Teleconnection between Solar Wind Parameters and Geomagnetic Activity

Ernest B. I. Ugwu

Abstract — The geomagnetic field of the earth shields the earth from the hazards of solar wind which is constantly buffeting the earth making the geomagnetic field assume a comet-like shape. In this paper, interplanetary and geomagnetic data were simultaneously analyzed for the period of the solar cycle 24. The analyses allowed us to determine any teleconnections between the solar wind and geomagnetic activity within the period. Results of the analyses show that solar wind and geomagnetic activity are highly connected at high latitudes but the same cannot be said for mid and low latitudes. Any correspondence between geomagnetic activity indices and solar wind parameters are mere coincidences.

Keywords — Cross-helicity, geomagnetic field, magnetohydrodynamics, residual energy, solar wind, teleconnection.

I. INTRODUCTION

Solar wind is a magnetohydrodynamic (MHD) fluid originating from the sun and causing some changes in the geomagnetic field of the Earth particularly in the polar caps and auroral zones. The Earth’s magnetic field shields the Earth from the solar wind which is seen in the variations of the geomagnetic field over timescales of hours or days. Solar wind and the magnetosphere are in a state of continuous interaction due to the shielding of the earth from solar wind as it travels away from the sun into the interplanetary medium [1].

There is abundant literature on the interactions between solar wind and magnetosphere/geomagnetic field but there are debates on some properties of geomagnetic field such as the role played by Alfvénic waves/turbulent eddies and the connection between the turbulent solar wind and geomagnetic field at low latitudes [2]-[4]. Ref. [5] uses some forms of classifications of solar wind based on, for example, solar wind plasma data, magnetic field data, proton density identified flows that drive geomagnetic storms of various ranges.

Solar wind as a stream of energized particles, a magnetofluid and quasi-neutral plasma containing mostly electrons and protons flows outwards from the sun towards the interplanetary medium at a very high speed and temperature. As it flows outwards, it expands in the interplanetary medium leading to ubiquitous fluctuations in the flow velocity creating magnetic and electric fields within it [6]. Because of turmoil and a very large amount of energy being impacted on the earth’s magnetosphere, geomagnetic activity in the form of geomagnetic storms, sub-storms and aurorae are common events associated with these perturbations [7].

Strong connections existing between magnetosphere and solar wind have been studied by several researchers (e.g., [8]-[14]. Some of the studies focused on the changes in the morphology of the polar caps and auroral zone, even reversal in the geomagnetic fields, changes in solar wind parameters during geomagnetic storm while some are on the effects of solar wind turbulence on geomagnetic activity.

II. MATERIALS AND METHOD

Geomagnetic activity indices for solar cycle 24 were downloaded from World Data Center, C2, Kyoto, Japan (http://omniweb.gsfc.nasa.gov/ow.html). These data are auroral electrojet (AE), symmetric-H (SYM-H) and asymmetric-H (ASY-H). While AE measures geomagnetic processes at high latitudes where auroras form, SYM-H and ASY-H are for monitoring geomagnetic processes at mid-low latitudes. Solar wind data sets for the same period were got from the OMNI website (http://omniweb.gsfc.nasa.gov/ow.html). Solar cycle 24 started in December 2008 and ended in December 2019 with the least activity in early 2010 and
maximum activity in April, 2019 and had a twenty-three month smoothed sunspot number 81.8 which is lower than had been observed in recent cycles.

Both solar wind and magnetosphere are plasmas with high Reynolds number exhibiting scale-invariant dynamics and power-law power spectral density of magnetic fluctuations that are similar to turbulence. This behaviour is associated with non-linear interactions. The turbulent nature of solar wind (a major driver of the solar wind system) and magnetosphere is the main focus of this paper. Alfvén waves that are generated as a result of the continuous vibrations of the magnetic field lines are present in the solar wind. Alfvén waves only interact when propagating in opposite directions. That is, inward propagating Alfvén waves and outward propagating Alfvén waves can interact but neither of them cannot interact on their own. Turbulence in the solar wind has been analyzed using normalized cross-helicity, $\sigma_C$ and normalized residual energy, $\sigma_R$. Cross-helicity refers to the correlation between velocity and magnetic field vectors while residual energy is the difference in energy per unit mass between kinetic energy, $e^V$ and magnetic energy, $e^B$.

According to [15], normalized cross-helicity, $\sigma_C$ is defined as:

$$\sigma_C = (e^+ - e^-)/(e^+ + e^-)$$

where $e^+$ and $e^-$ are the energy per unit mass linked to positive and negative modes respectively. The positive modes ($Z^+$) are the outward fields (moving away from the sun) while the inward ($Z^-$) fields (moving towards the sun) are referred to as the negative modes. These modes are called the Elsässer variables defined as:

$$Z^\pm = v \pm b$$

where $v$ is the velocity of solar wind and $b$ is the magnetic field in Alfvén speed unit.

In other words,

$$b = B/\sqrt{4\pi \rho}$$

where $B$ is the magnetic field in nT and $\rho$ is the proton density in n/cc.

Ref. [15] also defined the normalized residual energy, $\sigma_R$ as:

$$\sigma_R = (e^V - e^B)/(e^V + e^B)$$

where $e^V = 1/2 v^2$ and $e^B = 1/2 b^2$. Normalized cross-helicity and normalized residual energy are measured in Alfvén units.

Previous researchers used only the $z$ components of the interplanetary magnetic field $B_z$ and velocity $v_z$ in GSE coordinate system which was considered more Alfvénic than the other components [9], [11], [16]. However, this choice does not totally eliminate non- Alfvénic turbulences. In this study, the total magnetic field and total velocity were used to see if any difference exists in the results. Also, the data used covered the period of solar cycle 24 which has not been studied extensively. The time series of all the data sets were also made to see if there are any casual relationships between them.

III. RESULTS

Fig 1 (a and b) shows the distributions of $\sigma_C$ and $\sigma_R$ for the period of solar minimum (2010) and solar maximum (2014), respectively. Both have prominent peaks at $\Delta \sigma_C = \pm 0.002$ and $\Delta \sigma_R = 1$ and these values are generally low in occurrence. The kinetic structures are predominant over magnetic structures. There is a very low degree of Alfvénicity ($\Delta \sigma_C \neq \pm 1$ and $\Delta \sigma_R \neq 0$) which are not the conditions for Alfvénicity. For Alfvénicity $\Delta \sigma_C = \pm 1$ and $\Delta \sigma_R = 0$. The reason for this may be due to the presence of non-Alfvénic turbulence which cannot be totally eliminated.

Fig. 2 (a and b) shows prevalence of slow solar wind ($V_{sw} < 500$ km/s) over fast solar wind in the two quadrants for the periods considered. There are outward fluctuations which are predominantly kinetic structures ($\Delta \sigma_R = 1$) at both periods of low and high solar activities. The results agree with the works of [9], [17].
Fig. 1. 2-D Histograms for 2010 (a) and 2014 (b), respectively.

Fig. 2. 2-D Histograms of $\sigma_C-V_{sw}$ for 2010 (a) and 2014 (b), respectively.

Fig. 3 represents the averaged values of AE over every square bin of $\Delta \sigma_R - \Delta \sigma_C$. The peaks are at $\Delta \sigma_R = 1$ and $\Delta \sigma_C = \pm 0.002$ for both 2010 and 2014. The peaks values are high which suggests links between solar wind and geomagnetic activity at high latitudes. It is likely that solar wind drives geomagnetic activity at high latitudes. Auroras have been shown to be connected with geomagnetic activity which in turn is influenced by solar wind turbulence. There are outward fluctuations which are predominantly kinetic structures ($\Delta \sigma_R = 1$) at both periods of low and high solar activities. The results are also in agreement with the works of [9], [17].

Fig. 3. Histograms of average AE over every square bin of $\Delta \sigma_R - \Delta \sigma_C$ for 2010 (a) and 2014(b), respectively.
SYM-H measures geomagnetic activity at mid-low latitudes. The prominent peaks for the two periods are at \( \Delta \sigma_R = 1 \) and \( \Delta \sigma_C = \pm 0.002 \). This implies that it is distributed over two quadrants. However, the very low peak values of SYM-H suggest that solar wind does drive geomagnetic activity at mid-low latitudes even as it appears that there are some correspondences. This may be due to some convective structures within the solar wind or as was suggested by [18] that solar wind is not a direct driver for SYM-H scaling.

Prominent peak values at \( \Delta \sigma_R = 1 \) and \( \Delta \sigma_C = \pm 0.002 \) for the two years are very low similar to what was obtained with SYM-H (Fig. 5). It is not surprising since ASY-H is derived from SYM-H. It could then be concluded that solar wind and geomagnetic activity are not connected at mid-low latitudes. Any observed connections may just be mere coincidences or correspondences which have not been proven experimentally.

Fig. 6 represents the values of geomagnetic indices (AE, SYM-H and ASY-H) for the month of April which is the month with the highest values of Sunspot number for the period of solar maximum. ASY-H and AE appear to follow a particular trend. For instance, the periods just after 9th and on the 29th of April, 2014 SYM-H recorded highest values, ASY-H and AE have very low values, while on the 13th of April when ASY-H and AE recorded highest values, SYM-H has a very low value. Similar trends are noticeable in Fig. 7 which is for the month of January, 2010 when the least values of sunspot numbers were recorded. In the time series analysis, it should be noted that the values of both SYM-H and ASY-H are very low compared to that of AE which suggests that solar wind does not have any serious effect on geomagnetism at mid-low latitudes.
Fig. 6: Time series analysis of Avg. SYM-H (A), Avg. ASY-H (B) and Avg. AE (C) for April 2014.

Fig. 7: Time series analysis of Avg. SYM-H (A), Avg. ASY-H (B) and Avg. AE (C) for the month of January 2010.
REFERENCES

[1] D’Amicis R., Telloni D., Bruno R. The effect of solar wind turbulence on magnetospheric activity. Front. Phys., 2020; 8:604857. doi: 10.3389/fphy.2020.604857.
[2] Bruno Z., Fagre M., Amiri H., Elias A.G. Polar caps reversal during geomagnetic polarity reversals. Geophys. J. Int., 2019;216(2):1334-1343.
[3] Hulot G., Lhuillier E., Aubert J. Earth’s dynamo limit predictability. Geophys. Res. Lett., 2010. doi.org/10.1029/2009GL041869.
[4] Morzfeld M., Fournier A., Hulot G. Coarse predictions of dipole reversals by low-dimensional modeling and data assimilation. Planet. Int., 2017;262:8-27.
[5] Richardson I. G., Cane H.V. Solar wind drivers of geomagnetic storms during more than four solar cycles. SWSC, 2012; 2:A01-p2-A01-p7.
[6] Chandran B.D.G. Strong anisotropic MHD turbulence with cross-helicity. ApJ, 2008;685:646-658.
[7] Gonzalez W.D., Josely J.A., Kamide Y., Korehi H.W., Rostoker G., Tsurutani B.T., Vasyliunas V.M. What is a geomagnetic storm qm? J. of Geophys. Res., 1994;99:5771-5792.
[8] Kershengolts S.Z., Barkova E.S., Plotnikov I. Ya. Dependence of Verscharen geomagnetic disturbances on extreme values of solar wind Ey component. Geomagn. Aeron., 2007;47(1):56-164.
[9] D’Amicis R., Bruno R., Bavassano B. Response of geomagnetic activity to solar wind turbulence during solar cycle 23. JASTP, 2011;23(5-6):653-657.
[10] Zebo J-L. Z., Ouattara F., Mazaudier C.A., Legarand J-P., Richardson J.D. Solar Activity, Solar Wind and Geomagnetic Signatures. ACS, 2013;3(4):610-617. doi: 10.4236/acs.2013.34063.
[11] Ugwu E.B.I., Okeke F.N., Ugonabo O.J. Solar wind turbulence as a driver of geomagnetic activity. ASR, 2015;5:5:1748-1753.
[12] Balan N., Batista I.S., Tulasi Ram S., Rajesh P.K. A new parameter of geomagnetic storms for the severity of space weather. Geosci. Lett., 2016;3:3, 1-5, doi:10.1186/s40562-016-0036-5.
[13] Subedi A., Adhikari B., Mishra R.K. Variation of solar wind parameters during intense geomagnetic storms. The Himalayan Physics, 2017;6 and 7:80-85.
[14] Verscharen D., Klein K.G., Maruca B.A. The multi-scale nature of solar wind. Living Rev. Sol. Phys., 2019;17(5). doi: 10.1007/s41116-019-0021-0.
[15] Tu C.Y., Marsch E. MHD structures, waves and turbulence in solar wind: observations and theories. Space Sci. Rev., 1995;73:1-210.
[16] D’Amicis R., Bruno R., Bavassano B. Is geomagnetic activity a driver of solar wind turbulence? Geophys. Res. Lett., 2007;34:5108-5111.
[17] Bruno R.D., D’Amicis R., Bavassano B., Carbone V., Sorriso-Valvo L. Magnetically dominated structures as an important component of solar wind turbulences. Ann. Geophys., 2007;25:1913-1927.
[18] Wanli G., Uritsky V. Understanding busy behaviour in mid-latitude geomagnetic activity. J. Geophys. Res., 2010;115. doi.org/10.1029/2009JA014642.