS_2F (Ritter et al., 2013). C. Xiong et al. (2014) suggested that the latitude where the meridional gradient of FAC intensity is largest can be used as a proxy of the auroral oval boundary. Applying their technique to FAC intensities obtained from Swarm A and B, magnetic apex latitudes for equatorward boundaries of FACs and their $1\text{-}\sigma$ uncertainties are determined.

3. Results and Discussion

3.1. January 2026 Geomagnetic Storm Event

Figure 3a shows solar X-ray fluxes at the long (0.1–0.8 nm) and short (0.05–0.4 nm) wavelengths during 18–20 January 2026, as measured by the X-Ray Sensor (XRS) onboard the Geostationary Operational Environmental Satellite (GOES)-19 (Woods et al., 2024). During this period, solar X-ray activity was relatively high, with an X-class (X1.9) solar flare on 18 January 2026 (17:27 UT), an M-class flare on 19 January (11:09 UT), and numerous C-class flares. According to the *Space Weather Alerts* by the British Geological Survey, UK (British Geological Survey, 2026), the coronal mass ejection (CME) associated with the X1.9 solar flare on 18 January 2026 arrived at the Earth's magnetosphere on 19 January 2026, causing a severe geomagnetic storm.

Figures 3b and 3c display the interplanetary magnetic field (IMF) and solar wind speed, respectively, as obtained from the OMNI data base (Papitashvili & King, 2020) at the Goddard Space Flight Center, Space Physics Data Facility, USA. The OMNI data represent solar wind parameters, originally collected at the L1 Lagrangian point, time-shifted to the Earth's bow shock nose. The impact of the CME is seen as sudden increases in the IMF magnitude (Bt) from ~ 8 nT to ~ 70 nT and in the solar wind speed from ~ 450 km/s to $\sim 1,100$ km/s toward the end of the day on 19 January 2026, although reliable data are unavailable to identify the exact time of the CME arrival.

Figure 4a shows the time series of Hp30, representing overall geomagnetic activity. Hp30 underwent a rapid increase at 19:00–19:30 UT on 19 January 2026, reaching its maximum value of 10 during 21:00–22:00 UT on the same day, and remained active ($\text{Hp30} \geq 6$) for the most part of the rest of the period. According to the storm list by the Kakioka Magnetic Observatory, Japan (Kakioka Magnetic Observatory, 2026), the storm onset was at 19:17 UT on 19 January 2026, which is marked by vertical magenta lines in Figure 4.

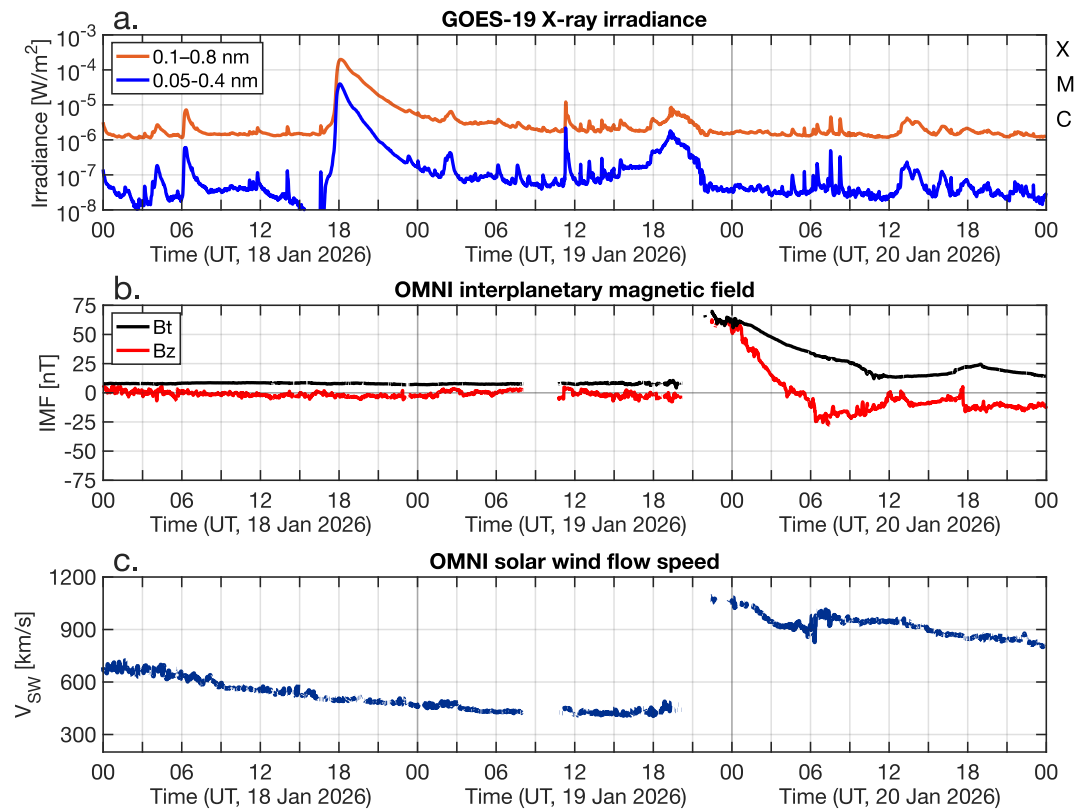


Figure 3. (a) GOES-19/X-Ray Sensor solar X-ray fluxes in the 0.1–0.8 nm and 0.05–0.4 nm wavelength bands during 18–20 January 2026. (b) OMNI interplanetary magnetic field total magnitude (B_t) and northward component (B_z). (c) OMNI solar wind speed.

The SYM-H index, plotted in Figure 4b, represents the strength of the magnetospheric ring current. After the storm onset (19:17 UT on 19 January 2026), the SYM-H showed a rapid decrease to a local minimum value of -243 nT at 21:42 UT on 19 January 2026. After a brief recovery to approximately -100 nT, it again began to rapidly decrease around 07:25 UT on 20 January 2026 and reached the minimum value of -257 nT at 11:52 UT on the same day.

As noted by Kamide et al. (1998), two-step geomagnetic storms are very common, especially among intense geomagnetic storms. Kamide et al. (1998) attributed this behavior to the presence of closely spaced intervals of southward IMF B_z. Because CME ejecta generally propagate faster than the ambient solar wind, they compress and intensify the upstream IMF. Southward IMF B_z embedded within the compressed upstream field drives the initial phase of storm development, whereas southward IMF B_z within the CME ejecta itself produces the second phase. The January 2026 storm was likely driven by a similar mechanism, although the southward IMF associated with the first phase was not observed because of a data gap (Figure 3b).

The AE index, plotted in Figure 4c, represents auroral electrojet activity. Very high activity with the AE index exceeding 2,000 nT was observed following the storm onset around 19:20–22:10 UT on 19 January 2026, as well as around 07:25–12:00 UT on 20 January 2026, reflecting the two-step development of the geomagnetic storm. During both the intervals, the maximum AE index exceeded 4,000 nT.

Geomagnetic storms lead not only to the intensification of the auroral electrojet but also to the expansion of the auroral oval toward lower latitudes. Figure 4d shows the equatorward boundary of the high-latitude FACs obtained from Swarm A in the midnight sector (22:40–00:30 magnetic LT, MLT) and Swarm B in the dusk (16:50–18:50 MLT) and dawn (04:30–06:50 MLT) sectors for the Northern Hemisphere. Following the storm onset, the equatorward boundary of the auroral oval expanded from 60 to 65°N magnetic apex latitude under pre-storm quiet conditions to ~50°N magnetic apex latitude. After a brief recovery to ~55°N magnetic apex latitude, it again expanded to ~50°N magnetic apex latitude, during the second active phase of the storm.

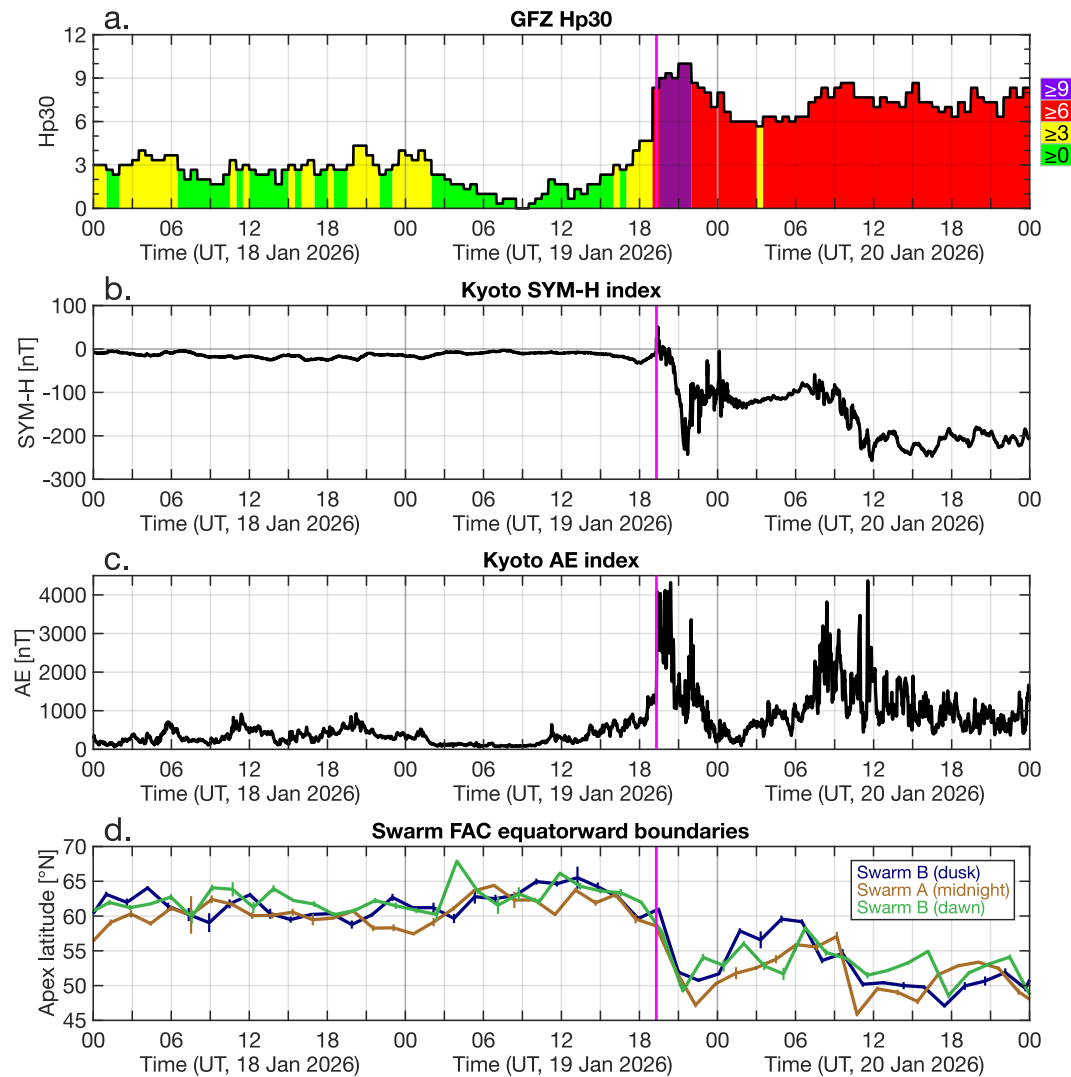


Figure 4. (a) Hp30 geomagnetic activity index during 18–20 January 2026. (b) SYM-H index. (c) AE index. (d) Apex magnetic latitudes of the equatorward boundaries of field-aligned currents in the Northern Hemisphere derived from Swarm observations. Vertical magenta lines indicate the storm onset at 19:17 UT on 19 January 2026.

Note that we present the Swarm FAC results only for the Northern Hemisphere, where the LT remains nearly constant for all ascending (or descending) crossings of the auroral oval boundary. In contrast, in the Southern Hemisphere, the LT varies from orbit to orbit because of the larger displacement between the geographic and magnetic poles. Consequently, the observed variations in the Southern Hemisphere reflect a complex combination of local-time effects and storm-time changes in the auroral boundary, making them more difficult to interpret.

3.2. Equatorial Electrojet (EEJ) Response

3.2.1. Longitude/Local-Time Dependence

Figure 5 displays ΔH_{EEJ} in the (a) Peruvian sector, (b) Brazilian sector, (c) Ethiopian sector, (d) Indian sector, (e) Thailand sector, and (f) Philippine sector. In each panel, the E-region daytime is also indicated, which is defined here as the time interval when either station in the pair satisfies the solar zenith angle $\theta_z < 102.3^\circ$. Outside this time interval, there is no solar illumination up to 150 km at both the stations.

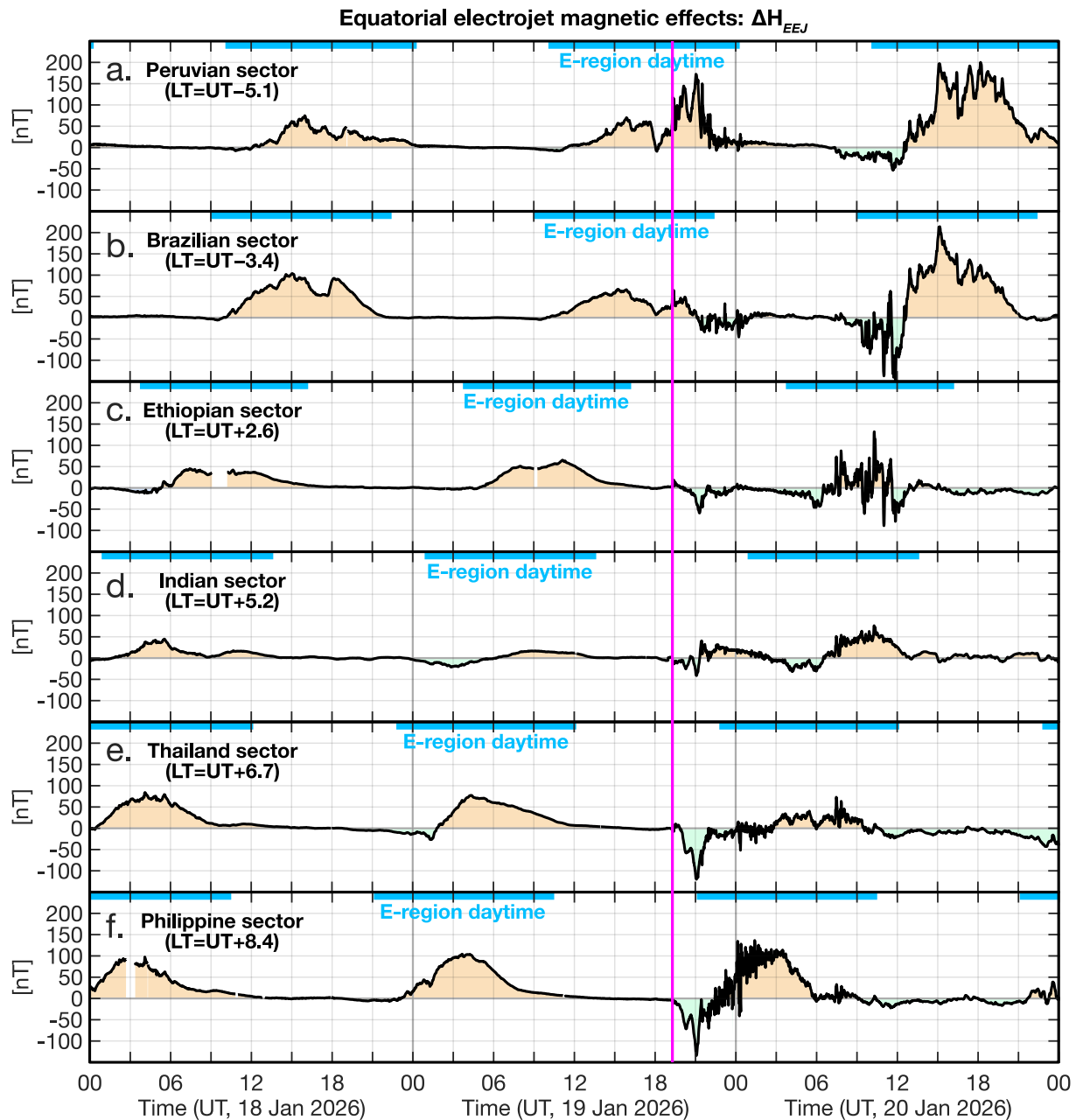


Figure 5. ΔH_{EEJ} , a proxy of EEJ strength derived using the two-station method, in the (a) Peruvian sector, (b) Brazilian sector, (c) Ethiopian sector, (d) Indian sector, (e) Thailand sector, and (f) Philippine sector during 18–20 January 2026. For each sector, periods when any part of the ionosphere below 150 km was sunlit above either station used in the two-station method are indicated. The vertical magenta line marks the storm onset at 19:17 UT on 19 January 2026.

The behavior of the EEJ before the storm onset (19:17 UT on 19 January 2026) was as expected in all longitude sectors, with mostly eastward EEJ currents (i.e., $\Delta H_{EEJ} > 0$) during day and close to zero during night. In the Brazilian sector (Figure 5b), the effect of the X-class solar flare at 17:27 UT on 18 January 2026 is visible as a brief increase in ΔH_{EEJ} from ~ 50 nT to ~ 90 nT around 17:40 UT on the same day. This is due to a temporary increase in the dayside ionospheric conductivity caused by the solar flare (e.g., Liu et al., 2021; R. Zhang et al., 2017).

Following the storm onset, the EEJ in different longitude sectors exhibited diverse responses. In the Peruvian sector (Figure 5a), there was an enhancement in the eastward EEJ current, with ΔH_{EEJ} increasing from ~ 50 nT to ~ 150 nT during the few-hour interval after the storm onset. In the Thailand and Philippine sectors (Figures 5e

and 5f), on the other hand, westward EEJ currents were observed, with pronounced reductions in ΔH_{EEJ} from ~ 0 nT to below -100 nT. The maximum westward EEJ occurred around 21:00 UT on 19 January 2026, when the *E*-region ionosphere was completely dark in the Thailand sector while it was around the *E*-region sunrise time in the Philippine sector. At the same time, the westward EEJ was also observed in the Ethiopian sector (Figure 5c) and Indian sector (Figure 5d) but with much smaller amplitudes.

EEJ intensity perturbations at 21:00 UT on 19 January 2026 are plotted in Figure 1c (“x” marks in red) as a function of LT. Soares et al. (2022) derived formulas to relate ground magnetic effects of the EEJ (ΔH_{EEJ} in nano teslas) and EEJ intensities derived from satellite observations (J_s in milliamperes per meter) by comparing their simultaneous observations during ground-satellite conjunctions. The formulas are expressed in the form

$$J_s = a\Delta H_{EEJ} + b. \quad (7)$$

Soares et al. (2022) presented the regression coefficients a and b for eight pairs of ground-based magnetometers in different longitudes. For example, $a = 1.72$ and $b = 0.90$ for the TIR-ABG pair in the Indian sector. For the other pairs of the stations used in this study, however, the exact values of a and b are unknown. We therefore applied the eight pairs of a and b values reported by Soares et al. (2022) and adopted the mean of the resulting eight J_s values as our estimate. For Figure 1c, we subtracted the J_s values of the previous day from the corresponding values at 21:00 UT on 19 January 2026 to obtain the perturbations relative to the quiet-time references. Note that ΔJ_s values in Figure 1c are not particularly sensitive to the choice of reference values, as they are dominated by storm-time changes in J_s . The error bars indicate the range between the maximum and minimum J_s values among the eight estimates obtained using the different pairs of a and b values. Although this range does not guarantee that the true value lies within it, it provides an indication of the potential magnitude of the uncertainty in J_s .

In Figure 1c, the EEJ intensity values derived from ground-based magnetometer data (red crosses) are greater than those based on theoretical considerations (black dots and connecting line) by approximately an order of magnitude. This could be partly due to the underestimation of the prompt penetration electric field depicted in Figure 1b, which is given by C.-S. Huang (2015) as the average over five geomagnetic storm events. In some extreme cases, the prompt penetration electric field can exceed 5 mV/m (e.g., R. Zhang et al., 2025).

Additionally, there is uncertainty in the accuracy of the Cowling conductivity estimated by the WDC Kyoto ionospheric conductivity model (Figure 1a). For example, Hashimoto et al. (2017) estimated the nighttime height-integrated Cowling conductivity to be 2.7 S, which is somewhat larger than our predictions (1–2 S depending on LT). Since Cowling conductivity is governed primarily by *E*-region plasma density, uncertainties in the modeled plasma density directly affect the conductivity estimate. At low latitudes, *E*-region plasma density depends mainly on solar flux and solar zenith angle, and the WDC Kyoto model derives it from the 2016 version of IRI (Bilitza et al., 2017). Although the model was evaluated for 21:00 UT on 19 January 2026 to enable a meaningful comparison with the EEJ observations, it does not include the effects of geomagnetic activity on *E*-region plasma density. The storm-time response of low-latitude *E*-region plasma density remains poorly constrained. While global satellite observations have shown a strong correlation between *E*-region plasma density and Kp at auroral latitudes (Salinas et al., 2025; Wu, 2018), no comparable relationship has been firmly established at lower latitudes.

As a brief summary, the observed EEJ intensity perturbations during the main phase of the January 2026 storm (red crosses in Figure 1c) do not agree with theoretical predictions (black dots and connecting line in Figure 1c). Discrepancies exist in both the magnitude of the perturbations and its local-time pattern. Addressing the driving mechanism of the nighttime westward EEJ requires improved descriptions of both the Cowling conductivity (Figure 1a) and the prompt penetration electric field (Figure 1b). However, developing more realistic representations of these quantities is beyond the scope of this study and will require further work.

3.2.2. Latitudinal Structure

ΔH_{EEJ} obtained using the conventional two-station method suggests the presence of a nighttime westward EEJ in the Thailand and Philippine sectors during the main phase of the January 2026 storm. However, it remains unclear whether ΔH_{EEJ} can reliably represent EEJ strength during geomagnetic storms. A large ΔH_{EEJ} merely indicates a strong latitudinal gradient in ΔH across low latitudes and does not necessarily imply an enhancement of ΔH near the magnetic equator. Here, we further investigate whether the large negative ΔH_{EEJ} observed in the Thailand

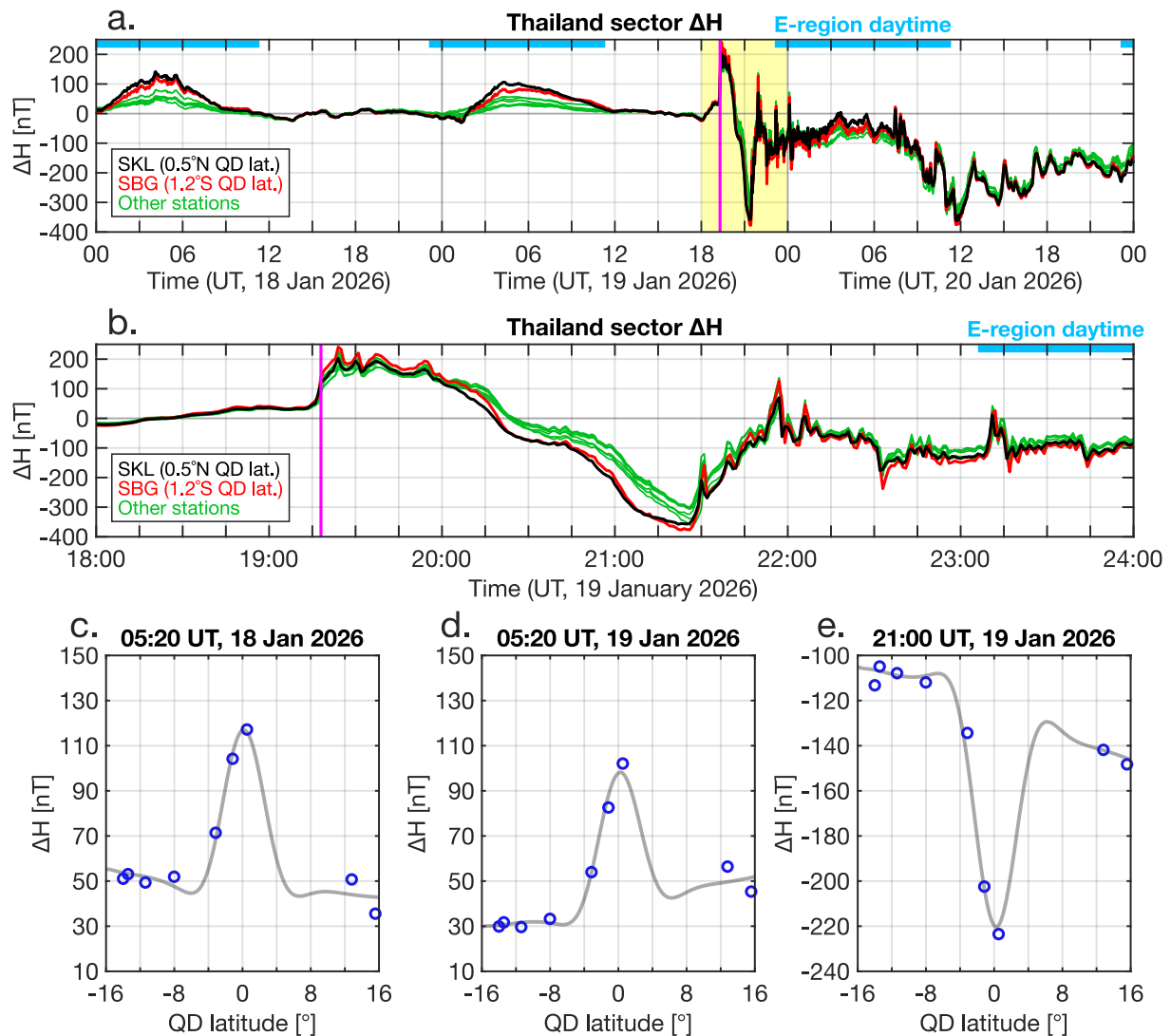


Figure 6. (a) H-component magnetic field perturbations, ΔH , observed by nine ground-based magnetometers in the Thailand sector during 18–20 January 2026. Data from Songkhla (SKL; 0.52°N QD latitude) and Sabang (SBG; 1.16°S QD latitude), located well within the EEJ belt, are highlighted by black and red lines, respectively, while data from the remaining stations are shown in green. (b) Same as (a), but for the interval 18:00–24:00 UT on 19 January 2026. (c, d) Latitudinal distributions of ΔH at 05:20 UT under local-noon conditions for 18 and 19 January 2026. Gray curves show least-squares fits of the EEJ surface magnetic signature given by Soares et al. (2020) to the observed ΔH values. (e) Same as (c, d) but at 21:00 UT ($\sim 03:40$ local time) on 19 January 2026. Vertical magenta lines indicate the storm onset at 19:17 UT on 19 January 2026.

sector during pre-sunrise hours is associated with a nighttime westward EEJ by analyzing ΔH perturbations from a chain of low-latitude magnetometers distributed across the magnetic equator within the same longitude sector. This analysis allows us to validate the interpretation of ΔH_{EEJ} as a signature of the nighttime westward EEJ.

Figure 6a shows time series of ΔH observed at nine low-latitude stations in the Thailand longitude sector (see also Figure 2 and Table 1 for their locations). The Songkhla (SKL; 0.52°N QD latitude) and Sabang (SBG; 1.16°S QD latitude) stations are located well within the EEJ belt, and ΔH at these two stations are highlighted by black and red lines, respectively. ΔH at all the other low-latitude stations are shown by green lines. Before the storm onset, ΔH is around zero during night at all the stations, and the difference in ΔH among the stations is very small, whereas during day, ΔH shows predominantly positive values, with an apparent enhancement in ΔH near the magnetic equator (i.e., at SKL and SBG). These results represent classical behavior of ΔH associated with quiet-time ionospheric currents over low latitudes (e.g., Matsushita & Maeda, 1965; Yamazaki et al., 2011). The currents are effectively absent during night, while they are primarily eastward during day, with an enhancement in the current intensity at the magnetic equator due to the presence of the EEJ.

Figure 6b is the same as Figure 6a but a close-up over the period 18:00–24:00 UT on 19 January 2026 around the storm main phase. ΔH at all the stations behave similarly before the storm onset. However, after the storm onset, especially around 20:00–21:30 UT, ΔH at SKL and SBG exhibit strong negative deviations from ΔH at the other low-latitude stations in the same longitude sector, indicating the presence of a localized westward current over the magnetic equator.

Figures 6c–6e depict the dependence of ΔH on QD latitude at 05:20 UT ($\sim 12:00$ LT in the Thailand longitude sector) on 18 and 19 January 2026 and at 21:00 UT ($\sim 03:40$ LT) on 19 January 2026. Also depicted in these figures are least-squares fits of average daytime ground-level EEJ effects, as given by Soares et al. (2020) based on CHAMP and Swarm satellite observations, to the observed ΔH data. The daytime results (Figures 6c and 6d) show an enhancement in ΔH confined mostly within $\pm 3^\circ$ QD latitude. The nighttime profile during the storm main phase (Figure 6e) is similar to the daytime profiles except that the equatorial enhancement is in the negative direction, indicating a westward EEJ current in contrast with daytime eastward EEJ currents. This is the first time that the latitudinal profile of ground magnetic field effects associated with the nighttime westward EEJ is revealed. The similarity in the latitudinal profiles of ΔH between day (Figures 6c and 6d) and night (Figure 6e) suggests that their driving currents likely flow within the same height range (e.g., the *E* region) with similar latitudinal structures. Distant currents in the magnetosphere cannot explain a localized ΔH enhancement near the magnetic equator as depicted in Figure 6e. Also, F-region dynamo currents (>150 km) are not expected to produce a substantial equatorial enhancement in ΔH (Maute & Richmond, 2017).

We have also examined the latitudinal structure of magnetic field perturbations in the vertical (*Z*) component. However, ΔZ did not exhibit expected latitudinal patterns with peak perturbations at approximately $\pm 3^\circ$ QD latitude with opposite signs (e.g., Doumouya et al., 1998). This was the case not only during the geomagnetic storm event but also during pre-storm periods. One explanation for this is the effect of electric currents and associated magnetic fields induced in the solid Earth and ocean by external time-varying magnetic field, which could cause substantial station-to-station differences in ΔZ perturbations, especially in coastal regions like Sumatra (e.g., Grayver et al., 2025; Olsen & Kuvshinov, 2004).

3.3. Geomagnetic Field Disturbances at Mid Latitudes

Figure 7a displays ΔH_{EEJ} in the Peruvian, Thailand, and Philippine sectors during the period 18:00–24:00 UT on 19 January 2026. Note that the Peruvian and Thailand sectors are approximately 12 hr apart in LT. There is a tendency toward a negative correlation between ΔH_{EEJ} in the Peruvian sector and those in the Thailand and Philippine sectors. For example, enhancements in the dayside eastward EEJ current in the Peruvian sector around 20:15 UT and 21:00 UT coincide with enhancements in the nighttime westward EEJ currents in the Thailand and Philippine sectors. This probably reflects dayside eastward and nightside westward prompt penetration electric fields from high latitudes.

We now examine geomagnetic field disturbances at higher latitudes to provide insight into the connection between the occurrence of the nighttime westward EEJ and higher-latitude processes. Figure 7b shows that there were enhancements in both the ASY-H and ASY-D indices around 20:15 UT and 21:00 UT, concurrently with the intensifications of dayside eastward and nightside westward EEJ currents.

Figures 7c and 7d depict time evolutions of geomagnetic field perturbations in the magnetic northward (*N*) and eastward (*E*) components observed along $\sim 50^\circ$ N QD latitude (see also Figure 2 and Table 2) as a function of LT. As noted earlier, these magnetic field perturbations (ΔN and ΔE) are residuals after the removal of SYM-H and *Sq* fields, and thus exclude the contributions of the symmetric ring current and *Sq* currents. Zonal wavenumber-1 patterns are evident in both ΔN and ΔE , which are intensified around 20:15 UT and 21:00 UT, consistent with the temporal evolution of ASY-H and ASY-D.

Previous studies have reported zonal wavenumber-1 patterns in geomagnetic field disturbances at mid and low latitudes during geomagnetic storms (e.g., Iyemori, 1990). These disturbances arise from storm-time magnetosphere-ionosphere current systems. Modeling studies have shown that region-1 and region-2 FACs, the partial ring current, and ionospheric currents all contribute to the zonal wavenumber-1 structure, with FACs providing the dominant contribution (e.g., Fukushima & Kamide, 1973).

Although the emergence of zonal wavenumber-1 patterns in ΔN and ΔE are expected, their phase structures are different from those previously reported. Storm-time geomagnetic disturbances in *H* at mid and low latitudes are

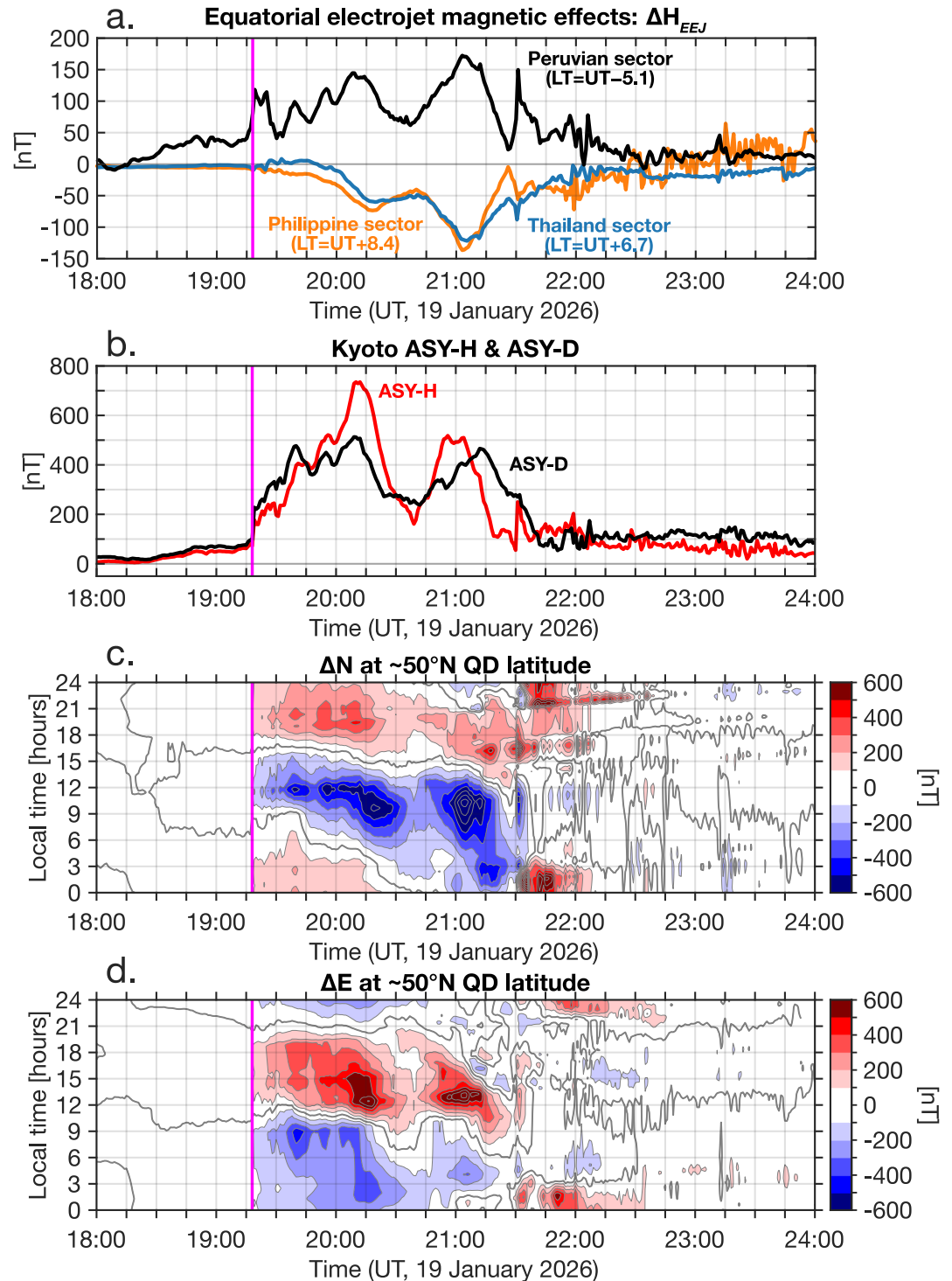


Figure 7. (a) ΔH_{EEJ} , a proxy of EEJ strength derived using the two-station method, in the Peruvian, Thailand, and Philippine sectors during 18:00–24:00 UT on 19 January 2026. (b) ASY-H and ASY-D geomagnetic indices. (c, d) Magnetic field perturbations in the magnetic north (ΔN) and eastward (ΔE) components observed near 50° Quasi-Dipole (QD) latitude as a function of local time. ΔN and ΔE have been corrected for SYM-H and Sq fields. Vertical magenta lines indicate the storm onset at 19:17 UT on 19 January 2026.

usually characterized by a dusk-dawn asymmetry with greater negative perturbations in the dusk sector than in the dawn sector (e.g., Love & Gannon, 2009; Newell & Gjerloev, 2012; Tulasi Ram et al., 2025). As ΔN and ΔH perturbations are nearly identical, one might expect positive and negative ΔN perturbations around 6 LT and 18 LT, respectively. However, in Figure 7c, positive and negative ΔN perturbations are seen around 21 LT and 9 LT, respectively. Also, storm-time ΔE perturbations are expected to be positive and negative around the midnight and noon, respectively (e.g., Iyemori, 1990). However, in Figure 7d, positive and negative ΔE perturbations dominate 00–12 LT and 12–24 LT, respectively. These discrepancies between the observed and expected zonal wavenumber-1 patterns may be due to equatorward expansion of the auroral oval during this time (see Figure 4d). It could cause the mid-latitude stations along $\sim 50^\circ$ N QD latitude to be directly under the high-latitude ionospheric current system, which is, under normal circumstances, confined above 60° magnetic latitude or so (e.g., Laundal et al., 2018; Matsushita & Xu, 1982).

3.4. Geomagnetic Field Disturbances at Auroral and Subauroral Latitudes

The intensities of the eastward and westward auroral electrojet are represented by the AU and AL indices shown in Figure 8b. Note that the AE index presented earlier in Figure 4c is the difference between the AL and AU indices. The nighttime westward and daytime eastward EEJ intensified around 20:15 UT (Figure 8a) when a strong westward auroral electrojet was present ($AL \approx -2,000$ nT, Figure 8b). In contrast, the strongest nighttime westward and daytime eastward EEJ occurred around 21:00 UT (Figure 8a), when the westward auroral electrojet was relatively weak ($AL \approx -1,000$ nT, Figure 8b). This lack of correlation suggests that the westward auroral electrojet does not directly control the strengths of the nighttime westward and daytime eastward EEJ.

Figures 8c and 8d show geomagnetic field perturbations ΔN and ΔE observed by IMAGE and INTERMAGNET magnetometers in the European sector (see also Figure 2 and Table 3). During the interval shown, the European sector ($LT = UT + \sim 1$ hr) was in the pre-midnight local-time sector. The occurrence of the peak westward auroral electrojet is usually later around 22:30–06:30 LT (e.g., Guo et al., 2014). Because auroral electrojet currents flow predominantly in the zonal direction, ΔE perturbations (Figure 8d) are substantially smaller than ΔN perturbations. The negative ΔN associated with the westward auroral electrojet intensified following the storm onset and remained pronounced until $\sim 20:30$ UT, consistent with the behavior of the AL index (Figure 8b).

Despite the absence of a clear correlation between the strengths of the auroral electrojet and the EEJ, the two phenomena may not be entirely independent. In Figure 8c, negative ΔN perturbations are observed to extend equatorward around 20:15 UT and 21:00 UT, coinciding with intensifications of the daytime eastward and nighttime westward EEJ currents (Figure 8a). These observations point to the involvement of a physical process that could drive both the equatorward expansion of the auroral oval and the occurrence of the nighttime westward EEJ. However, this process remains to be identified.

3.5. Swarm Satellite Observations of the EEJ

Satellite magnetic field measurements may provide additional support for the existence of the nighttime westward EEJ discussed above. In a recent study, Y. Xiong et al. (2026) analyzed magnetic field data from Swarm and Macau satellites during the May 2024 geomagnetic storm. On one occasion, they identified a localized positive perturbation in the total residual field ΔB_{total} near the magnetic equator around midnight and attributed it to a nighttime westward EEJ. However, the peak ΔB_{total} perturbation occurred not directly at the magnetic equator but approximately 6° away from it, leaving room for alternative interpretations.

We examine the residual magnetic field perturbations ΔB_{north} and ΔB_{center} measured by Swarm A and B. A total of 16 equatorial crossings occurred between 18:00 UT and 24:00 UT on 19 January 2026. Figure 9b shows the local times of these equatorial crossings (orbits #1–#16) together with the local times of the EEJ observed from ground-based magnetometers in the Peruvian, Thailand, and Philippine sectors. The descending and ascending crossings of Swarm A occurred at $\sim 11:30$ LT and $\sim 23:30$ LT, respectively, where those of Swarm B occurred at $\sim 05:50$ LT and $\sim 17:50$ LT.

Figure 9c presents ΔB_{north} (black) and ΔB_{center} (green) over $\pm 20^\circ$ QD latitude for each equatorial crossing. It should be noted that the vertical scales are not the same across the panels. Based on visual inspection, the results are classified into three categories. The first category consists of cases in which ΔB_{north} remains relatively small (within ± 15 nT) across all latitudes, indicating the absence of a strong EEJ current. This category includes orbits

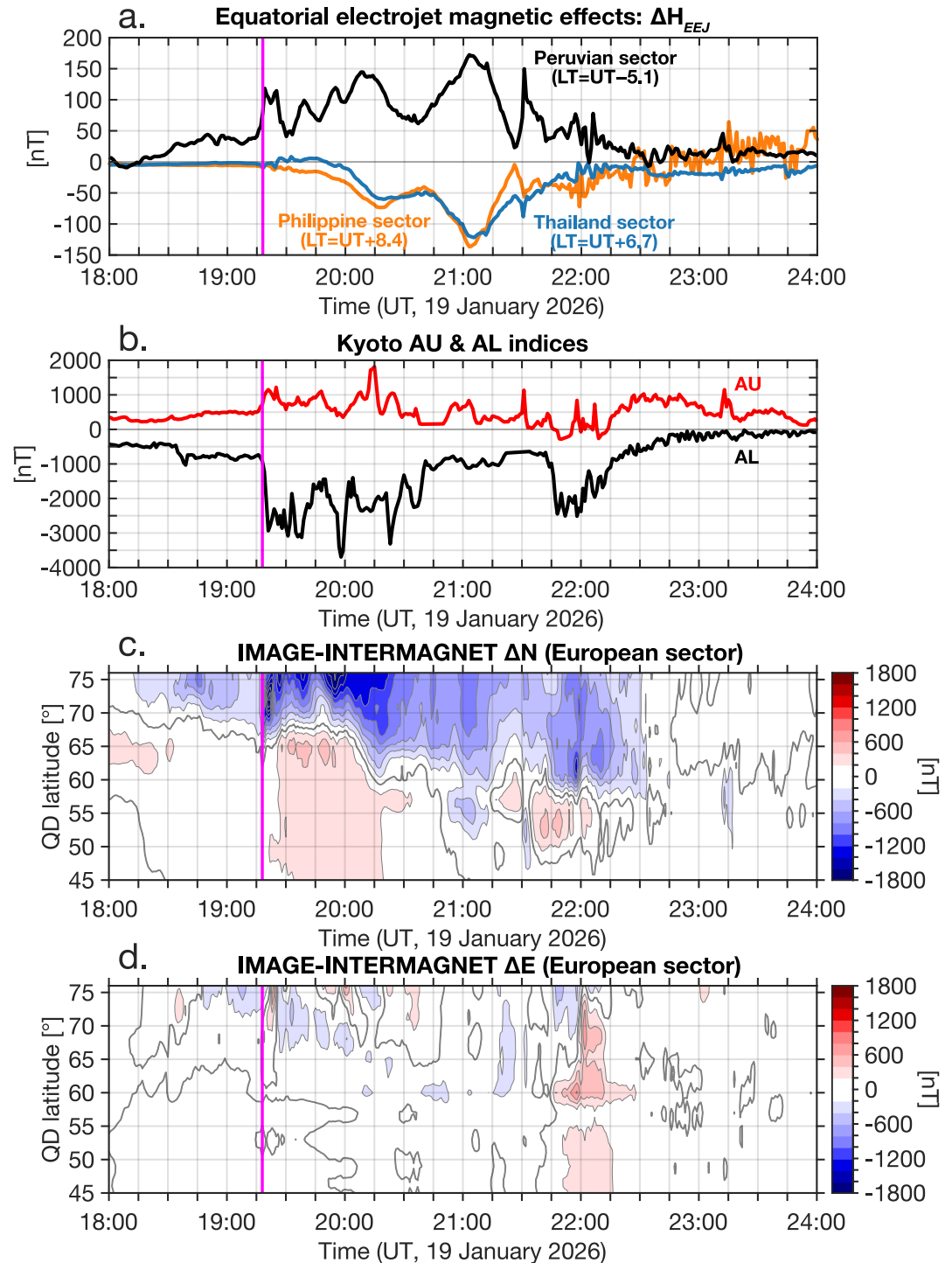


Figure 8. (a) Same as Figure 7a, presenting ΔH_{EEJ} in the Peruvian, Thailand, and Philippine sectors during 18:00–24:00 UT on 19 January 2026. (b) AU and AL auroral electrojet indices. (c, d) Magnetic field perturbations in the magnetic north (ΔN) and eastward (ΔE) components observed in the European sector as a function of Quasi-Dipole (QD) latitude. ΔN and ΔE have been corrected for SYM-H and Sq fields. Vertical magenta lines indicate the storm onset at 19:17 UT on 19 January 2026.

#2, #3, #7, and #8. The second category consists of cases in which ΔB_{north} exhibits a local peak at the magnetic equator with an absolute magnitude exceeding 15 nT, indicating the presence of an EEJ current. A negative (positive) equatorial peak in ΔB_{north} corresponds to an eastward (westward) EEJ. This category includes orbits #1,

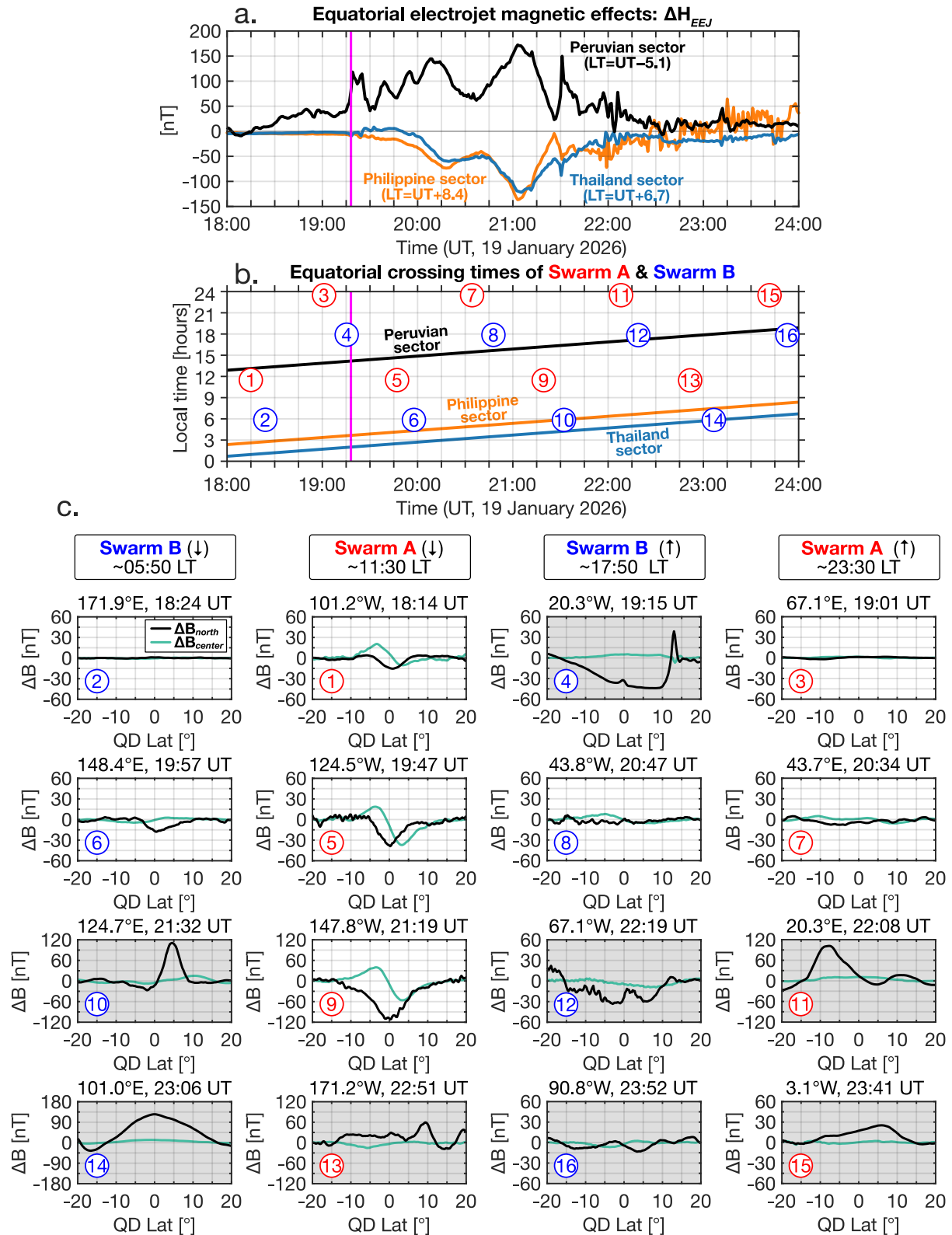


Figure 9.

#5, #6, and #9. The remaining cases are assigned to the third category, in which an EEJ current may be present but cannot be reliably identified because the ΔB_{north} perturbations are dominated by magnetic field disturbances originating from sources other than the EEJ. Because the interpretation of the third category is inherently uncertain, these cases are highlighted with a gray background.

The magnetic field measurements from the descending crossings of Swarm A reveal a rapid intensification of the noon time EEJ from orbit #1 (18:14 UT, before the storm onset) to orbit #5 (19:47 UT, after the storm onset) and orbit #9 (21:19 UT). The corresponding EEJ intensities are ~ 80 mA/m, ~ 145 mA/m, and ~ 270 mA/m, respectively. The noontime EEJ intensity likely exceeded 270 mA/m at 21:00 UT, when the eastward EEJ in the Peruvian sector and the westward EEJ in the Thailand and Philippine sectors reached their peak intensities (Figure 9a). These observations help fill gaps in the local-time variation of EEJ intensity perturbations shown in Figure 1c, where noontime coverage is lacking due to the absence of ground-based magnetometers over the central Pacific longitude sector.

The descending crossings of Swarm B sampled the dawn sector around 05:50 LT, when ground-based stations observed the nighttime westward EEJ during the storm. Before the storm onset (orbit #2; 18:24 UT), no clear EEJ signature was detected. Data from orbit #6 (19:57 UT, after the storm onset) show a negative equatorial peak in ΔB_{north} , which could be associated with an eastward EEJ current. However, ΔB_{center} does not exhibit the expected negative and positive perturbations on the northern and southern sides of the magnetic equator, respectively, as observed in orbits #1, #5, and #9. We therefore do not have strong confidence that the observed magnetic field perturbations in orbit #6 are associated with the eastward EEJ.

It is tempting to interpret the localized positive perturbation in ΔB_{north} near the magnetic equator during orbit #10 (21:32 UT) as a signature of a nighttime EEJ current. The ΔB_{north} peak is observed slightly off the magnetic equator, at approximately 5° QD latitude, which is similar to the event reported by Y. Xiong et al. (2026) for the May 2024 storm. However, as shown in Figures 9a and 9b, orbit #10 coincides with a period of rapid geomagnetic field variation. Although ΔB_{north} has been corrected for large-scale magnetospheric fields using the CHAOS-7 model, this correction relies on the RC index (Olsen et al., 2014), which has a temporal resolution of 1 hour. Consequently, variations in magnetospheric fields on timescales shorter than 1 hour are not represented in the model. In fact, a comparison between ΔB_{north} during orbit #10 and the SYM-H index (with one-minute temporal resolution) reveals similar temporal variations (not shown), suggesting the localized positive perturbation in ΔB_{north} near the magnetic equator during orbit #10 is mainly due to the temporal variation in large-scale magnetospheric fields. This result underscores the importance of carefully distinguishing between spatial and temporal variations when interpreting satellite magnetic field perturbations during geomagnetic storms, particularly in studies of the EEJ.

4. Summary and Conclusions

In January 2026, an intense geomagnetic storm was triggered by a CME associated with the X1.9 solar flare on 18 January 2026 (Figure 3). Following storm onset at 19:17 UT on 19 January 2026, geomagnetic activity indices revealed a two-step development of the storm (Figure 4), similar to events previously described by Kamide et al. (1998). We investigated the response of the equatorial electrojet (EEJ) using ground-based magnetometer observations from six different longitude sectors (Figure 2 and Table 1). The main results are summarized as follows.

ΔH_{EEJ} , a proxy of EEJ strength derived using the conventional two-station method, showed large negative values (< -100 nT) in the Thailand and Philippine sectors at pre-sunrise local times during the storm main phase, indicating the presence of strong nighttime westward EEJ currents (Figure 5). These currents, with estimated intensities of 150–200 mA/m, occurred simultaneously with a strong daytime eastward EEJ in the Peruvian sector

Figure 9. (a) Same as Figures 7a and 8a, showing ΔH_{EEJ} in the Peruvian, Thailand, and Philippine sectors during 18:00–24:00 UT on 19 January 2026. (b) Local times of the equatorial crossings (orbits #1–#16) of Swarm A (red) and Swarm B (blue), together with the local times of EEJ observations from ground-based magnetometers in the Peruvian, Thailand, and Philippine sectors. Vertical magenta lines indicate the storm onset at 19:17 UT on 19 January 2026. (c) Magnetic field perturbations in the north (ΔB_{north} ; black) and center (ΔB_{center} ; green) components measured by Swarm A and Swarm B. From left to right, the columns correspond to the descending crossings of Swarm B (orbits #2, #6, #10, and #14) at $\sim 05:50$ LT, the descending crossings of Swarm A (orbits #1, #5, #9, and #13) at $\sim 11:30$ LT, the ascending crossings of Swarm B (orbits #4, #8, #12, #16) at $\sim 17:50$ LT, and the ascending crossings of Swarm A (orbits #3, #7, #11, #15) at $\sim 23:30$ LT. Cases in which ΔB_{north} perturbations are dominated by magnetic field disturbances from sources other than the EEJ are highlighted with a gray background.

(~ 250 mA/m). This day-night polarity pattern is consistent with the influence of the prompt penetration electric field from high latitudes, which are predominantly eastward on the dayside and westward on the nightside.

The latitudinal structure of horizontal magnetic field perturbations associated with the nighttime westward EEJ was revealed for the first time using data from nine ground-based magnetometers distributed across the Thailand sector (Figure 6). The results show that the magnetic signature of the nighttime westward EEJ closely resembles that of the daytime eastward EEJ observed on preceding quiet days, but with the opposite polarity. These findings provide new evidence for the existence of nighttime westward EEJ currents during geomagnetic storms, a phenomenon previously discussed in the literature (e.g., Abdu et al., 2007; Tsuji et al., 2012).

The strong nighttime EEJ intensities are not predicted by our assessment of storm-time EEJ perturbations based on the height-integrated Cowling conductivity derived from the WDC Kyoto ionospheric conductivity model and the prompt penetration electric field constrained by previous satellite observations (Figure 1). Additional theoretical and modeling studies are therefore needed to quantitatively explain the driving sources of such strong nighttime westward EEJ currents.

During intervals of nighttime westward EEJ activity, magnetic field perturbations observed along 50°N QD latitude exhibited prominent zonal wavenumber-1 patterns (Figure 7). The phase structures of these perturbations are different from the previously reported patterns of storm-time geomagnetic field disturbances at mid and low latitudes (e.g., Iyemori, 1990). We attributed this difference to the exposure of stations near $\sim 50^\circ\text{N}$ QD latitude to high-latitude ionospheric current systems as the auroral oval expanded equatorward. Analysis of Swarm FAC measurements supports the occurrence of such auroral oval expansion during the storm main phase (Figure 4d).

The strongest nighttime westward EEJ current was observed during a period of weakening westward auroral electrojet activity (Figure 8). Magnetic field perturbations in the European sector suggest that the westward auroral electrojet expanded toward lower latitudes during intensifications of the nighttime westward EEJ currents.

We also analyzed magnetic field measurements from Swarm satellites (Figure 9). These observations revealed a substantial enhancement in the noontime EEJ, from ~ 80 mA/m before the storm onset to ~ 270 mA/m during the storm main phase. No evidence of a nighttime westward EEJ was identified in the Swarm data because the equatorial crossing times and local-time coverage were not favorable for its detection. We emphasize the importance of carefully distinguishing between spatial and temporal magnetic field perturbations when interpreting satellite observations during geomagnetic storms, as rapid geomagnetic field variations detected near the magnetic equator can be easily misinterpreted as EEJ signatures. Further satellite-based studies of the nighttime EEJ during geomagnetic storms are needed to better establish its characteristics and occurrence conditions.

Inclusion in Global Research Statement

This study uses observations from international magnetometer networks and satellite missions. Researchers who contributed to the acquisition, curation, interpretation, and analysis of the data are represented among the co-authors. The study was conducted through collaboration among institutions from multiple countries.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The WDC Kyoto ionospheric conductivity model is available online at the WDC Kyoto website (<https://wdc.kugi.kyoto-u.ac.jp/ionocond/sightcal/index.html>). Apexpy, the software package to compute the Quasi-Dipole coordinates, is available from the DOI in van der Meeren et al. (2024). LISN, SEALION, MAGDAS, INTERMAGNET, and IMAGE magnetometer data can be obtained through their respective websites: (LISN) <http://lisn.igp.gob.pe/>; (SEALION) <https://aer-nc-web.nict.go.jp/sealion/>; (MAGDAS) <http://magdas2.i-spes.kyushu-u.ac.jp/>; (INTERMAGNET) <https://intermagnet.org/>; and (IMAGE) <https://space.fmi.fi/image/>. The Hp30 index is available at the GFZ website (<https://kp.gfz.de/hp30-hp60>); see also Matzka et al. (2024). The SYM-H, ASY-H, ASY-D, AE, AL, and AU indices can be downloaded from the WDC Kyoto website (<https://wdc.kugi.kyoto-u.ac.jp/aeasy/>); see also World Data Center for Geomagnetism, Kyoto et al. (2015) and World Data Center for

Geomagnetism, Kyoto et al. (2022). The CHAOS-7 model is available at the DTU Space website (<https://www.spacecenter.dk/files/magnetic-models/CHAOS-7/>). The GOES-19/XRS X-ray fluxes and OMNI solar wind data can be downloaded from the NOAA website (https://data.ngdc.noaa.gov/platforms/solar-space-observing-satellites/goes/goes19/12/data/xrsf-12-avg1m_science) and OMNIWeb (https://omniweb.gsfc.nasa.gov/form/omni_min.html), respectively. The Swarm Level 1b product MAGx_LR_1B, Level 2 products FACxTMS_2F, and EEfxTMS_2F can be downloaded from the ESA website (<https://earth.esa.int/eogateway/missions/swarm/data>).

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