DOI: 10.31401/WS.2020.proc.11

Strong High-Latitude Geomagnetic Response to the Initial Phase of the Magnetic Storm on 5 April 2010

Kleimenova N.G.[1], Gromova L.I.[2], Gromov S.V.[2], Malysheva L.M.[1]

[1]Schmidt Institute Physics of the Earth RAS, Moscow, Russia
[2]IZMIRAN, Moscow, Russia
e-mail: kleimen@ifz.ru

Abstract

The global high-latitude geomagnetic signature of the first magnetic storm (5-6 April 2010) of the very beginning of the solar cycle 24 has been studied using the ground-based magnetometer networks (SuperMAG, IMAGE and INTERMAGNET) data as well as the data of the ionospheric magnetometer satellite system AMPERE. Non-typical geomagnetic response of this storm was found: the strongest geomagnetic disturbances have been observed in the storm initial phase, but not in the storm main phase. The high-latitude dayside magnetic effects as the occurrence of the negative magnetic bays at polar latitudes and their association with a very strong night-side substorm are discussed. It was shown that this geomagnetic feature was caused by the peculiar properties of the solar wind and Interplanetary Magnetic Field (IMF) disturbances in the sheath ahead of the magnetic cloud.

Introduction

The fast-moving (*Vsw* about~ 800 km/s) coronal mass ejection (CME) preceded by an interplanetary shock (SHEATH) arrived at the Earth at 08:26 UT of April 5, 2010 [*Möstl et al.,* 2010; *Liu et al*. 2011], and was identified as SC of a moderate magnetic storm (Dst_{min} = -81 nT on 6 April). It was the first notable magnetic storm in the very beginning of the 24-th solar cycle, i.e. during the solar minimum, therefore different separate geophysical aspects of this event were widely discussed by many authors, e.g. [*Kinrade et al.,* 2012; *McComas et al.,* 2012; *Shimeis et al.,* 2012; *Kleimenova et al.,* 2013; *Fathy et al*., 2014; *Lu et al.,* 2014; *Baishev et al*., 2015; *Victor et al.,* 2016; *Nishimura et al.,* 2020]. However, the high-latitude geomagnetic disturbances in the polar region of the dayside magnetosphere remained unexplored, despite these regions are the first magnetosheath areas where the solar wind impacts the magnetosphere. The aim of this paper is to study the dayside high-latitude geomagnetic disturbances associated with this magnetic storm and to show the global feature of the storm geomagnetic response. In our study we used the data from the globally distributed ground-based magnetometer networks: SuperMAG (http://supermag.jhuapl.edu/), IMAGE (http://space.fmi.fi/image/) and INTERMAGNET (http://www.intermagnet.org/)) as well as the ionospheric magnetometer data from the 66 Iridium Communications satellites AMPERE (http://www.ampere.jhapl.edu/).

Interplanetary conditions

The solar wind and Interplanetary Magnetic Field variations during the magnetic storm on 5 April 2010 were non-typical (Fig. 1): the main solar wind and IMF irregularities occurred not in the storm main phase, as it is typical, but during the ahead interplanetary shock (SHEATH) under strong solar wind dynamic pressure (*Psw*) reached ~10 nPa and even more (Fig. 1). The duration of the southward IMF was only about 1 hour, up to 09:25 UT, thus, the significant Dst (*SymH*) decreasing could not develop. The steady southward IMF occurred only after ~ 13 UT, and the real storm main phase started. Thus, the preceded time interval (up to ~ 13 UT) can be attributed to the storm initial phase. After the SC, the estimated location [after *Kuznetsov and Suvorova*, 1998] of the dayside magnetopause shifted from ~10.5 Re to ~ 7.5 Re.

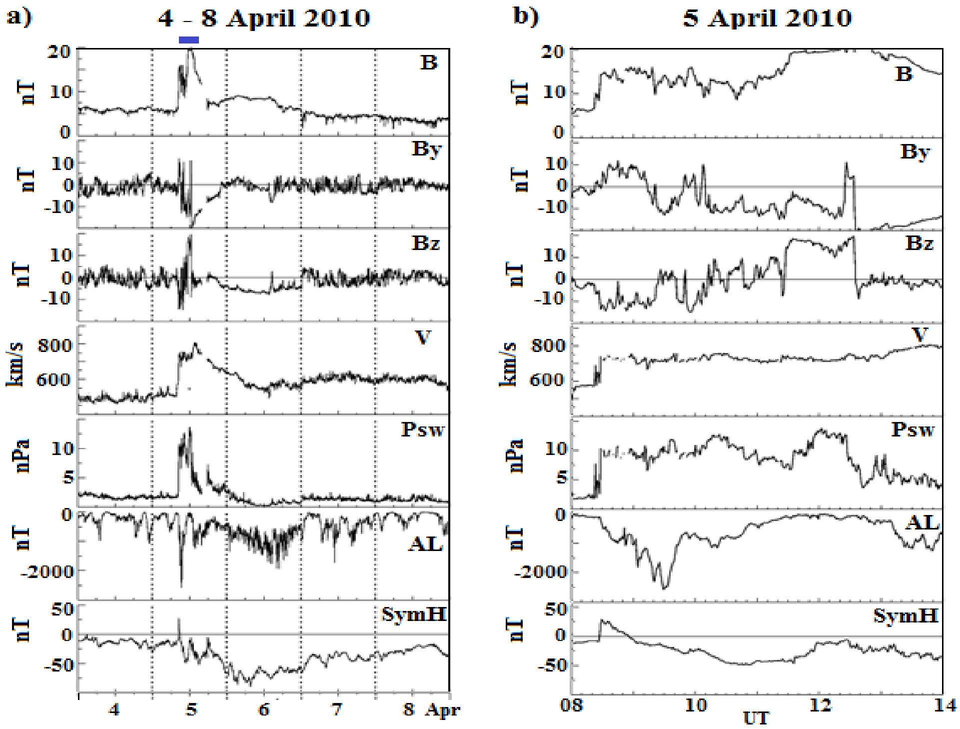

Fig. 1. The interplanetary conditions of the magnetic storm on 5-6 April 2010: a)-during 5 days around this storm, b) in the storm beginning before its main phase.

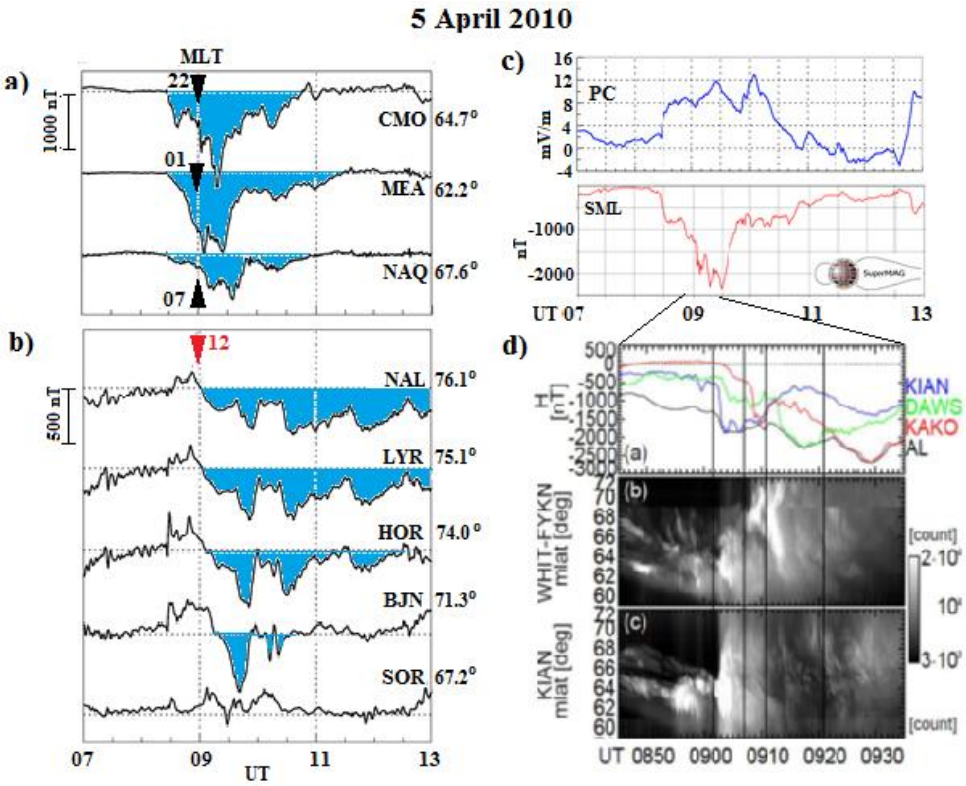

Fig. 2. Magnetograms from selected high-latitude stations: a) night-side, b) dayside; c) the variations of the PC and SML indexes; d) magnetograms from selected THEMIS ground-based stations and auroral keograms demonstrating the substorm growth phase and auroral breakup (adapted from [Nishimura et al., 2020*]).*

High-latitude geomagnetic response

An interplanetary shock with a large southward IMF compressed the Earth's magnetosphere and created the shock aurora [*Nishimura et al.,* 2020]. About 20 min later, the substorm growth phase arc can be seen as a latitudinally thin arc starting at 08:38 UT at 65º MLAT (Fig. 2d) followed by rapid equatorward motion which was much faster than that for typical substorms. About 20 min later, the large dipolarizations ("overdipolarization") took place at GOES 11 at 09:03 and 09:08 UT in the midnight sector [*Nishimura et al.,* 2020], and also by the three THEMIS spacecraft near $X = -11$, $Y = -2$ RE [*Connors et. al.,* 2011]. That resulted the bright auroral breakup (Fig. 2d) followed by the very strong substorm (supersubstorm) as it seen in Fig. 2c demonstrated very strong values of the SML index (up to ~2500 nT). This index is similar to the well-known AL-index, but derived from the 88 auroral SuperMAG stations [*Gjerloev et al.,* 2012].

The magnetograms from the selected high-latitude nightside and dayside stations are shown in Fig. 2a, b for the time interval of the storm initial phase. It is seen that simultaneously with the strong nighttime negative magnetic bays, developed after the dipolizations and auroral breakup (Fig. 2d), the bay-like geomagnetic disturbances occurred at the dayside polar latitudes (71-76º MLAT) but with the significant smaller amplitudes (note the different scale of the night and day graphs). Moreover, there were two additional negative magnetic bays at the dayside 74-76º MLAT: at 10:20-11:20 UT (which is not discussed here) and 11:30-12:30 UT, both observed under the northward IMF (IMF Bz>0).

Global feature of the geomagnetic response

The global distribution of the magnetic vectors measured by the SuperMAG stations is shown in Fig. 3 for three intervals: a) few minutes after the SC, b) near the maximum of the SML-index, and c) in the middle of the last polar negative magnetic bay (Fig. 2b). It is shown (Fig. 3a) that the SC under the southward IMS caused the moderate geomagnetic disturbances on the day and night sides but with the different directions. The ground-based data (Fig. 2) indicate the negative magnetic deviation on the nightside and positive one on the dayside. The same effect is demonstrated by the AMPERE ionospheric satellites (Fig. 4). It is seen (Fig. 4a) that the ionospheric current direction is different in the afternoon (upward field aligned current FAC enhancement) and before noon (downward FAC enhancement).

In the supersubstorm maximum (near 09:30 UT), the strongest ground-based magnetic disturbances according to the SuperMAG data (Fig. 3b) were observed in the evening. They were accompanied by the high-latitude magnetic disturbances on the dayside and in the early morning.

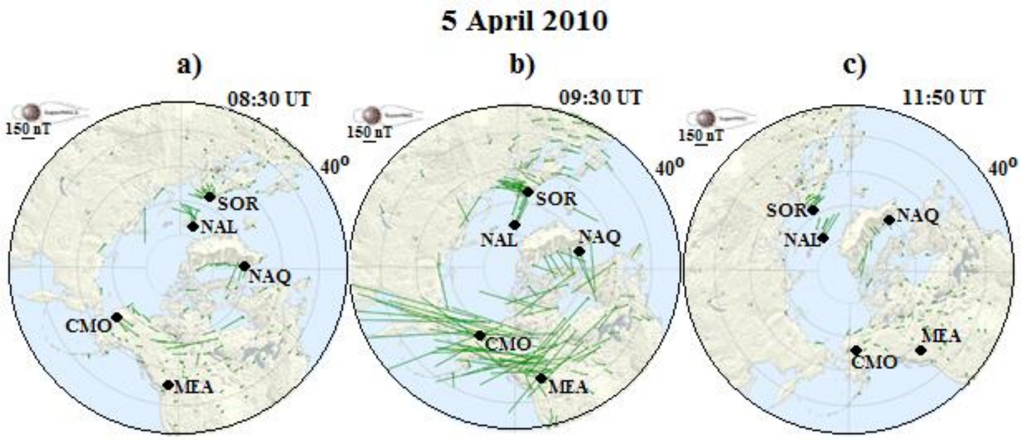

Fig.3. The global SuperMAG maps of the magnetic vectors rotated by 90° to show the direction of ionospheric equivalent electric currents at selected UT moments

That was confirmed by the AMPERE ionospheric measurement (Fig. 4b) demonstrated the strong vortex in the evening indicating the very enhanced upward FACs as well as the westward electrojet from the noon to the Harang discontinuity before the midnight.

The negative magnetic bay at 11:30-12:30 UT (Fig. 2b) was observed only at the polar latitudes in the dayside (Scandinavian IMAGE magnetometer chain). There was no notable magnetic activity in the night sector (Fig. 2a) as it is also seen by SuperMAG measurements (Fig. 3c). The ionospheric AMPERE satellite data (Fig. 4c) show the polar-latitudes vortex located near the noon and the correspondent enhancement of a pair of the downward and upward FACs at the dayside polar latitudes. The night sector was very slightly disturbed.

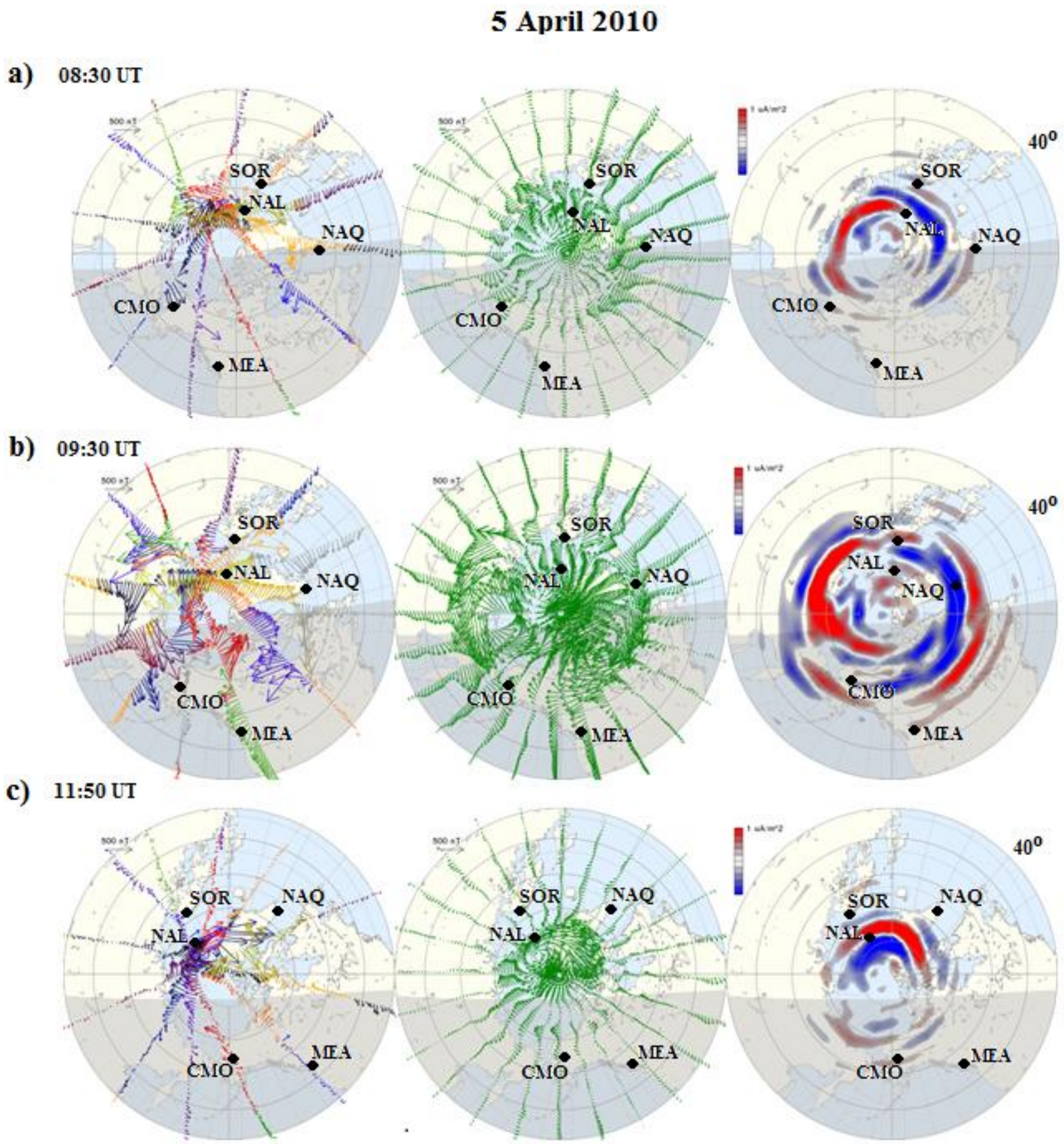

Fig. 4 The AMPERE magnetic field perturbations over the northern polar region (different color vectors represent measurements from the different satellites) and the result of their spherical harmonic analysis as well as calculated distribution of the field aligned currents (FACs) at the selected UT times where the blue marks the downward FAC and the red marks the upward FAC.

Discussion

The first notable geomagnetic storm of the solar cycle 24 has happened on 5-6 April 2010. The storm was triggered by the compressed solar wind sheath region preceding a fast-moving CME. Despite being a relatively weak storm (the minimum *Dst* was ~ 80 nT on 6 April), it had some devastating space weather impacts, including developing of the strong supesubstorm with the magnitude ~2500 nT. This auroral electrodynamics is strongly driven but without the intense ring current injection which is typically associated with major storms. This is an interesting feature of the storm of 5 April 2010.

The strongest geomagnetic perturbations have been observed during the passage of the sheath ahead of the CME. A few minutes after SC under southward IMF and elevated solar wind dynamic pressure, the auroral oval moved equatorward and a supersubstorm started to develop. These processes in the nightside magnetosphere and ionosphere have been detailly analyzed in the paper [*Nishimura et al., 2020*]. It was shown that the supersubstorm exhibited multi-step enhancements of unusually large electrojets with an extremely large poleward boundary intensification (PBI). Very large vortex in the evening ionosphere and the corresponding enhanced FACs were observed by AMPERE data (Fig. 4). The magnetic disturbances spaced in the longitude to the day side where the negative magnetic bay was observed near the poleward boundary of the auroral oval (Fig. 2). Thus, the supersubstorm was recorded in the global scale.

At 09:25 UT the sign of IMF suddenly changed and the night side magnetic activity and SML index began to decrease, but the magnitude of dayside polar bay increased due to occurred and enhanced *NBZ* FACs caused by the positive IMF Bz.

The third interval from ~11:30 to ~12:45 UT shown in the SuperMAG and AMPERE data corresponds to the magnetosphere response of a jump of the strong northward field (IMF-*Bz* ~ +15 nT) under strong negative IMF By. The negative magnetic bay was observed only in the dayside polar region. The fluctuations of *Bz* and *By* IMF components (Fig. 1) lead to conditions where the magnetic reconnection occurs near the cusp, generating intense dayside field-aligned currents (FACs) [*Möstl et al.*, 2010] caused the considered polar magnetic bay.

One of the indicators of the solar wind energy input to the magnetosphere is an increasing of the polar cap PC-index [*Stauning,* 2013; *Troshichev et al*., 2014]. The strong enhancement of PC-index before the maximum of supersubstorm (SML-index minimum) is seen in Fig. 2c. The second PC-index remarkable enhancements were observed before the dayside polar negative magnetic bays supporting that their source is associated with the solar wind energy input.

Conclusion

The strong high-latitude geomagnetic response of the not strong magnetic storm was found. The significant geomagnetic disturbances have been observed in the storm initial phase during the passage of the SHEATH ahead a CME. The large supersubstorm occurred accompanying by the dayside negative magnetic bay observed near the poleward boundary of the auroral oval. The similar bays were also recorded at the cusp latitudes under the northward IMF appearance.

It was shown that this geomagnetic feature was caused by the peculiar properties of the solar wind and IMF irregularities in the SHEATH region ahead of the magnetic cloud that triggered this magnetic storm.

References

Anderson, B.J., Korth, H., Waters, C.L., Green, D.L, Merkin, V.G, Barnes, R.J., and Dyrud, L.P. (2014). Development of large-scale Birkeland currents determined from the Active Magnetosphere and Planetary Electrodynamics Response Experiment, Geophys. Res. Lett., 41(9), 3017–3025. https://doi.org/10.1002/2014GL059941

Baishev, D.G., Moiseyev, A.V., Boroyev, R.N., Kobyakova, S.E., Stepanov, A.E., Mandrikova, O.V., Solovev, I.S., Khomutov, S.Yu., Polozov, Yu.A., Yoshikawa, A., and Yumoto, K. (2015). Magnetic and ionospheric observations in the far eastern region of Russia during the magnetic storm of 5 April 2010, Sun and Geosphere, 10(2),133-140.

Connors, M., Russell, C.T., and Angelopoulos, V. (2011). Magnetic flux transfer in the 5 April 2010 Galaxy 15 substorm: an unprecedented observation, Ann. Geophys., 29, 619–622. https://doi.org/ 10.5194/angeo-29-619-2011

Fathy, I., Amory-Mazaudier, C., Fathy, A., Mahrous, A.M., Yumoto, K., and Ghamry, E. (2014). Ionospheric disturbance dynamo associated to a coronal hole: Case study of 5–10 April 2010, J. Geophys. Res. Space Physics, 119, 4120–4133. https://doi.org/10.1002/2013JA019510

Gjerloev, J.W. The SuperMAG data processing technique (2012). J. Geophys. Res., V. 117(A9), A09213. https://doi.org/10.1029/2012JA017683

Kinrade, J., Mitchell, C.N., Yin, P., Smith, N., Jarvis, M.J., Maxfield, D.J., Rose, M. C., Bust, G.S., and Weatherwax, A.T. (2012). Ionospheric scintillation over Antarctica during the storm of 5–6 April 2010, J. Geophys. Res., 117, A05304. https://doi.org/10.1029/2011JA017073

Kleimenova, N.G., Zelinskii, N.R., Kozyreva, O.V., Malysheva, L.M., Solov'ev, A.A., and Bogoutdinov, Sh.R (2013). *Pc*3 geomagnetic pulsations at near-equatorial latitudes at the initial phase of the magnetic storm of April 5, 2010, Geomagnetism and Aeronomy, 53 (3), 313–320. https://doi 10.1134/S0016793213030092

Kuznetsov, S.N. and Suvorova, A.V.(1998). An empirical model of the magnetopause for broad ranges of solar wind pressure and *Bz* IMF, in *Polar Cap Boundary Phenomena*, Moen, J., Egeland, A., and Lockwood, M., Eds., Norwell, MA: Kluwer, 1998, 51–61.

Liu, Y., Luhmann, J. G., Bale, S.D., and Lin, R.P. (2011), Solar source and heliospheric consequences of the 2010 April 3 coronal mass ejection: A comprehensive view, Astrophys. J., 734 (84), https://doi.org/10.1088/0004-637X

Lu, G., Hagan, M. E., Häusler, K., Doornbos, E., Bruinsma, S., Anderson, B. J., and Korth, H. (2014), Global ionospheric and thermospheric response to the 5 April 2010 geomagnetic storm: An integrated data-model investigation, J. Geophys. Res. Space Physics, 119, 10,358–10,375, https://doi.org/10.1002/2014JA020555.

McComas, D.J., Buzulukova, N., Connors, M.G., Dayeh, M.A., Goldstein, J., Funsten, H.O., Fuselier, S., Schwadron, N.A., and Valek, P. (2012). Two wide-angle imaging neutral-atom spectrometers and interstellar boundary explorer energetic neutral atom imaging of the 5 April 2010 substorm, J. Geophys. Res., 117, A03225, https://doi.org/10.1029/2011JA017273

Möstl, C., Temmer, M., Rollett, T., Farrugia, C.J., Liu, Y., Veronig, A.M., Leitner, M., Galvin, A.B., and Biernat, H.K. STEREO and Wind observations of a fast ICME flank triggering a prolonged geomagnetic storm on 5–7 April 2010 (2010), Geophys. Res. Lett., 37, 24103, https://doi.org/10.1029/2010GL045175

Nishimura, Y., Lyons, L.R., Gabrielse, C., Sivadas, N., Donovan, E.F., Varney, R.H., Angelopoulos, V., Weygand, J.M., Conde, M.G., Zhang, S.R. (2020). Extreme magnetosphere-ionosphere-thermosphere responses to the 5 April 2010 supersubstorm, J. Geophys. Res. https://doi.org/10.1029/2019JA027654

Stauning, P. (2013). The Polar Cap index: A critical review of methods and a new approach. J. Geophys. Res. Space Physics, 118, 5021–5038. https://doi.org/10.1002/jgra.50462

Shimeis, A., Fathy I., Amory-Mazaudier, C., Fleury, R., Mahrous, A.M., Yoshikawa, A., and Groves, K. (2012). Signature of the coronal near the north crest equatorial anomaly over Egypt during the strong geomagnetic storm 5 April 2010, J. Geophys. Res., 117, A07309. https://doi.org/10.1029/2012JA017753

Troshichev, O.A., Podorozhkina, N.A., Sormakov, D.A., and Janzhura, A.S. (2014). PC index as a proxy of the solar wind energy that entered into the magnetosphere: Development of magnetic substorms, J. Geophys. Res.: Space Physics, 119, 6521–6540. https://doi.org/10.1002/2014JA019940

Victor, N.J., Manu, S., Frank-Kamenetsky, A.V., Panneerselvam, C., Anil Kumar, C.P., and Elango, P. (2016), Network of observations on the atmospheric electrical parameters during geomagnetic storm on 5 April 2010, J. Geophys. Res. Space Physics, 121, 2407–2417. https://doi.org/10.1002/2015JA022080