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Sun-Related Energy, Induced Ring, Auroral Electrojet and Magnetopause Currents Variability during Solar Cycles 23 and 24

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Abstract

In this study, we examined variability of sun-related energies, auroral electrojet current, ring current, and magnetopause current during solar cycles 23 and 24. The study revealed a dependence of sun-related energies to the Sun and Earth currents systems with solar activity from 1996 to 2019. A decrease in the correlation between sun-related energies and sunspot number was observed over solar cycles 23 and 24 (0.88 for the solar cycle 23 and 0.66 for the solar cycle 24), with a drop in the speed of magnetic disturbances in the solar wind. These results could be attributed to the decrease in Sun's magnetic field toroidal component magnitude induced by a weak in sunspots number and solar flares during the solar cycle 24. A weak in the Earth currents systems (auroral electrojet current, ring current, and magnetopause current) is also observed. During the decrease in the Earth currents, several peaks are observed, indicating a nonlinear dependence in the Earth currents variation (ring current, auroral electrojet current, and magnetopause current) from solar cycle 23 to solar cycle 24. This could be attributed to the Corotating Interaction Regions (CIRs) observed during the declining phase of solar cycle 23 and the deep minimum preceding solar cycle 24.

Keywords

Solar Activity, Sun-Related Energy, Corotating Interaction Region, Currents Systems

1. Introduction

The Sun is the main source of energy for Earth. Earth receives a significant amount of energy from the Sun through phenomena such as magnetic storms, radiation, etc. Magnetic storms are phenomena that are generally produced by massive solar flares that release large amounts of energetic charged particles into interplanetary space. These particles can disrupt Earth's magnetic field and cause variations in the near-Earth space environment. Many authors have reviewed on that sun-earth relation to better understand space weather. Some authors such as [1]-[3] have shown through their studies that Sun's variability influences ionosphere, magnetosphere, and Earth climate. Some others [2] [4]-[7] have out lighted a significant decrease in solar activity during recent solar cycles. These authors have also reported that magnetic storms occurrence during Solar Cycle 23 is greater than Solar Cycle 24. This decrease in activity which could impact Earth's environment may be related to unidentified mechanism related to long-term solar activity, according to [2]. It is therefore crucial to quantify Sun-related energies and examine their coupling with Earth currents systems in order to contribute to better understand how these systems are configured and disrupted in our space environment, including navigation and communication systems.

The aim of the present paper is to investigate the relationship between the Sun-related energies and Earth currents systems through some parameters such as Sun's magnetic energies density, Alfvén velocity, geomagnetic indices, and solar magnetic pressure.

The second section presents data and methodology. The third section is devoted to results and discussion. A conclusion section ends the paper.

2. Data and Methodology

In this study, we used annual mean values: (1) data from the recently revised sunspot number. This sunspot number, available on website http://www.sidc.be/silso/ is used to obtain information about solar activity; (2) solar magnetic field (B_{sol}) used to calculate solar magnetic energy density using relation:

$$P_{magne} = \frac{B_{sol}^2}{2\mu_0} \tag{1}$$

where B_{sol} is Sun's daily magnetic field and μ_0 is magnetic permeability. These data are available on https://omniweb.gsfc.nasa.gov. Solar magnetic energy density teaches on Sun pressure. Recent studies [8] [9] have shown that solar magnetic pressure plays an important role in solar activity variation. It is thought to be influenced by phenomena such as solar flares and sunspots. (3) Alfvén velocity, used to estimate speed at which magnetic field disturbances in the solar plasma propagate. It was calculated with the relationship:

$$V_A = \frac{B}{\sqrt{Nm_p\mu_0}} \tag{2}$$

where B and N are respectively solar magnetic field and protons density available on https://omniweb.gsfc.nasa.gov; m_p and μ_0 are proton mass and magnetic permeability respectively. Alfvén velocity permit to study plasmas variability.

For Earth currents systems response, we examined at Representative Proxies (4) high latitude currents such as auroral electrojet (AE) to estimate auroral activity and (5) low-latitude currents such as ring current (Dst). Negative Dst values indicate geomagnetic storms according to [10] (Dst ≤ −100 nT for intense storms, −100 nT ≤ Dst ≤ −50 nT for moderate storms, −50 nT ≤ Dst ≤ −30 nT for weak storms and Dst≥ −30 nT for calm storms). These two parameters are Available on https://omniweb.gsfc.nasa.gov. We also used Sun dynamic pressure p_{dyn}, available on https://omniweb.gsfc.nasa.gov to calculate (6) magnetopause current effect (DCF) with the following formula:

$$DCF = k\sqrt{2\mu_0 p_{dyn}} \tag{3}$$

As used by [11]; where μ_0 is magnetic permeability, coefficient k often varies from 0.2 to 0.3 according to [12]. DCF index is used to follow magnetopause current effects, which is a current that flows at interface between solar wind and magnetosphere. A strong magnetopause current means a great energy transfer of energy from charged energetic particles of solar wind into Earth's magnetosphere.

A correlation between Sun magnetic pressure and Alfvén velocity with solar activity has been studied through calculation of correlation coefficients. A morphological study of annual means of these indices was carried out from 1996 to 2019.

3. Results and Discussion

3.1. Sun-Related Energies and Solar Activity

Figure 1 shows the profiles of annual mean values of solar magnetic energy density and sunspots number for five recent solar cycles (1964 to 2019). These two profiles evolve in an almost similar way. Maximum and minimum values of magnetic energy density are observed during the descending and the minimum phase of each solar cycle. These observations suggest that strong disturbances associated with fast solar wind flows impact solar magnetic energy density, leading to an increase in Sun's magnetic pressure. The increase in Sun's magnetic pressure could be associated with solar flares. Solar flares can emit solar energetic particles that can affect Earth's space weather. We observe a lag between solar magnetic energy density peaks and sunspot number. In addition, there is a double peak constitute of a small peak followed by a larger one in solar magnetic energy density profile during each solar cycle. These two peaks are observed around maximum phase of each solar cycle. The appearance of these double peaks would be attributed to expression of two components of solar magnetic field (toroidal magnetic component and poloidal magnetic component). The toroidal solar magnetic field is generated by Sun differential rotational motion. The lines of the Sun's toroidal magnetic field can often open and extend into interplanetary space, resulting in magnetic surges as they interact with solar wind [13].

From our study, we observe a significant decrease in the correlation between solar magnetic energy density values and sunspots number during last two solar cycles (0.83 at SC20; 0.79 at SC21; 0.96 at SC22; 0.88 at SC23 and 0.66 at SC24). The correlation coefficient decreased from 0.88 in Solar Cycle 23 to 0.66 in Solar Cycle 24. This result shows that there is a good dependence of solar magnetic energy density values with sunspots number at SC23 compared to SC24. This decrease in correlation observed at SC24 could be attributed to decrease in toroidal solar magnetic field, which would have led to a decrease in the sunspots number. Sunspots are active regions where magnetic field is stronger. This result also shows that although sunspots and Sun's magnetic pressure are related to solar magnetic fields, changes in Sun's magnetic field structure can influence solar magnetic pressure independently of sunspots number.

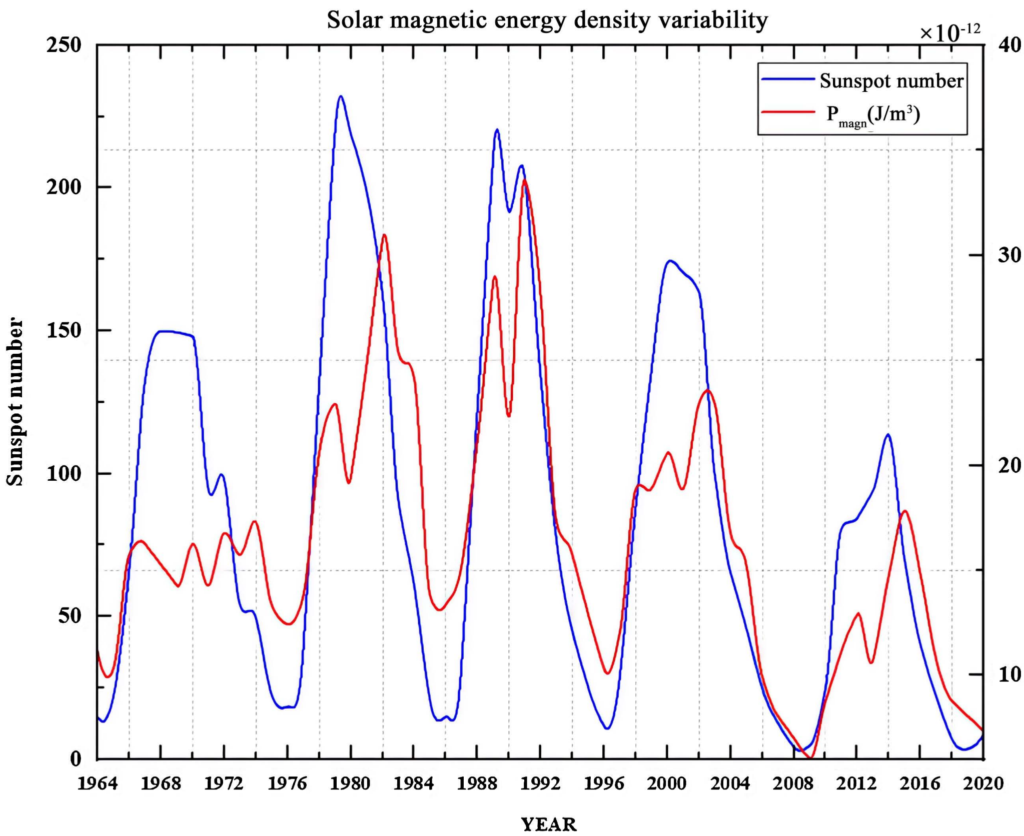

Figure 1. Variations of Annual means of Solar Magnetic Energy Densities and Sunspots numbers of 5 Solar Cycles (1964 to 2019).

Compared to Solar Cycle 23, solar magnetic energy densities values significant weak is observed at Cycle 24. This Sun's magnetic energy density weakening reflects a significant weakening of Sun's magnetic power [2]. This solar magnetic energy density weakening would be attributed to solar magnetic field decreasing during recent solar cycles [14]

Figure 2 are shown profiles of annual means values of Alfvén velocities and sunspots numbers from 5 recent solar cycles (1964 to 2019). These two profiles evolve in an almost similar way. Alfvén velocity maximum and minimum values are observed respectively at descending phase (74 km/s at 2003 and 54.9 km/s at

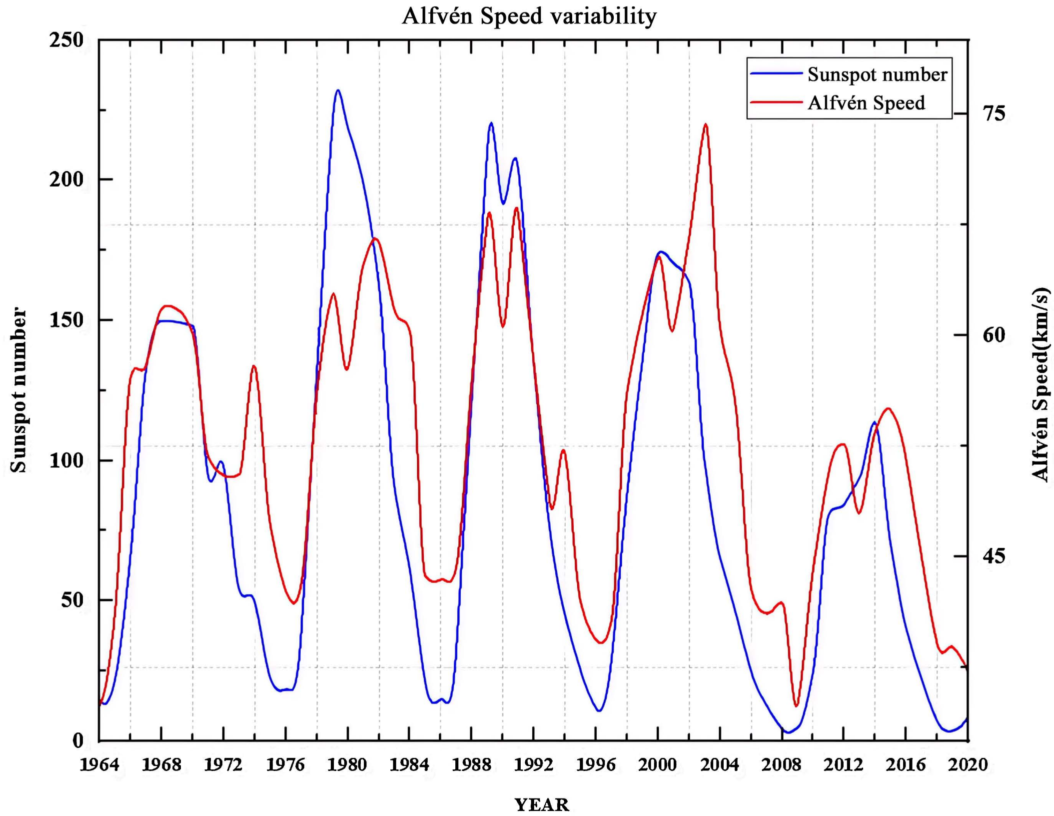

Figure 2. Variations of annual means Alfvén velocities and sunspot numbers of 5 solar cycles (1964 to 2019).

2015) and phase minimum (35 km/s at 2009) of each solar cycle. This could be link to the fact that during descending phase of the solar cycle, sunspots number gradually decreases, leading to a decrease in overall magnetic activity. Since sunspots are high-density regions, a decrease in sunspots number also leads to a decrease in the density of solar plasma resulting in high Alfvén velocities. There is also good correlation between Alfvén velocity and sunspots number during solar cycles 23 and 24. The correlation coefficients are 0.837; 0.798; 0.966, 0.839 and 0.836 at solar cycles 20, 21, 22, 23 and 24 respectively. These observations show that there is a strong dependence of values of Alfvén velocity with sunspots numbers. Sun's active regions, often associated with sunspots, can be important sources of Alfvén waves that could propagate through in solar wind. Alfvén waves could play a great role in energetic solar particles acceleration and geomagnetic storms occurrence that can affect Earth's environment. Compared to Solar Cycle 23, a significant weakening of Alfvén velocity values is observed during Solar Cycle 24. These observations show that flux energy carried by Alfvén wave decreased significantly during solar cycle 24. This result would be attributed to solar magnetic field decrease [6] [7] [10].

Table 1 shows geomagnetic storms numbers of solar cycles 23 and 24 according to their intensity. It can be seen from this table that SC23 experienced more magnetic storms than SC24.

Table 1. Solar storms numbers classification at solar cycles 23 and 24.

Geomagnetic activity level	Dst	Solar cycle	
		SC 23	SC 24
Intense	Dst ≤ −100 nT	41	5
Moderate	−100 nT ≤ Dst ≤ −50 nT	176	63
Weak	−50 nT ≤ Dst ≤ −30 nT	486	242
Calm	Dst ≥ −30 nT	4415	3711

3.2. Index AE, Dst and DCF Variability with Solar Activity

Figures 3(a)-(c) show the profiles of annual values of AE, Dst and DCF during the last five solar cycles (196-2020). The largest values of AE index are observed at the descending phase of each solar cycle (283 nT at 1974, 299 nT at 1982, 228 nT at 2003 and 216 nT at 2015) except in solar cycle 21 where we record large value at maximum phase of solar cycle (401 nT at 1989) due to a solar storm four times larger than normal observed at this time by Carrington from Earth [15]. Weak values are observed at minimum phase of each solar cycle (113 nT at 1965, 192 nT at 1986, 167 nT at 1996 and 70 nT at 2009). These observations would be attributed to Alfvén waves present in solar wind which play an important role in auroral currents generation [16] [17]. During the descending phase of solar

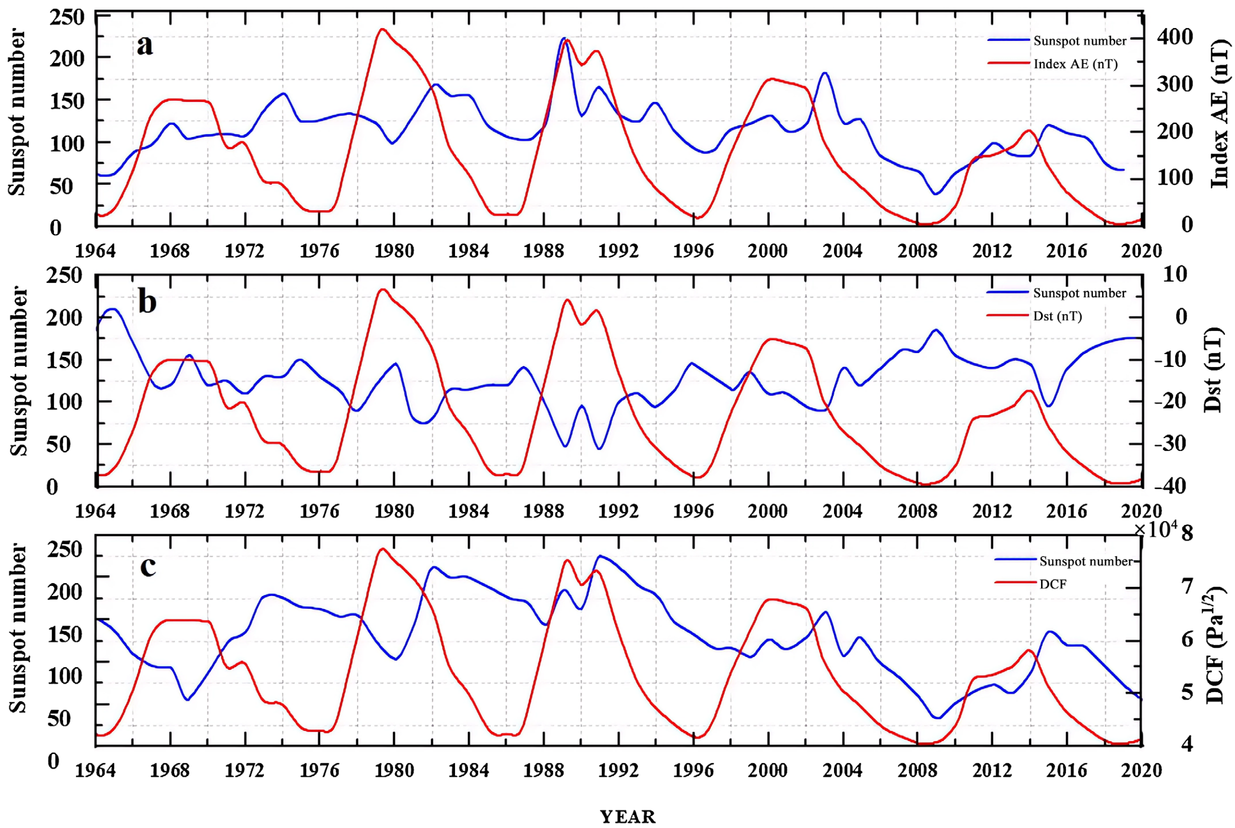

Figure 3. Variations of annual means of AE (a), Dst (b) and DCF (c) index during the last five solar cycles.

cycle, changes in dynamics of solar wind and solar magnetic field can influence generation and amplification of Alfvén waves, contributing to stronger auroral currents [18] [19].

Weak and high values of Dst index during each solar cycle are observed respectively around maximum phase (−18 nT at 1972, −24 nT at 1982, −31 nT at 1991, −22 nT at 2003 and −21 nT at 2015) and at minimum phase (2 nT at 1965, −10 nT at 1975, −12 nT at 1987, −11 nT at 1996 and −3 nT at 2009) of each solar cycle. These observations would be attributed to solar magnetic field. At solar cycle maximum phase, sunspots number reaches its maximum with remarkable increase in solar flares number. [9] examined the relationship between sunspots number and occurrence of solar flares of different classes during SC23 and SC24. Annual means values of DCF index evolves randomly with several peaks throughout each solar cycle. Magnetopause current effects are generally more pronounced during the descending phase and less pronounced at the minimum phase of each solar cycle.

In general, it can be seen that annual means of auroral current, ring current and magnetopause current show several peaks throughout each solar cycle. These currents are all improved during magnetically disturbed periods. This could be explained by the fact that during the periods of strong magnetic disturbance, solar magnetic field is highly disordered giving rise to magnetic reconnections due to high number of CMEs and ICMEs observed during these periods. On the other hand, at minimum phase, solar magnetic field is dipole and there are few CMEs and ICMEs [20] [21] have shown that ICMEs can contribute to magnetic field because they carry a magnetic flux with them. [22] also showed that ICMEs occurrence rate follows solar activity.

We also observe a significant weakening of Earth's current systems during these five solar cycles and particularly from solar cycle 23 to solar cycle 24. However, this diminution is not linear, as several peaks are observed during descending phase and during the deep minimum observed in solar cycle 23 [23]. This current systems diminution is attributed to ambient conductivities and weaker electric fields observed from long solar minimum to solar cycle 24 [24]. We suggest this non-linearity observed current systems would be attributed to the Co-rotating interaction regions (CIRs) that occur as a result of interaction between rapid wind flow of coronal holes and slower wind flow present in interplanetary space. According to [25] [26], High-velocity fluxes emitted by coronal holes can interact with ambient slow solar wind flows, compressing plasma at boundary, increasing density in slow solar wind region. CIRs are more common at solar minimum and play an important role as a source of geomagnetic disturbances [27]. Magnetic storms caused by CIRs are small in terms of disturbance of Dst index. However, storms caused by CIR are of longer duration and produce a more severe level of relativistic electrons in radiation belt [19].

4. Conclusion

We studied variability of Sun-related energies and Earth's current systems (ring current, auroral electrojet current, and magnetopause current) from Solar Cycle 23 to Solar Cycle 24. Solar cycles 23 and 24 showed themselves stronger and weaker respectively magnetically. We used Sun's magnetic energy density and Alfvén's velocity values to measure the Sun's power and strong, respectively, in order to quantify different energies related to the Sun. This study allows us to observe good dependence of Sun-related energies at SC23 compared to SC24 with solar activity. In addition, there is a decrease in sun-related energies and Earth's currents systems (auroral electrojet current, ring current and magnetopause current) with solar activity. However, we observe decrease in currents systems is non-linear from solar cycle 23 to solar cycle 24 due to the CIRs observed during the descending phase of solar cycle 23 and the deep minimum preceding solar cycle 24.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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