

1 **Solar wind-magnetosphere-ionosphere coupling and its impact on equatorial**
2 **ionospheric electrodynamics during the 23 March 2023 geomagnetic storm:**
3 **Effect of sudden decrease of solar wind dynamic pressure**

4
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18 **Key Points:**

- 19
20 1. Direct evidence of prompt penetration of electric field in the equatorial ionosphere caused
21 by negative solar wind pressure pulse
22
23 2. Transient counter electrojet caused by westward penetration electric field after the arrival of
24 negative pressure pulse
25
26 3. Significant decrease of global large-scale FACs and transient enhancement of localized FAC
27 in response to negative pressure pulse
28
29

30 **Abstract**

31 We present a study of the magnetosphere-ionosphere coupling during the 23 March 2023 magnetic
32 storm, focusing on the effect of the drastic decrease of the solar wind dynamic pressure occurred
33 during the main phase. Our observations show that the negative pressure pulse had significant
34 impact to the magnetosphere-ionosphere system. It weakened large-scale field-aligned currents and
35 paused the progression of the storm main phase for ~ 3 hrs. Due to the sudden decrease of the
36 plasma convection after the negative pressure pulse, the low-latitude ionosphere was over-shielded
37 and experienced a brief period of westward penetration electric field, which reversed the direction
38 of the equatorial electrojet. The counter electrojet was observed both in space and on the ground. A
39 transient, localized enhancement of downward field-aligned current was observed near dawn,
40 consistent with the mechanism for transmitting MHD disturbances from magnetosphere to the
41 ionosphere after the negative pressure pulse.

42

43 **Plain Language Summary**

44 The solar wind is a continuous stream of charged particles blowing from the Sun. The Earth's
45 magnetic field forms a protective shield around our planet, called the magnetosphere, which deflects
46 most of the solar wind particles away from the Earth. Disturbances in the solar wind can interact
47 with the magnetosphere and impact the Earth's upper atmosphere (ionosphere). The interaction
48 creates electric fields forcing charged particles to move in the magnetosphere, which creates electric
49 currents flowing along the magnetic field lines connecting to the high-latitude ionosphere and drives
50 the movement of charged particles there. The low-latitude ionosphere is generally shielded from
51 these electric fields. Sudden changes in the solar wind can break such balance, leading to the
52 electric field penetration to low latitudes. We examined how the magnetosphere and ionosphere
53 interacted during the 23 March 2023 geomagnetic storm, focusing on what happened when the solar
54 wind dynamic pressure suddenly decreased. We found the pressure drop caused a sudden decrease
55 of the high-latitude electric field, resulting in a brief period of overshielding and the electric field in
56 the equatorial ionosphere reversed its direction. This changed the direction of the equatorial
57 electrojet, a major electric current in the ionosphere at the magnetic equator.

58 **1 Introduction**

59

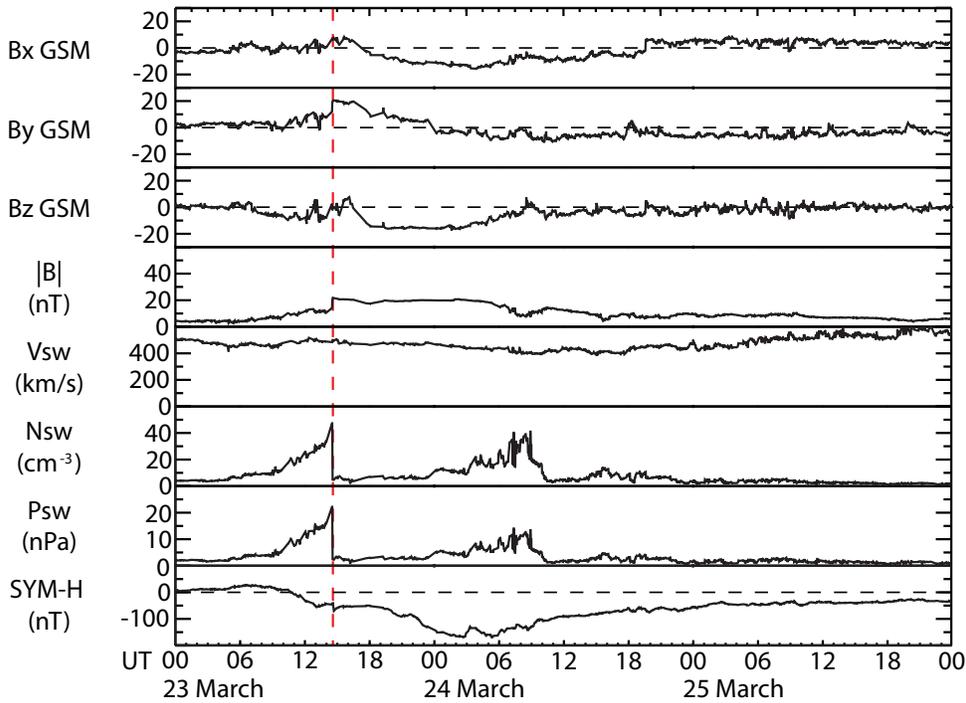
60 In steady-state conditions, the low-latitude ionosphere is shielded from the high-latitude convection
61 electric field due to the partial ring current-associated region-2 (R2) field-aligned currents (FACs)
62 which act to oppose the electric field associated with region-1 (R1) FACs (e.g., Southwood, 1977).
63 However, it can be directly coupled to the magnetospheric disturbances through prompt penetration
64 of the convection electric field during active times (Nishida, 1968; Jaggi and Wolf, 1973; Fejer et
65 al., 1979).

66
67 The equatorial electrojet (EEJ), an intense band of eastward electric current flowing along the
68 dayside magnetic equator in the E-region ionosphere (~ 110 km altitude), is driven by an eastward
69 zonal electric field from plasma-neutral collisional interactions known as the E-region wind dynamo
70 (Richmond, 1973; Heelis, 2004). The intensity and polarity of the EEJ respond directly to the
71 perturbations of the zonal electric field. Variations of the EEJ often serve as an indicator for the
72 equatorial zonal electric field perturbations, which can be caused by either neutral wind changes
73 from lower atmosphere forcing or prompt penetration electric fields (PPEFs) from enhanced
74 magnetosphere-ionosphere (M-I) coupling. Many studies have used EEJ variations to probe the
75 presence of PPEFs that are attributed to interplanetary magnetic field (IMF) variations (e.g.,
76 Yizengaw et al., 2011, 2016) or solar wind dynamic pressure pulses (e.g., Nilam et al., 2020, 2023).
77 Understanding the sources and the process of PPEFs continues to be a subject of ongoing
78 investigation (Kelly et al., 2003; Fejer et al., 2024).

79

80 This paper reports the observations of the M-I coupling and its effect on the equatorial ionosphere
81 in response to a sudden decrease of the solar wind dynamic pressure during the main phase of the
82 23 March 2023 geomagnetic storm. Figure 1 shows 1-min resolution OMNI data for the IMF and
83 solar wind parameters along with ground-based SYM-H index for 23-25 March 2023. This large
84 storm (minimum Dst ~ -170 nT, $K_p \sim 7$) was associated with the passage of an interplanetary
85 coronal mass ejection (ICME), triggered by the southward IMF in both the sheath and the ICME
86 regions. A drastic density decrease was observed at the boundary crossing from the sheath to the
87 ICME by the WIND spacecraft. As a result, a significant negative solar wind pressure pulse hit the

88 Earth's magnetosphere during the main phase of the storm (1440 UT, marked by the red dashed line
 89 in Figure 1). The solar wind density as well as the dynamic pressure decreased by a factor of ~ 10 .



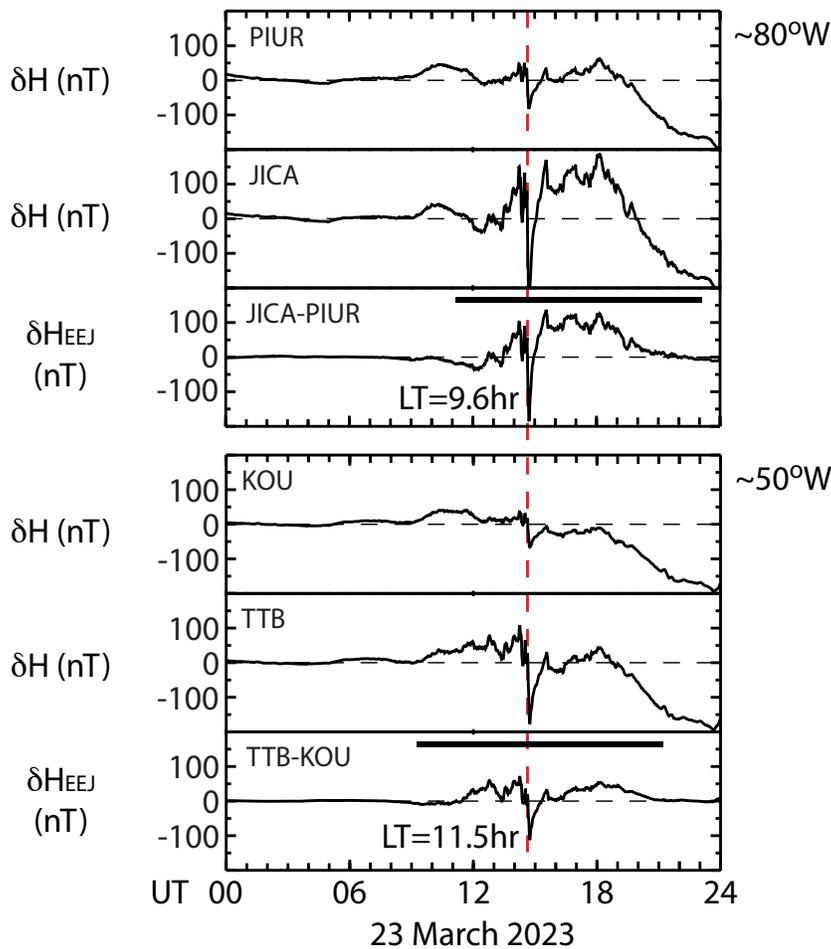
90
 91 **Figure 1. The 1-min resolution OMNI data with IMF/solar wind parameters (top 7 panels) and SYM-H index**
 92 **(bottom panel) for 23 March 2023 magnetic storm. The negative pressure pulse during the main phase of the**
 93 **storm is marked by the red dashed line.**

94
 95
 96 We examine how FACs at high latitudes and the EEJ at the equator responded to the negative
 97 pressure pulse using both space and ground-based magnetic field data. In the following sections, we
 98 first present evidence for a transient PPEF associated with the pressure pulse from the ground based
 99 EEJ observations. Then we examine the response of large-scale FACs globally by AMPERE and
 100 locally by Swarm satellites. We also analyze the EEJ observations in space by Swarm, which
 101 provide additional evidence for the transient PPEF associated with the pressure pulse. Finally, we
 102 discuss the dynamic processes involving solar wind pressure pulse interacting with the
 103 magnetosphere and coupling into the polar ionosphere, that allow us to understand the behaviors of
 104 the equatorial ionosphere.

105
 106 **2 Observations**

107
108 2.1 Ground-based Observations of the EEJ
109
110 The EEJ signals can be obtained from a pair of ground magnetometer stations located near the
111 magnetic equator on the same meridian, one directly under the EEJ at the equator (within $\pm 3.5^\circ$) and
112 the other just off the EEJ region (6° – 9° from the magnetic equator) (Anderson et al., 2004;
113 Yizengaw et al., 2014). The EEJ signals can only be detected by the station at the magnetic equator
114 because the EEJ current is confined in a narrow latitudinal band (within $\pm 3^\circ$). But both stations are
115 expected to record the same magnetic field variations from other large-scale current sources, such as
116 the solar quiet (Sq) currents, the ring current, and the magnetopause current. The EEJ signals are
117 extracted from the difference of the H-components between the two stations. In this study, we used
118 two pairs of geomagnetic observatories at two meridians ($\sim 80^\circ\text{W}$ and $\sim 50^\circ\text{W}$). One pair is located
119 at Jicamarca (JICA, $11.95^\circ\text{S}/76.87^\circ\text{W}$ GEO, MLat = 0.6°N) and Piura (PIUR, $5.2^\circ\text{S}/80.6^\circ\text{W}$ GEO,
120 Mlat = 6.9°N) in Peru. The other pair is located at Tatuoca, Brazil (TTB, $1.21^\circ\text{S}/48.5^\circ\text{W}$ GEO) and
121 Kourou, French Guyana (KOU, $5.21^\circ\text{N}/52.7^\circ\text{W}$ GEO). TTB and KOU are well located under and
122 far enough from the EEJ, respectively. They are within the region of South Atlantic Anomaly with
123 rapid northward moving of the magnetic equator, and the magnetic equator passed the TTB in
124 March 2013 (Morschhauser et al., 2017).
125
126 Figure 2 shows the magnetic field observations from the 2 pairs of ground observatories on 23
127 March 2023 with three subpanels for each pair, from top to bottom, showing the H-component with
128 the background removed (δH) off the magnetic equator, at the magnetic equator, and the EEJ signal
129 (δH_{EEJ} , the differences between δH at the geomagnetic equator and off the equator), respectively.
130 The horizontal bar in the 3rd subpanel indicates dayside hours (6–18 LT) at the equator station. The
131 red dashed line indicates the time of the negative pressure pulse (1440 UT) in Figure 1. The local
132 time (LT) of the pressure pulses at the two equator stations are also noted in Figure 2.
133
134 The eastward zonal electric field from the wind dynamo drives the eastward EEJ, producing a
135 positive magnetic field perturbation ($\delta H_{EEJ} > 0$) in the dayside. This is generally the case in Figure 2
136 except for a brief period immediately following the negative pressure pulse. There was a transient
137 negative impulse of the H-component at all the stations, consisting of a sharp decrease (~ 6 min) and

138 a relatively gradual (~ 1 hour) return, apparently due to the sudden decrease of the magnetopause
 139 current and expansion of the magnetosphere in response to the negative pressure pulse (Araki and
 140 Nagano, 1988). However, the transient negative impulse at the equator station is much stronger than
 141 its off-equator counterpart, and the EEJ signature reversed its sign showing a transient counter
 142 electrojet flowing westward. This observation indicates the negative pressure pulse set up a
 143 transient westward electric field (~ 1 hour) in the equatorial ionosphere.
 144



145
 146 **Figure 2. Ground-based observations of the H-component from 2 pairs of ground observatories on 23 March**
 147 **2023, JICA-PIUR and TTB-KOU, respectively. The red dashed line marks the negative pressure pulse in Figure**
 148 **1. The black horizontal bars indicate the daytime (06-16 LT) at the equator stations.**

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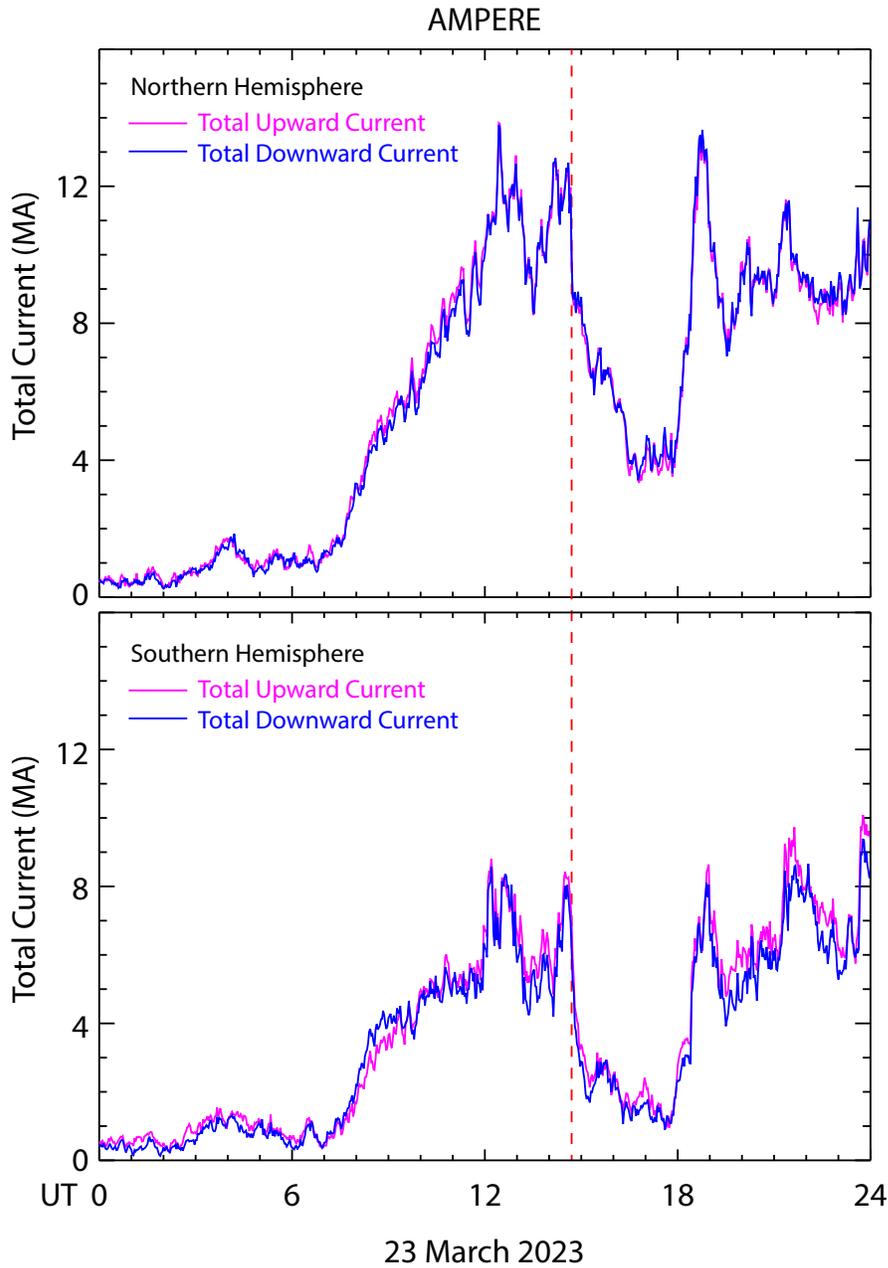
151 2.2 AMPERE Observations of Large-scale FACs

152
153 AMPERE observations of large-scale FACs are derived from global measurements of magnetic
154 field perturbations from the Iridium constellation of more than 70 near-polar orbiting satellites
155 [Anderson et al., 2000]. It collects 10-min data to generate one global pattern of large-scale FAC
156 distributions and provides a continuous monitor of the state of the global M-I system. (AMPERE
157 data will unlikely reveal transient and localized variations due to the limitation of spatial and
158 temporal resolution.) Figure 3 shows the AMPERE observations of the total field-aligned currents
159 flowing into and out of the ionosphere on 23 March 2023 (Figure S1 provides the magnetic field
160 perturbations and global FAC maps). The total upward current out of one hemisphere is calculated
161 by integrating all the upward current density over the entire area above 40° latitude, and likewise for
162 the total downward current. Again, the red dashed vertical line corresponds to the negative pressure
163 pulse in Figure 1.

164
165 Starting from ~ 07 UT, the total FACs gradually intensified as the storm progressed with the SYM-
166 H index became more negative, representing an increasing active magnetosphere as FACs facilitate
167 the electromagnetic energy input from the magnetosphere into the ionosphere. There is a brief
168 period (~ 1 hr) of total current drop starting at ~13 UT, apparently associated with the northward
169 excursion of the IMF Bz component (Figure 1) which turned off the dayside reconnection and
170 reduced the magnetospheric convection temporally.

171
172 Figure 3 shows the total currents responded to the negative pressure in two stages. The total currents
173 dropped sharply at ~1440 UT due to the sudden sunward motion of the magnetopause and
174 expansion of the magnetosphere. The sudden reduction of the magnetopause current also caused a
175 step decrease of the SYM-H index (Figure 1). Then the total currents continued to decrease
176 gradually. The decreasing trend of the SYM-H index has flattened out within the storm main phase,
177 indicating the pause of the ring current development (Figure 1). This is expected as IMF Bz
178 fluctuated around zero and the expanded magnetosphere adjusted to the new state of reduced
179 geomagnetic activity level. At ~1630 UT, the IMF Bz gradually turned southward, which
180 terminated the decreasing trend of the total currents. At ~ 18 UT, both the total currents (Figure 3)
181 and the SYM-H index (Figure 1) showed that the magnetospheric activities began to intensify

182 rapidly with the prolonged steady southward IMF in the ICME. In summary of the AMPERE
183 observations, large-scale FACs were significantly weakened by the negative pressure pulse.
184
185



186
187 **Figure 3. AMPERE Observations of the total amount of upward and downward FACs in northern and southern**
188 **hemisphere, respectively.**

189
190

191 2.3 Swarm Observations of FACs and EEJ

192
193 Swarm is a three-satellite mission in a high-inclination (87.5°) low-Earth orbit, which provides
194 vector magnetic field data for frequent in situ measurements of FACs at high latitudes (Lühr et al.,
195 2015) and scale magnetic field strength for the EEJ in the equatorial region (Alken et al., 2015).
196 Among the three satellites, A and C form a pair flying side by side at the same altitude ($\sim 460\text{km}$)
197 with a longitudinal separation of 1.4° . Swarm B has slightly higher altitude ($\sim 530\text{km}$) and its orbital
198 plane slowly drifts apart from those of Swarm A/C. In this study, we used two official Swarm level-
199 2 data products: (1) the vector magnetic field residuals $\delta\mathbf{B}$ for the study of FACs, and (2) the height-
200 integrated latitudinal profile of eastward EEJ current. The EEJ current profile is estimated from the
201 Swarm scalar magnetic field measurements by isolating the EEJ signal from the many other
202 geomagnetic sources and then fitting the EEJ signal with a line current model (Alken et al., 2015).
203 The EEJ current peak at the magnetic equator provides a good estimate of the EEJ strength.

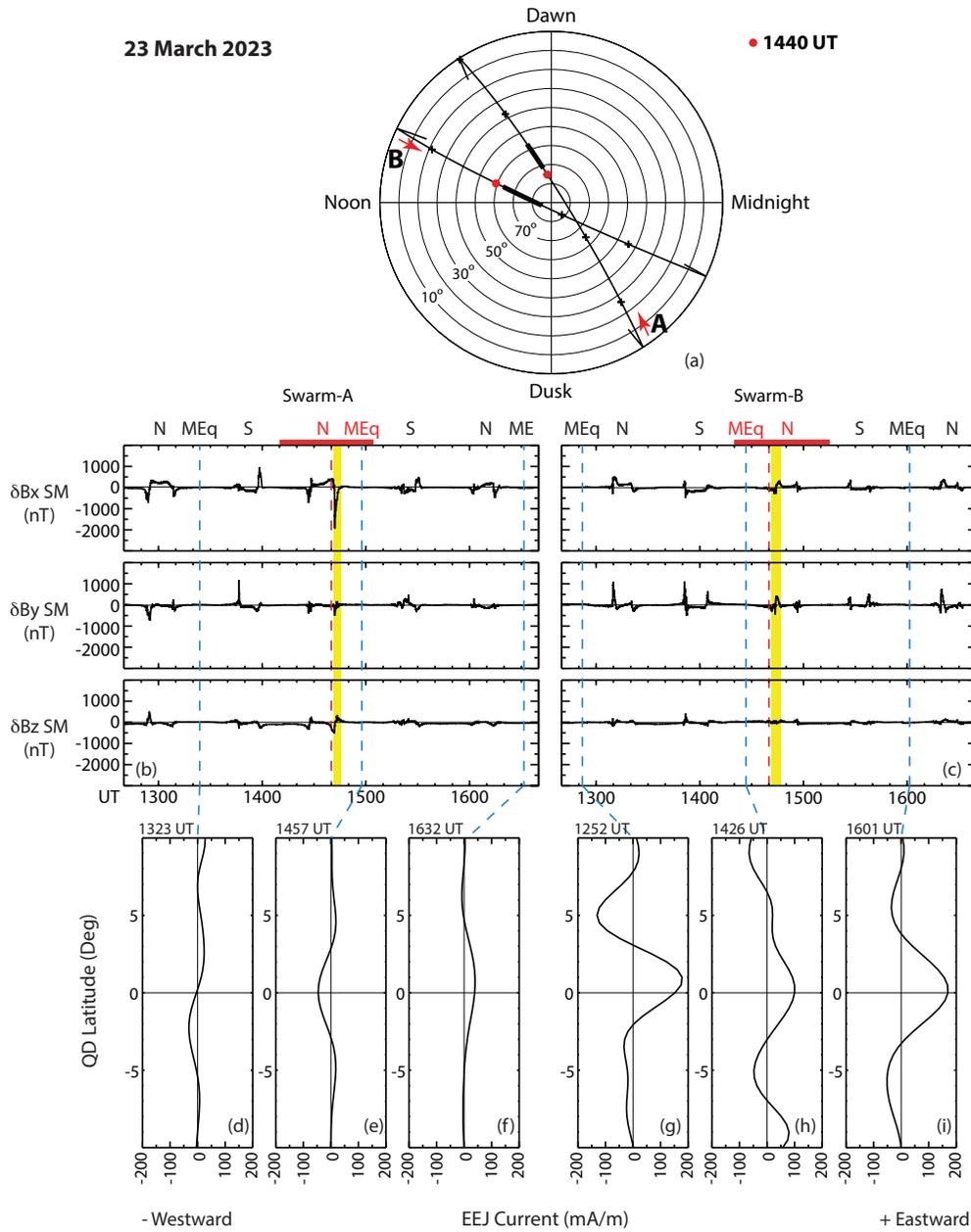
204
205 Figure 4 presents an overview of the Swarm observations. Figure 4a shows the spacecraft orbits for
206 the polar cap pass near 1440 UT, the intervals marked by the red bars in Figures 4b/4c. Figures 4b
207 and 4c contain 4 hours of Swarm vector magnetic field residuals $\delta\mathbf{B}$ in solar magnetic (SM)
208 coordinate system centered at 1440 UT (red dashed line) for Swarm A and B, respectively. Swarm
209 C data are nearly the same as Swarm A (not shown). During this interval, Swarm made 5 passes of
210 the polar cap, denoted by N (S) for the northern (southern) hemisphere, and 3 crossings of the
211 dayside magnetic equator marked by MEq and the blue dashed lines. The perturbations in $\delta\mathbf{B}$ are
212 the signals of FACs, occurring at auroral latitudes on both sides of the magnetic pole. The
213 latitudinal profiles of the estimated EEJ current at the dayside magnetic equator crossings are
214 presented in Figures 4d-4f for Swarm A and 4g-4i for Swarm B. The positive current is for eastward
215 EEJ.

216
217 Both Swarm A and B were in the dayside morning sector over the northern polar cap at the time of
218 the negative pressure pulse (red dots in Figure 4a). In Figure 4a, the tick marks on each trajectory
219 are separated by 10 min. The red arrows indicate the directions of the spacecraft motion. Swarm A
220 was moving from nightside to dayside and Swarm B from dayside to nightside with ~ 2 hr local
221 time separation of the orbital planes.

222
223 In Figures 4b&4c, the FACs observed before the negative pressure pulse were generally stronger
224 than those after at Swarm, in agreement with the AMPERE observations. The only exception is that
225 the FAC signal was significantly enhanced to ~ 2000 nT in magnitude shortly after the negative
226 pressure pulse at Swarm A (highlighted in yellow in Figure 4b) at ~ 7 LT (Figure 4a). The magnetic
227 field perturbations were mainly in the $-x$ direction (anti-sunward), which is the signature of a pair of
228 FACs flowing downward at higher and upward at lower latitudes, respectively. The enhanced FAC
229 pair had the same polarity of the regular R1/R2 FACs in the dawn sector. The enhanced δB_x
230 magnitude was mainly due to the much-enhanced dawnward FAC at higher latitudes since the
231 gradient (i.e., time rate of change) of δB_x was significantly higher at the poleward edge. The FACs
232 observed by Swarm B at nearly the same time (yellow-highlighted interval in Figure 4c) but at ~ 11
233 LT (Figure 4a) did not show the same feature, neither did the subsequent FACs in the pre-midnight
234 sector. When Swarm A returned to the same region in next orbit about 90 min later (~ 1615 UT),
235 the FACs have returned to the weakened state. These observations indicate the much-enhanced
236 downward FAC is a localized (near dawn) and transient (duration < 90 min) phenomenon in
237 response to the sudden decrease of the solar wind dynamic pressure. The AMPERE observations
238 did not capture such a localized transient response.

239
240 We now examine the EEJ profiles. As Swarm B is much closer to the local noon at the dayside
241 equator, the EEJ signal is expected to be much stronger at Swarm B than Swarm A. Before the
242 negative pressure pulse, the EEJ profile is not well defined at Swarm A (1323 UT, Figure 4d),
243 mostly likely due to a very weak EEJ in early morning. But closer to the local noon, Swarm B
244 detected the typical eastward EEJ profile at 1252 UT (Figure 4e) and 1426 UT (Figure 4f). Then
245 about 17 min after the negative pressure pulse, Swarm A observed a well-defined westward EEJ, or
246 counter electrojet (Figure 4e). The observed counter electrojet appeared to be a transient
247 phenomenon. The EEJ returned to nominal eastward direction in the next two profiles, 1601 UT at
248 Swarm B (Figure 4i) and 1632 UT at Swarm A (Figure 4f). These observations are in agreement
249 with the ground-based EEJ currents in Figure 2.

250
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252



254

255 **Figure 4. Swarm A and B observations of FACs and the EEJ: (a) Spacecraft trajectories near the negative**
 256 **pressure pulse; (b-c) the vector magnetic field residuals; (d-i) the latitudinal profiles of the EEJ around the**
 257 **magnetic equator.**

258

259

260

261 3 Discussion

262

263 We first summarize the observations presented above.

- 264 • The solar wind dynamic pressure decreased suddenly and significantly at the boundary of
265 the ICME that caused the 23 March 2023 magnetic storm. The negative pressure pulse
266 arrived at the Earth at 1440 UT during the main phase of the storm and the IMF Bz
267 fluctuated between northward and southward (Figure 1).
- 268 • The total large-scale FAC currents flowing into and out of the ionosphere decreased
269 significantly soon after the arrival of the negative pressure pulse based (Figure 3). The
270 overall geomagnetic activity level in the magnetosphere was weakened for more than 3 hrs,
271 which paused the progression of the storm main phase. The activity level picked up again
272 only after the IMF Bz turned strongly southward for an extended period during the passage
273 of the ICME.
- 274 • Swarm A observed a significant enhancement of the downward FAC at the poleward edge
275 of the FAC region near dawn shortly after the negative pressure pulse, which appeared to be
276 localized and transient (Figure 4). Nearly simultaneous Swarm B observations closer to the
277 local noon showed weakened FACs, consistent with the AMPERE observations.
- 278 • A transient counter electrojet was observed both in space by Swarm A (Figure 4) and on the
279 ground (Figure 2) within minutes after the arrival of the negative pressure pulse. The counter
280 electrojet lasted for ~ 1 hr and then returned to its regular eastward direction. The observed
281 transient reversal of the EEJ to the westward direction suggests that the equatorial
282 ionosphere experienced a brief period of a westward electric field after the negative pressure
283 pulse.

284

285 These observations demonstrate the profound impact to the M-I system by the negative pressure
286 pulse. The observed counter electrojet clearly shows that a transient westward electric field
287 associated with the negative pressure pulse penetrated to the equatorial ionosphere from over-
288 shielding (Hori et al., 2012; Fujita et al., 2012). The penetration electric field was much stronger in
289 magnitude than the background eastward electric field from the wind dynamo so that the overall
290 zonal electric field was reversed. Our observations indicated there was a sudden decrease of the
291 dawn-to-dusk (eastward) convection electric field as evident by the sudden decrease of the total

292 FAC currents flowing into and out of the polar ionosphere immediately after the negative pressure
293 pulse (Figure 3). The total FACs then gradually decrease with a time scale of hours. However,
294 SYM-H, the ring current index, was flattened out in the same period, indicating the ring current did
295 not immediately respond to the weakened convection electric field (Figure 1). The delayed response
296 of the ring current reflects the time scale for the M-I system to gradually adjust to the expanded
297 state of the magnetosphere with decreased level of plasma convection (Earle and Kelley, 1987).
298 Thus, there was a short period when the low-latitude ionosphere was over-shielded and experienced
299 a dusk-to-dawn (westward) electric field. Based on the duration of the counter-electrojet in the
300 ground-based observations (Figure 2), the response of the ring current-R2 FAC system was delayed
301 for ~6 min, and it took ~ 1 hr for the M-I system to gradually adjust itself to the decreased plasma
302 convection level and the low-latitude ionosphere to return to be fully shielded.

303
304 To understand the transient responses and localized enhancement of FACs, it is necessary to review
305 the current understanding of the underlying physical process. The M-I system responds to a sudden
306 pressure pulse in two phases, including a preliminary impulse (PI) and a two-stage main impulse
307 (MI) (e.g., Tamao, 1964a&b; Araki, 1977; Araki and Allen, 1982). The PI is due to the propagation
308 and conversion of a compressional wave front launched from the magnetopause when the
309 magnetosphere is suddenly compressed or expanded. The PI is transient by nature because its driver
310 is the interaction between the pressure pulse and the magnetopause, which disappears in minutes
311 after the impulse front propagates away from the dayside.

312
313 Although more previous studies focused on sudden pressure increases than decreases, the basic
314 physics is the same. Based on Tamao's (1964a&b) pioneer work, Araki (1994) proposed a M-I
315 coupling PI model to explain the global observations after geomagnetic sudden commencements.
316 As illustrated in their Figure 12, the magnetopause moves inward and the dawn-to-dusk
317 magnetopause current increases when the solar wind dynamic pressure suddenly increases. A
318 compressional MHD wave is excited on the magnetopause, which propagates into the equatorial
319 magnetosphere. The solar wind-magnetosphere interaction as a dynamo generates an enhanced
320 dusk-to-dawn electric field at the magnetopause ($\mathbf{J} \cdot \mathbf{E} < 0$). A dusk-to-dawn electric field and
321 associated inertia electric current are induced inside the magnetosphere. The extra magnetopause
322 current and the inertia current would form a counterclockwise current loop. The compressional

323 wave will be converted into the transverse Alfvén wave due to the nonuniformity of the
324 magnetosphere (Tamao, 1964b; Southwood and Kivelson, 1990). When the compressional wave
325 front reaches the region where the Alfvén speed has a largest spatial gradient, converted Alfvén
326 waves are generated and propagate along the field lines with associated FACs. A pair of FACs will
327 be a part of the current loop, downward in the dusk side and upward in the dawn side. This process
328 happens in time scale of minutes. So, the pair of FACs exists transiently at lower latitudes than the
329 regular R1 currents with opposite polarity. A quantitative detail of the PI process is provided in the
330 MHD simulations by Fujita et al. (2003a&b, 2005), and the source region of the MHD wave mode
331 conversion for the generation of the transient FACs was found to be in the region of $6 < L < 7$
332 (Fujita et al., 2003a).

333
334 In the case of negative pressure pulses, the observations by Araki (1988) and simulations by Fujita
335 et al. (2004, 2012) showed that the magnetospheric and ionospheric signatures mostly mirror those
336 in pressure pulses. The negative pressure pulse causes the expansion of the magnetosphere and a
337 decrease of the magnetopause current. The PI is associated with a dawn-to-dusk transient dynamo
338 electric field at the magnetopause and induced electric field in the magnetosphere. The equatorial
339 current loop would be clockwise to effectively reduce the magnetic field strength in the
340 magnetosphere, and the pair of transient FACs would be downward in the dawnside and upward in
341 the duskside, in the same polarity of the regular R1 currents. The transient and localized
342 enhancement of the downward FAC observed by Swarm A near dawn (Figure 4) matches the
343 predicted polarity of the FACs. However, our observations differ in an important aspect from the
344 model prediction. The transient, localized FAC enhancement was observed at the poleward edge of
345 the FAC region, implying the source region was near the magnetopause, as in the earliest work of
346 Tamao (1964a). Further theoretical and numerical investigation is still needed to understand the
347 source region of the transient FACs during the PI. In addition, understanding the role of the ring
348 current/R2 FAC system to the undershielding/overshielding and its restoration is particularly needed
349 in future simulations.

350

351 **4 Conclusions**

352

353 A drastic decrease of the solar wind dynamic pressure occurred during main phase of the 23 March
354 2023 geomagnetic storm in association with the boundary between the ICME and its sheath. Our
355 observations show that the negative pressure pulse had significant impact to the M-I system. It
356 weakened the overall geomagnetic activities and plasma convection and paused the progression of
357 the storm main phase for ~ 3 hrs. Due to the sudden decrease of the dawn-to-dusk convection
358 electric field, there was a transient period when the low-latitude ionosphere was over-shielded and
359 experienced a brief period of dusk-to-dawn (westward) penetration electric field. The transient
360 westward penetration electric field reversed the direction of the equatorial electrojet, and the
361 counter electrojet was observed both in space and on the ground. The response of the ring current-
362 R2 FAC system was delayed for ~ 6 min, and it took ~ 1 hr for the M-I system to adjust itself to the
363 decreased plasma convection level until the low-latitude ionosphere was fully shielded again.
364 Although the overall large-scale FACs were weakened by the negative pressure pulse, a transient,
365 localized enhancement of downward FAC was observed near dawn, consistent with the mechanism
366 for transmitting MHD disturbances in the M-I coupling after the negative pressure pulse. But the
367 latitudinal location of the localized FAC enhancement differed from the model prediction, which
368 calls further investigation of the MI coupling in response to the pressure pulse.

369

370

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372

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376

377

378

379 **Data Availability Statement**

380

381 The OMNI data are available at <https://omniweb.gsfc.nasa.gov>. The JICA and PIUR magnetometer
382 data are available at <https://zenodo.org/records/10823058>. The KOU and TTB magnetometer data
383 are available at INTERMAGNET (www.intermagnet.org). The AMPERE data are available at
384 <https://ampere.jhuapl.edu>. The Swarm data are accessible at
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