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Investigation of a Possible Link between Solar Activity and Climate Change in Saudi Arabia: Rainfall Patterns

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Abstract

In this study, annual, quarterly, and monthly mean precipitation data in Saudi Arabia were correlated with sunspot number (SSN) and galactic cosmic ray (CR) flux over 35 years (1985-2019). The results show that the strength, magnitude, proportion and statistical significance of the relationship between precipitation and the two variables varied by season and month. We find that mean annual precipitation in Saudi Arabia, from May to November, and summer and autumn are correlated with cosmic rays and inversely correlated with SSN. Correlations of varying intensities and scales were found during the remaining months and during winter and spring. The relationships between the rainfall and SSN and CR for each solar cycle were investigated and showed that for all three cycles, the annual rainfall over Saudi Arabia has a positive correlation with CR. Different results were obtained when the seasonal rainfall data correlated with the SSNs and CRs during each cycle. The results obtained, in terms of their strength and magnitude, are affected by terrestrial and extra-terrestrial factors. These factors have been briefly presented and discussed. These findings represent a step towards understanding the possible role of solar activity in climate change for future meteorological phenomenon forecasting, even if the physical mechanism is still poorly quantified.

Keywords

Precipitation, Cosmic Rays, Solar Activity, Climate Change, Sunspot, Saudi Arabia

1. Introduction

Water is vital for the survival of life on Earth and plays a key role in many applications, including agriculture and water planning. It is also essential for a healthy terrestrial ecosystem, and risk and financial management. Rainfall is the main source of water in semi-arid or arid areas. Many areas have been studied to understand how climate changes affect rainfall patterns (e.g., [1]-[7]). Climate change has been reported to significantly alter natural water resources on a global scale. It is hence a cause of concern for governments, societies, and research institutions worldwide. Studying local rainfall patterns is critical to accurately understanding rainfall distribution (e.g., [8]-[13]).

The Sun plays a key role vis-a-vis the Earth and our lives. Even slight changes in solar activity can affect the Earth. The influence of space weather activities on Earth's environment has been attracting the attention of scientists from diverse fields. Assessing the effects of solar variability on Earth's climate is important for understanding the natural factors that influence climate (e.g., [14] [15] [16] [17] [18]) The influence of solar activity on several meteorological and climate variables, such as air temperature, has been studied and showed interesting results. For instance, solar-induced events appear to affect the stratospheric thermal structure, sea level pressure and upper stratospheric ozone level and the amount of low cloud cover, [19] [20]. For instance, Maghrabi [21] studied the periodicities in precipitable water vapour and confirmed the presence of peaks around 1.7 years and 1.3 years. Moreover, Maghrabi and Kudela [22] confirmed the existence of 1.7 years and 1.3-year-periodicities in the atmospheric aerosols, which both are found in solar and interplanetary parameters.

It is well known that solar disturbances affect the interplanetary medium which modulates the primary CRs in the heliosphere and their rate at the top of the atmosphere (e.g., [16] [23]). Once they reach the top of the atmosphere, these primaries interact with the atmospheric molecules and produce secondary particles, which cause ionization in the atmosphere at different levels. The most important result of this ionization is the aerosol formation and its subsequent condensation process (e.g., the production of ultrafine aerosols) (e.g., [24] [25]). These variations in ionization can directly or indirectly affect the physical and chemical properties of the atmosphere; for example, it can change the rate of cloud formation, precipitation, ozone production in the atmosphere, water vapour content, and atmospheric aerosols (e.g., [16] [22] [26]).

Over the past years, several studies have been conducted worldwide, using data from different time spans, to investigate the relationship between solar activity and rainfall (e.g., [27]-[33]).

Different results have been found, with some studies showing a positive relationship between rainfall and solar activity and others find negative relationships, while yet others found no relationships. The diversity of these results is due to different locations, different periods, regional and global factors, and different analytical methods. For instance, Laurenz *et al.* [27] studied the influence of the changes in solar activity on rainfall over Europe and found that February rainfall has the strongest relationship with solar activity in western and central Europe. Mostafa *et al.* [34] used the rainfall data from 19 stations in Sudan for the period 1910-2018 and confirmed a negative correlation between rainfall and the SSN over certain stations. Hiremath and Mandi [35] used 130 years of precipitation data for India and found that although a weak and insignificant correlation was obtained, precipitation was inversely correlated with SSN.

The relationship between solar activity and rainfall patterns is still unclear in different regions of the world, including Saudi Arabia. Therefore, we wondered whether the changes in solar activity could be reflected in measurable changes in the rainfall variations in Saudi Arabia.

In this study, historical records of rainfall from 19 meteorological stations across Saudi Arabia were used to investigate mutual correlations between rainfall and the sunspot number and the flux of the CR for the period 1985-2019.

2. Data and Methods

Monthly mean rainfall data series from 19 weather stations covering the period 1985-2019) were analysed for this study. These data were provided by the Ministry of Environmental Protection (MEP) of Saudi Arabia. The considered stations were selected according to the length and completeness of records and cover all the weather conditions experienced in the country (**Figure 1**). The mean monthly values from the considered stations were averaged to get the annual and seasonal rainfall over Saudi Arabia.

The data were subjected to extensive quality control procedures, including the nonparametric Kruskal-Wallis test [36] to assess the homogeneity of the data and to eliminate the random errors found in the original data. Additionally, linear interpolation methods were used to fill the gap caused by the missing data.

Daily cosmic ray data recorded by Oulu neutron monitor (Rc~0.8 GV) for the same period as the rainfall data were obtained from the Oulu neutron monitor website. Sunspot numbers (SSN) for the study period were obtained from the National Oceanic Atmospheric Administration, the National Geophysical Data Centre, USA, and the National Space Weather Prediction Centre, USA.

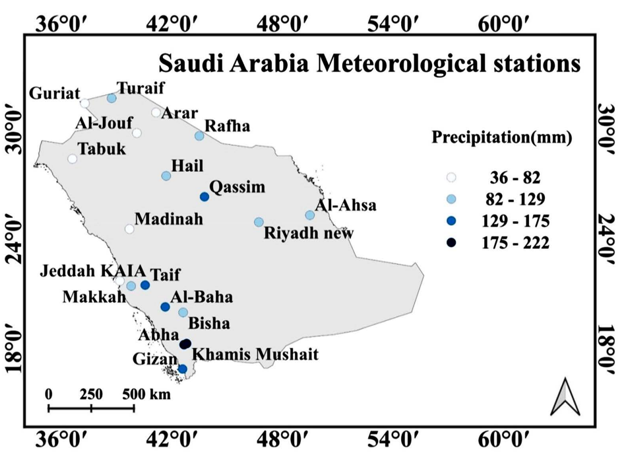

Figure 1. Displays the geographical coordinates of the sites included in this study, along with the corresponding range of total precipitation values.

The monthly distribution of rainfall was classified into 12 bins, and the seasonal variations were divided into 4 groups. Winter includes the months of December, January, and February (DJF), spring includes March, April, and May (MAM), summer comprises June, July and August (JJA) and autumn includes September, October and November (SON).

The least square method and associated statistical tests were conducted to assess the relationship between rainfall, the sunspot number and CR data.

3. Results

Figure 2 shows the mean annual variations of rainfall over Saudi Arabia for the period 1985-2019. The average rainfall was 170.4 mm. The maximum rainfall was in 1997, followed by 1998, 1992, and 1993. The dry years were 2012, 2009, 2008, 2007, 2008, and 2007. Only 42.85% of the annual records were above the average.

Table 1 presents the results of the correlation analyses of the annual, monthly, and seasonal rainfall over Saudi Arabia, and the sunspot number and cosmic rays during the study period.

Table 1. Correlation coefficients of the annual, monthly, and seasonal rainfall over Saudi Arabia, sunspot number (SSN) and cosmic rays (CRs) for the period 1985-2019.

	SSN		GCR count rate [cts/min]	
	Pearson coefficient	P value	Pearson Coefficient	P value
Annual	**−0.12***	0.035	**0.15***	0.045
January	0.08	0.323	−0.161	0.178
February	0.263	0.064	−0.268	0.059
March	0.092	0.299	−0.051	0.386
April	0.125	0.237	**−0.311***	0.035
May	**−0.339***	0.023	0.248	0.076
June	**−0.347***	0.021	**0.411****	0.007
July	−0.154	0.189	0.132	0.225
August	−0.01	0.477	0.028	0.436
September	−0.223	0.099	0.215	0.108
October	−0.197	0.128	0.216	0.106
November	−0.144	0.212	0.157	0.183
December	−0.012	0.476	−0.167	0.168
Winter	0.238	0.085	**−0.344***	0.021
Spring	0.053	0.382	−0.169	0.165
Summer	**−0.178***	0.014	**0.221***	0.011
Fall	**−0.219***	0.023	**0.244***	0.031

** 0.01 level of significance, * 0.05 level of significance, + 0.1 level of significance.

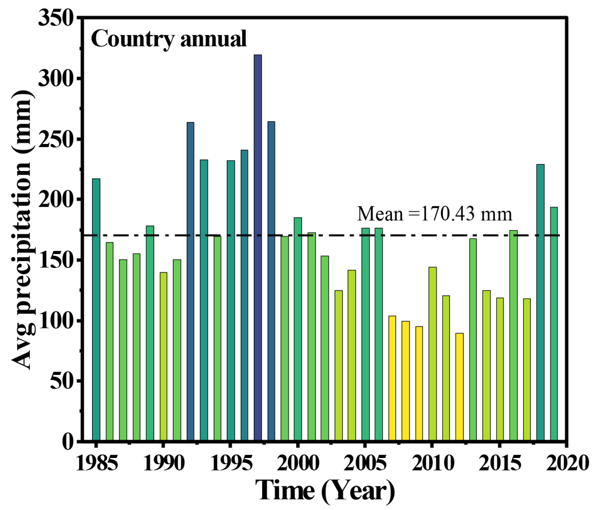

Figure 2. Time series of annual mean rainfall during 1985-2019. The solid line is the country mean rainfall value.

It can be seen that the mean annual precipitation in Saudi Arabia is positively correlated with CR (correlation coefficient 15%) and negatively correlated with SSN (correlation coefficient 12%). This implies that annual precipitation in Saudi Arabia increases with increasing CR and decreasing SSN. While these correlations are weak, they are statistically significant and agree with the proposed hypotheses for the relationships between these two variables. The solar activity modulates CR, which affects atmospheric ionization and aerosol formation, and cloud condensation nucleation, which in turn affects precipitation (e.g., [24] [25] [27] [29] [32]).

June was the only month with a significant positive relationship between CR and rainfall and a negative correlation with SSN. In April and May significant anti-correlations were found between precipitation and CR and SSN, respectively.

For the seasonal correlations, rainfall over Saudi Arabia correlates positively with CR and negatively with SSN during summer and fall. On the other hand, rainfall is anti-correlated with CR, and correlated with SSN during winter and spring seasons.

The correlation analyses between rainfall and both SSN and CRs for each solar cycle of the three cycles were conducted and the results are presented in **Table 2**. The strength, magnitude, and degree of association between rainfall and the two variables differ from one cycle to another.

For all three cycles, the annual rainfall in Saudi Arabia showed a positive correlation with CRs. While SSN has a positive correlation with annual rainfall in cycle 23, the opposite was observed for both the 22nd and 24th cycles.

A consideration of each season for each cycle revealed different correlations. For the winter season, rainfall correlated negatively with CRs in cycles 22 and 23, and positively in the 24th cycle. The average correlation coefficients for all three cycles were about 20%. Similarly, a positive correlation was obtained between

Table 2. Correlation coefficients of the annual and seasonal rainfall over Saudi Arabia, sunspot number (SSN) and Galactic cosmic rays (GCR) for the three solar cycles. N is the duration of the solar cycle.

		Cycle 22 (1987-1996) N = 10		**Cycle 23 (1997-2008) N = 12**		**Cycle 24 (2009-2019) N = 11**	
		SSN	GCR Count Rate [cts/min]	SNN	GCR Count Rate [cts/min]	SNN	GCR Count Rate [cts/min]
Annual	Pearson coeff.	−0.417	0.43	0.044	0.139	−0.383	0.306
	Sig. (1-tailed)	0.116	0.107	0.446	0.333	0.123	0.18
Winter	Pearson coeff.	0.147	−0.201	0.262	−0.211	−0.185	0.234
	Sig. (1-tailed)	0.342	0.288	0.206	0.255	0.293	0.245
Spring	Pearson coeff.	0.141	−0.175	−0.155	0.217	0.008	0.026
	Sig. (1-tailed)	0.349	0.314	0.315	0.249	0.491	0.469
Summer	Pearson coeff.	−0.385	0.433	−0.042	0.086	**−0.554***	0.449
	Sig. (1-tailed)	0.136	0.106	0.449	0.395	0.038	0.083
Fall	Pearson coeff.	**−0.620***	**0.633***	0.077	0.101	−0.286	0.220
	Sig. (1-tailed)	0.028	0.025	0.406	0.415	0.197	0.259

** 0.01 level of significance, * 0.05 level of significance, + 0.1 level of significance.

rainfall and SSN in the 22nd and 23rd cycles during winter, whereas SSN and rainfall were anti-correlated during the 24th cycle.

For spring, while CRs had a negative effect on rainfall during the 22nd and 23rd cycles, they had a positive effect in the 24th solar cycle. During the same season, rainfall correlated with SSN in the 22nd and 24th cycles and anti-correlated with SSN in the 23rd cycle.

In summer, and during the three cycles, rainfall had a positive correlation with CRs and a negative correlation with SSN. For the 22nd and the 24th cycles, the correlation between the rainfall and CRs was about 44%, whereas that between rainfall and SSN was about 40% in the 22nd cycle. The correlation between SSN and rainfall during the 24th cycle was statistically significant, with a correlation coefficient of 55%.

In the three cycles, rainfall correlated positively with CRs in fall. This correlation was significant only during the 22nd cycle, with a correlation coefficient of 63%. The correlation coefficient was about 10% and 22% between the CRs and the rainfall for the 23rd and the 24th cycles, respectively. In this season, the rainfall was anti-correlated with SSN in the 22nd and 24th cycles and correlated in the 23rd cycle. The correlation coefficient between SSN and rainfall during the 22nd cycle was significant at a 99% confidence level and had a correlation coefficient of about 62%.

By considering each cycle individually, the intensity and length of solar activity varied from cycle to cycle. Some cycles were longer than others, and the intensity and number of sunspots and resulting activity (e.g., CMEs, solar flares, coronal holes) could vary. For example, solar cycle 23 had a length of 12.4 years. Likewise, the maximum number of SSNs reported for cycle 22 was 216 with a duration of approximately 10 years, while the maximum number of SSNs reported for cycle 24 was 116, with a duration of 11 years. Therefore, each solar cycle had different effects on Earth's atmosphere, temperature, and precipitation patterns, which may explain the anomalous relationship observed between precipitation, SSN and GCR, as well as unusual activities such as flooding and/or droughts in Saudi Arabia during certain periods.

4. Discussion

Correlation analysis revealed a non-zero relationship between annual precipitation in Saudi Arabia and CR during the study period and inversely correlated with SSN. In contrast, these relationships were revised on certain occasions.

Though the correlations obtained between annual rainfall over Saudi Arabia and both SSN and CR have low correlation coefficients, they agree with some of the previous studies (e.g., [11] [27] [29]-[35] [37] [38]).

The strength, magnitude, and significant differences of the correlations presented here are affected by several factors. Besides statistical uncertainties associated with experimental data, these factors may originate from terrestrial and/or extra-terrestrial sources. While these factors play a potential role in determining the spatial distribution and intensity of precipitation in Saudi Arabia, their impact varies by location, season and month.

Terrestrial factors include global, regional, and local variations in large-scale atmospheric circulation, geographic location, and topological characteristics at each site. Spatiotemporal changes in atmospheric aerosols from local, regional (dust storms), global (e.g., volcanic eruptions) and extra-terrestrial (cosmic dust) sources lead to changes in precipitation (e.g., [8] [9] [13] [28] [39] [40] [41] [42] [43]). For instance, the precipitation pattern in Saudi Arabia is influenced mainly by three air masses, viz., a late autumn wind front, a continental tropical air mass from the Atlantic Ocean across the continents of Central and North Africa, and an oceanic polar air mass from the eastern Mediterranean [1]. These atmospheric patterns are influenced by global phenomena such as the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO) (e.g., [6] [7] [44] [45] [46]).

In addition, extreme precipitation events were found to contribute to total precipitation in Saudi Arabia, and the contribution of extreme events to total precipitation varied by month and region. For example, Al Mazroui [47] reports that the highest contribution (up to 56%) was found in southern regions in June, with the largest contribution coming from coastal regions.

The length of the study period may be an additional factor affecting the correlations between rainfall and the two variables considered. However, the data used in this study are reliable data available for the longest period.

Extra-terrestrial factors include the effects of meteor showers, lunar cycles, and solar activity, in which the impact of solar variability on the Earth's climate has become a widespread subject attracting scientific interest from different research fields (e.g., [14] [15] [16] [17] [48]).

While the exact mechanism of the relationships between solar activity, CRs and rainfall is yet to be ascertained, several investigations have demonstrated that the solar activity processes may directly or indirectly have a possible influence on the weather and climates on Earth.

Among the proposed theories concerning the impact of solar activity on weather and climate is the modulation of CRs by solar activity. In this hypothesis, the solar disturbances affect the interplanetary medium, which modulates the primary CRs in the heliosphere and their rate at the top of the atmosphere (e.g., [17] [49]). It is well-known that secondary cosmic rays, produced through the interactions between primary CRs and the atmospheric molecules, affect the physical and chemical properties of the atmosphere through ionizations (e.g., [19] [22] [50]). The variation in atmospheric ionization due to CR modulations influences the rate of cloud formation, water vapour content, precipitation, atmospheric aerosol concentration and size distributions (e.g., [25] [40] [51] [52]).

For instance, Pennycuick and Norton-Griffiths [53] for instance, noted an increase in rainfall during the minimum phase of the solar cycle. Hiremath and Mandi [35] used 130 years of precipitation data for India, and although a weak and insignificant correlation was obtained, found precipitation inversely correlated with SSN. Mostafa *et al.* [34] used precipitation data between 1910 and 2018 from 19 sites in Sudan and confirmed a negative correlation between site-specific precipitation and SSN.

Recent studies have identified a relationship between sunspot numbers and ENSO, which has significant implications for large-scale atmospheric circulations and the global weather system. The variability in the atmospheric circulations and the global weather system have an impact on precipitation and its relationship with solar SSN (e.g., [44] [54] [55] [56] [57]).

Under current conditions, it is difficult to assess which of the presented factors affects the relationship between precipitation in Saudi Arabia and both the

CR and SSN. The results presented in this study are preliminary and more detailed investigations are recommended.

5. Conclusions

The longest historical rainfall data from 19 stations in Saudi Arabia for the period 1985-2019 were used to investigate the possible effects of solar activity (represented by the SSN) and the associated CR modulation with mean monthly rainfalls.

Correlation analyses showed a nonzero positive correlation between the annual rainfall time series in Saudi Arabia and CR and a negative correlation with solar activity (SSN). Similar results were also found during the months of May-November, as well as in summer and fall. The rainfall during December-April and both spring and winter showed the opposite trend.

The relationships between rainfall, SSN and CR for each solar cycle were calculated and showed that for all three cycles, annual rainfall over Saudi Arabia had a positive correlation with the CR.

The relationships between rainfall and the two variables were different from season to the season during each cycle. Different correlations were obtained between seasonal rainfall and the CRs and SSNs from one cycle to another.

The strength of the relationships between the rainfall and the two considered variables differed from one season to another and from one cycle to another.

Several terrestrial and extra-terrestrial factors may affect these relationships. These include global, regional, and local variations in large-scale atmospheric circulation, geographic location, and topological characteristics of each site. Various distributions in atmospheric aerosols from local, regional, global and extra-terrestrial sources lead to changes in precipitation. The solar cycles themselves, their strengths and variations are a possible cause affecting these correlations. While these factors play a potential role in determining the spatial distribution and intensity of precipitation in Saudi Arabia, their impact varies by location, season and month.

In the present context, it is very difficult to judge as to which of these factors influences Saudi rainfall. These findings are a step towards understanding the possible role of solar activity on climate change for future meteorological phenomenon variability, even if the physical mechanism is still poorly quantified.

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Conflicts of Interest

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Abdullrahman Maghrabi, Hadeel Alamoudi and Aied Alruhili. The first draft of the manuscript was written by Abdullrahman Maghrabi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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