American Journal of Climate Change, 2023, 12, 204-217
https://www.scirp.org/journal/ajcc
ISSN Online: 2167-9509
ISSN Print: 2167-9495

Long-Term Rainfall Trends in South West Asia—Saudi Arabia

Abdullrahman H. Maghrabi[1*], Hadeel A. Alamoudi[2], Aied S. Alruhaili[2]

[1]National Centre for Applied Physics, King Abdulaziz City for Science and Technology, Riyadh, KSA
[2]Astronomy and Space Science Department, King Abdulaziz University, Jeddah, KSA
Email: *amaghrabi@kacst.edu.sa

How to cite this paper: Maghrabi, A. H., Alamoudi, H. A., & Alruhaili, A. S. (2023). Long-Term Rainfall Trends in South West Asia—Saudi Arabia. *American Journal of Climate Change, 12,* 204-217.
https://doi.org/10.4236/ajcc.2023.121010

Received: December 19, 2022
Accepted: March 28, 2023
Published: March 31, 2023

Copyright © 2023 by author(s) and Scientific Research Publishing Inc.
This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/
Open Access

Abstract

In this study, rainfall data from 19 stations in Saudi Arabia (SA) for the period 1985-2019 was utilized to investigate interannual, monthly, and seasonal rainfall variations and trends. The magnitudes of these trends were characterized and tested using Mann-Kendall (MK) rank statistics at different significance levels. During this study period, the mean rainfall in SA showed a slight and significant decreasing trend by about 2 mm/35 years. Investigation of seasonal trends of rainfall revealed that Winter and Spring rainfall decreased significantly by 2.7 mm/35 years and 5.4 mm/35 years respectively. Three months showed very slight significant decreasing trends of rainfall. These were the months of February, March and April. Mann-Kendall analyses were carried out to investigate the annual trends of rainfall during three sub-periods, i.e., 1985-1996, 1997-2008, and 2009-2019. The results revealed that while rainfall increased by 5.3 mm/12 years and 7.8 mm/11 years for the first and the third periods respectively, it decreased by about 11 mm/12 years during the second period. While trends of rainfall in Saudi Arabia are affected by large scale circulations and local factors, the effect of extraterrestrial factors, such as solar activity and its consequent effects on the climate may, additionally, play a potential role in affecting the pattern of rainfall in Saudi Arabia.

Keywords

Rainfall Trend, Long-Term, Saudi Arabia, Mann-Kendell

1. Introduction

Climate is one of the important drivers of ecosystems, composition and other Earth systems. Precipitation and temperature are two of the most important variables in climate science, often used to track the magnitude and variability of climate change. Climate variability will have unintended consequences in many parts of the world in terms of the frequency and magnitude of precipitation and temperature fluctuations (e.g., Hunt, 2000; Easterling et al., 2000; Goswami et al., 2006; Almazroui et al., 2017a; Myhre et al., 2019). Consequently, climate variability tends to affect specific sectors, such as agriculture, public health, water supply, energy production and use, and land use and development (Bell et al., 2018; Sung et al., 2015).

There are different sources of water among which, rainfall, in semi-arid and arid areas, is considered as the main source. Precipitation is a vital part of the hydrologic cycle and changes in its pattern would directly influence the water resources of a given area. Knowledge and understanding of the distribution, variations, and trends of rainfall are of vital importance, and have several applications (Augustine & McNaughton, 2006; Olayide et al., 2016; Zhang et al., 2007).

The pattern and trend of rainfall over different spatial and temporal scales have been investigated. It was found that global rainfall trend increased throughout the last century, although large areas were characterized by negative trends(e.g., Zhang et al., 2007; Funk et al., 2014; Bari et al., 2016; Wang et al., 2016; Tan et al., 2019).

The pattern of rainfall and its associated atmospheric circulation over Saudi Arabia have been discussed extensively in several articles (Hasanean & Almazroui, 2015; Almazroui & Saeed, 2020; Almazroui et al., 2017b; Almazroui, 2020).

The annual mean rainfall over Saudi Arabia varies considerably and displays a large spatial and temporal variability over the entire country. Also, it has strong seasonality, as the influence of both tropical and extra-tropical drivers causes extreme rainfall events at different times through the annual cycle. The southern region of the country receives the highest rainfall compared to the northwest territory, which is considered the driest region with the lowest average annual rainfall (e.g., Almazroui, 2020 and references therein).

The pattern of rainfall in SA is mainly affected by three major air masses; 1) the monsoon fronts during late Autumn, 2) the continental tropical air mass coming from the Atlantic Ocean through the central and northern parts of the African continent, and 3) the maritime polar air mass coming from the eastern Mediterranean Sea (Alyamani, 2001). For instance, the winter rainfall pattern is affected throughout North Africa, Europe, West Asia, and Central Asia, while Spring rainfall is mainly linked to the westerly systems vis-à-vis the central landmass of the Arabian Peninsula except in the northern Red Sea coastal area (Hasanean & Almazroui, 2015; Almazroui et al., 2017b; Almazroui, 2020).

Rainfall variability over large scales is affected by regional and/or local variations (Farnsworth et al., 2011, Olayide et al., 2016). Therefore, it is important to analyze rainfall variability on the local scale for better assessment of its variability and distribution.

In this study, the longest historical records of rainfall from 19 meteorological stations across Saudi Arabia were used to investigate monthly, seasonal, and annual, long-term rainfall trends and variations for the last 35 years (1985-2019). Mann Kendall test was used to investigate long-term trends at various significance levels. Sen's estimate was used to show the increasing/decreasing magnitudes of each trend.

2. Data and Methods

Data and Methodology

Saudi Arabia is a large country with an area of about 2,250,000 km^2, and it is stretches from 15.5˚N - 32.5˚N in latitude. It has a diverse climate which changes from region to region but, most of it lies within the subtropical desert climate zone. It is considered to be a dry country due to its low annual rainfall. However, precipitation varies over space and time, and the amount of precipitation also varies from region to region.

Monthly mean precipitation data series from 19 weather stations for the period between 1985-2019 was analyzed for the purpose of this study. This data was provided by the Saudi Arabian Ministry of Environmental Protection (MEP). The considered stations were selected according to the length and completeness of their records, and keeping in mind that a reasonable spatial and temporal coverage of the country is achieved (**Figure 1**).

The data was subjected to extensive quality control procedures including the non-parametric Kruskal-Wallis test (Essenwanger, 1986) so as to retain the homogeneity of the data, and to eliminate multiple random errors found in the original data. Furthermore, linear interpolation methods were used to fill gaps in the missing data.

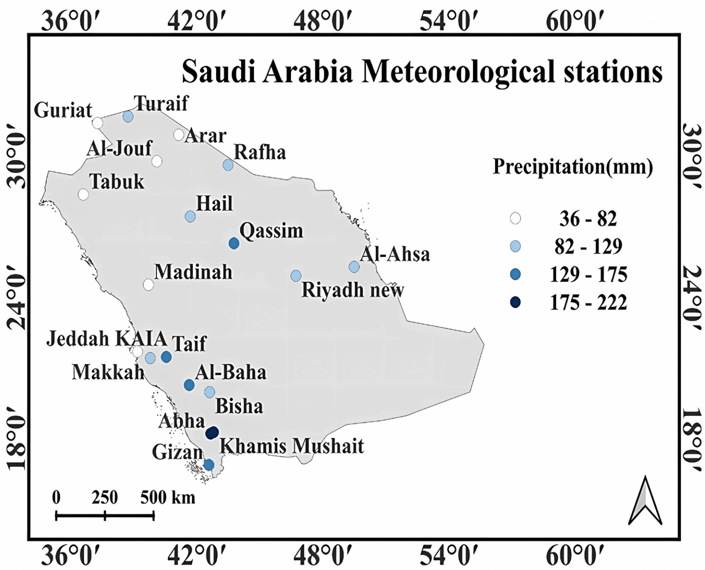

Figure 1. Shows the geographical coordinates of the sites considered in this study. The range of the total precipitations has been indicated.

The mean rainfall recorded by 19 stations during the period of study indicated that Abha had the highest precipitation while the lowest was recorded in Tabuk.

In general, relatively heavy precipitation was received over the south-western region. This is due to the orographic features of the region (Subyani, 2004). Around 38% of the country's rainfall was received by the south-western region (Abha, Khamis Mushait, Albaha, Gizan, Bisha), and it decreased moving north where least precipitation occurred.

To study the variability of rainfall for the whole country, the monthly mean values from each station for the considered period were utilized. The monthly distribution of rainfall was classified into 12 bins, and the seasonal variations were divided into 4 groups. Winter included the months of December, January and February (DJF); Spring included March, April and May (MAM); June, July and August (JJA) made up Summer; and Autumn included September, October and November (SON).

Mann-Kendall (MK) tests were carried out and Sen's slopes were determined to assess the trends of rainfall. These are non-parametric statistical tests that are widely used for analyzing trends in climatologic time series (e.g., Yue & Wang, 2004, Maghrabi, 2019).

The MK test can be applied to a time series x_i ranked from $i = 1, 2, \cdots, n-1$ and x_j ranked from $j = i+1, 2, \cdots, n$ such that

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases} \tag{1}$$

The Kendall test statistic S can be computed as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \tag{2}$$

where x_j and x_j are data values at times j and i, $j > i$, respectively, and $\operatorname{sgn}(x_j - x_i)$ is the signum function. S is assumed to be asymptotically normal, with the expectation value $E(S) = 0$ for a sample size of $n \geq 8$ and variance as follows (Yue & Pilon, 2004):

$$V(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p (t_p - 1)(2t_p + 5)\right] \tag{3}$$

Here, q is the number of tied groups, and t_p is the number of data values in group p.

The values of S and $V(S)$ are used to compute the test statistic Z as follows:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}} & \text{if } S < 0 \end{cases} \tag{4}$$

The standardized MK test statistic Z follows the standard normal distribution with a mean of zero and a variance of one and is used to measure the significance of the trend. If $|Z|$ is greater than Z_{crit} (Z_{crit} is the $(100 \times (1 - \alpha/2))^{th}$ percentile of the standard normal distribution with a chosen significance level α (e.g., 5% with $Z_{0.025} = \pm 1.96$)), then the null hypothesis is invalid, implying that the trend is significant.

3. Results and Discussion

3.1. General Precipitation Trends

Figure 2 shows the mean annual variations of rainfall over SA for the period between 1985-2019. The average rainfall recorded was 170.4 mm. Maximum rainfall was recorded in 1997 followed by 1998, 1992, and 1993. On the contrary, the driest years were 2007, 2008, 2009, and 2012. Only 42.85% of the annual records were above the average.

Figure 3 indicates monthly and seasonal average rainfall of the country. Evidently, the highest mean precipitation (356 mm, 269 mm, and 262 mm) was reported in April, March and November respectively. Lowest precipitation (39 mm and 49.5 mm) was recorded in June and September respectively.

The mean rainfall was 550 mm, 811 mm, 235 mm, and 447 mm for Winter, Spring, Summer and Fall respectively. Monthly rainfall received over the country during Spring was about 40% of the country's total compared to other seasons, with the highest contribution made in April which made up for about 44% of the Spring total. Winter rainfall was about 27% of the country's total, in which the highest contribution was made in January, which made up for 43% of the Winter total. The lowest rainfall was received during Summer (236 mm), which made up for 11.5% of the country's total, with the lowest contribution made in June, making up for 16.7% of the Summer total.

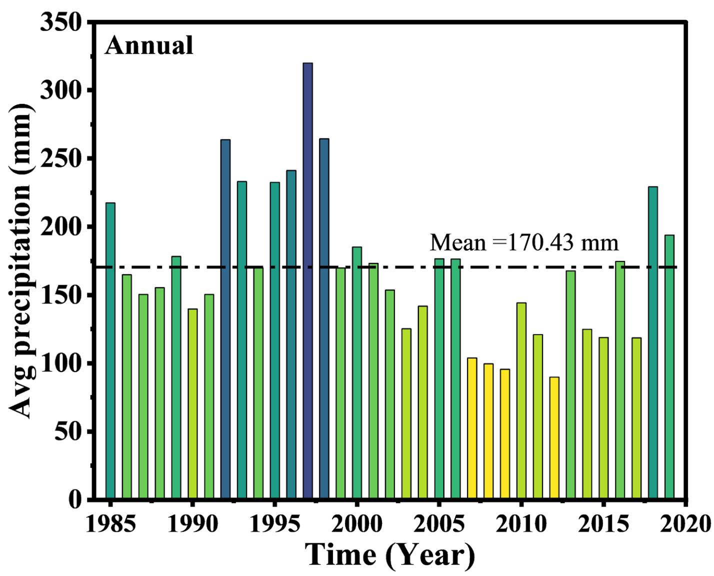

Figure 2. Time series of annual mean rainfall during the period 1985-2016. The solid line represents the country's mean rainfall value.

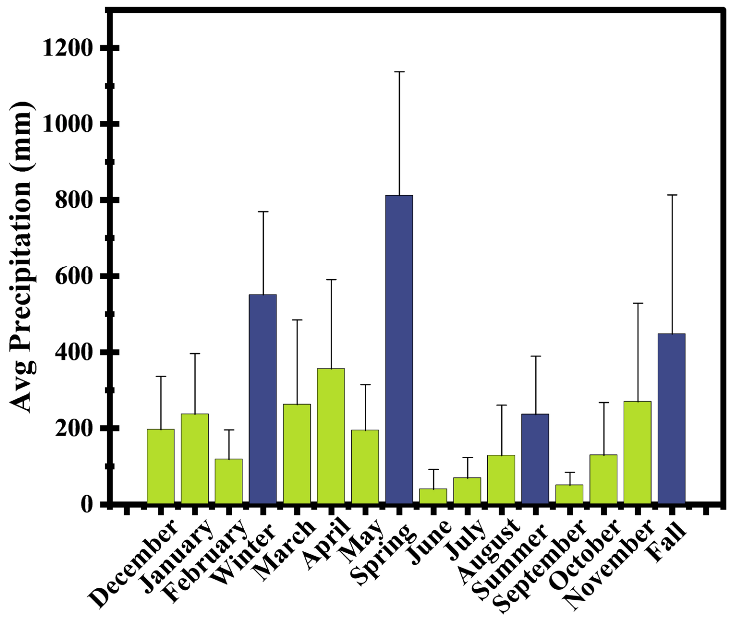

Figure 3. Shows monthly and seasonal variations of rainfall in the country for the period between 1985-2019.

Figure 4 indicates the seasonal variations of rainfall during the study period. The highest Winter rainfall found in 1999 and 1995, whereas the highest Winter and Summer rainfall was in 1992. Spring maximum values were attained in 1993 and 1998, whereas the highest Fall rainfall was received in 1997 and 2018. Winter and Spring recorded about 42.8% and 48.57% above the rainfall average respectively.

3.2. Mann-Kendall Analyses

Figure 5 indicates the trend of the annual mean values of rainfall, while the results of the MK tests, Sen's slope, and total trend for all 35 years are presented in **Table 1**. The mean annual rainfall over Saudi Arabia during the study period decreased by 1.78 mm/35 years at 95% confidence level.

Figure 6 indicates the seasonal variations of rainfall during the study period and the corresponding MK results are presented in **Table 1**. The MK tests revealed a decreasing trend at confidence level of 95% with 2.7 mm/35 years in Winter and 5.4 mm/35 years for Spring with 99% confidence level. On the other hand, rainfall showed non-significant increasing trend in Summer and non-significant decreasing trend in Fall during the whole study period.

Close inspection of the data shows that there were three distinctive periods in which rainfall changed substantially. These were the period between 1985 and 1996, between 1997 and 2008, and between 2009 and 2019. Hence, MK analyses were performed for each period separately.

The MK results revealed that for the first period (12 years), there was non-significant increasing trend in the rainfall with about of 5.73 mm/12 years. For the third period between 2009 and 2019, MK results indicated non-significant

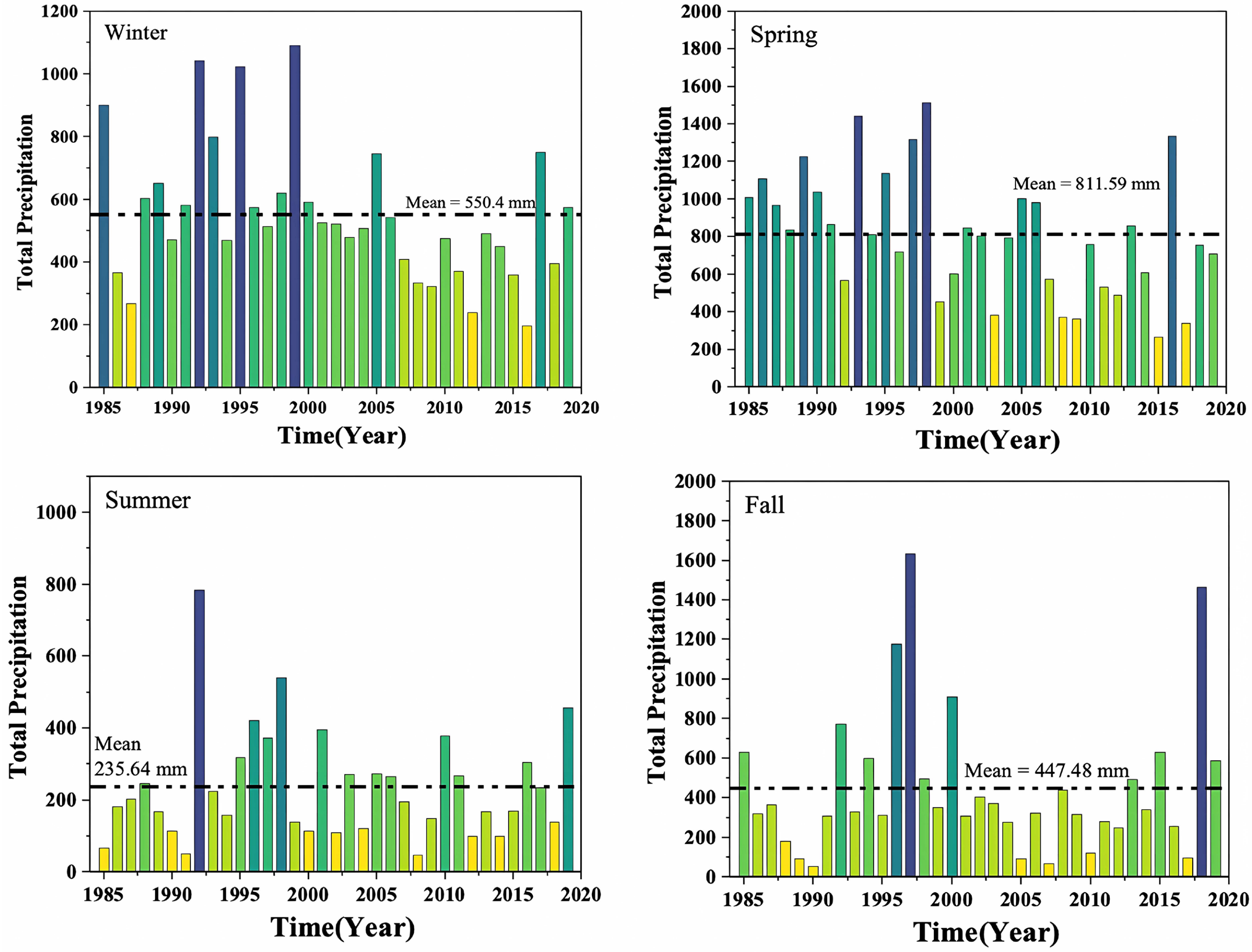

Figure 4. Shows time series of the seasonal mean values of rainfall: (a) Winter; (b) Spring; (c) Summer; and (d) Fall in the period 1985-2016. The dashed line is the mean value of the corresponding season.

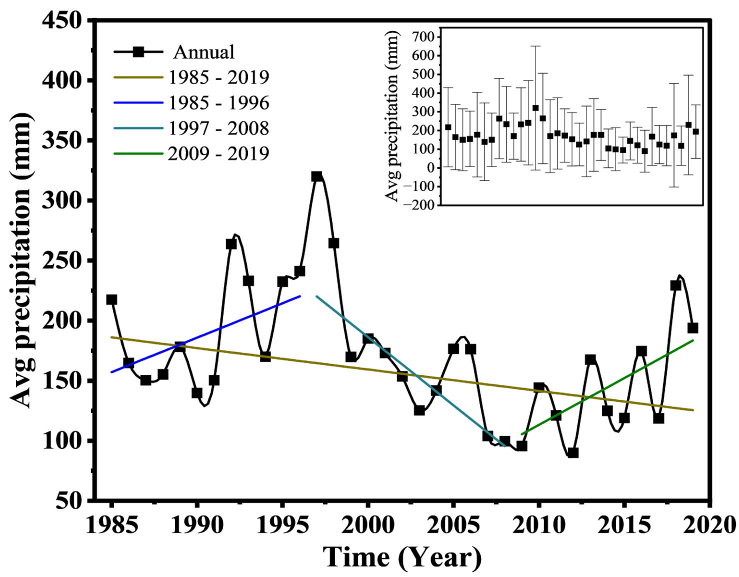

Figure 5. Yearly mean variations of rainfall for the period 1985-2019. The solid lines are the trend line. The inset graph represents the standard deviations.

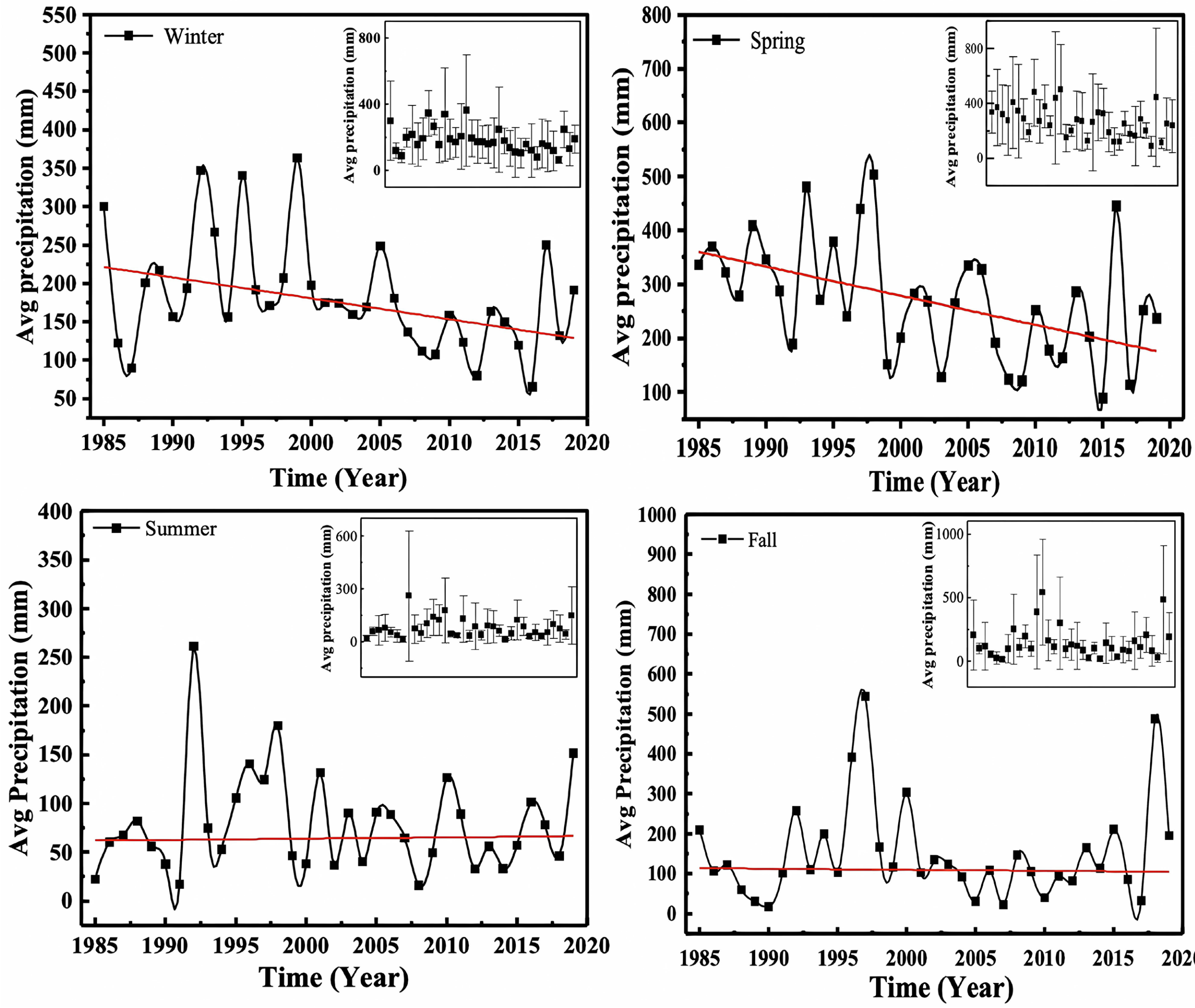

Figure 6. Time series of the seasonal mean values of rainfall (a) winter; (b) spring; (c) summer; and (d) fall in the period 1985-2016. The solid lines are the trend lines.

increase in the rainfall by about of 7.8 mm/11 years. On the other hand, significant decreasing trend with 11.32 mm/12 years at 0.01 significant level for the period between 1997-2008 was detected.

For seasonal rainfall during the sub-periods, rainfall showed increasing trends in one period and decreasing trends in another. For instance, for the period between 1997-2008, rainfall for all the seasons showed decreasing trends, whereas the periods between 2009-2019 showed increasing trends. For the former period, there was significant decrease by 15.18 mm/12 years with a significance level of 95% in Fall, and significant decrease by 7.21 mm/12 years (confidence level 90%) in Winter. For the period between 1985-1996, while the rainfall showed decreasing trend in Spring, the opposite happened for the remaining seasons.

The trend of rainfall in Saudi Arabia for each month was computed using MK tests and the results for the same are given in Table 1. With different confidence levels, only three months showed significant decreasing trends in rainfall during the 35-year study period. The rainfall decreased ($\alpha = 0.1$) by 0.11 mm/35 years in

Table 1. Summary of the Mann-Kendall test results and Sen slope, for the annual, seasonal, and monthly changes in rainfall values for Saudi Arabia for the period 1985-2019 and the three sub-periods.

Time series	*1985-2019*		*1985-1996*		*1997-2008*		*2009-2019*	
	n	*Q mm/35 yrs*	*n*	*Q mm/12 yrs.*	*n*	*Q mm/12 yrs*	*n*	*Q mm/11 yrs*
Annual	35	**−1.78***	12	5.73	12	**−11.32****	11	7.80
January	35	−0.07	12	0.52	12	−0.62	11	−0.07
February	35	**-0.11^{+}**	12	0.72	12	−0.02	11	0.34
March	35	**−0.37****	12	−0.05	12	**−3.57****	11	−0.01
April	35	**-0.37^{+}**	12	−0.85	12	1.24	11	0.10
May	35	0.02	12	0.65	12	0.16	11	0.12
June	35	0.00	12	0.04	12	**-0.17^{+}**	11	−0.03
July	35	0.00	12	**0.34^{+}**	12	−0.08	11	−0.20
August	35	0.01	12	0.08	12	**-0.86^{+}**	11	0.05
September	35	−0.01	12	0.01	12	**-0.12^{+}**	11	0.15
October	35	−0.08	12	1.00	12	−0.42	11	0.63
November	35	0.20	12	0.40	12	**−1.98***	11	1.31
December	35	−0.18	12	0.08	12	−0.58	11	−0.07
Winter	35	**−2.72***	12	7.78	12	**-7.21^{+}**	11	4.13
Spring	35	**−5.42****	12	−7.24	12	−13.20	11	8.28
Summer	35	0.135	12	6.94	12	−5.84	11	2.16
Fall	35	−0.255	12	8.41	12	**−15.18***	11	14.95

***trend at $\alpha = 0.001$ level of significance; **trend at $\alpha = 0.01$ level of significance. *trend at $\alpha = 0.05$ level of significance; $^{+}$trend at $\alpha = 0.1$ level of significance.

February, by 0.37 mm/35 years ($\alpha = 0.01$) in March, and with the same decreasing rate at $\alpha = 0.1$ in April.

While non-statistically significant decreasing trend was found in January, December, September, and October, increasing trends were found for the remaining months.

By considering the sub-periods, MK results for the period 1985-1996 revealed that rainfall in Saudi Arabia for each month increased slightly with different magnitudes. Rainfall was only significant at 0.1 significance level (0.34/12 years) in the month of July. For the period between 1997-2008 and at 0.1 significance level, rainfall decreased in June, August, and September by 0.17 mm, 0.86 mm, and 0.12 mm per 12 years, respectively. For the same period, and at 0.05 significance level, the rainfall decreased by 1.98/12 years in November. In addition, MK test indicated a decreasing trend by −3.57/12 years at 0.01 significance level in March. For the rest of the months in this period, and for the period between 2009-2019, monthly trends of rainfall in Saudi Arabia varied between increasing or decreasing trends.

3.3. Discussions

Saudi Arabia is categorized mainly as a semi-arid to arid climatic zone (Köppen & Geiger, 1930) middle to northern regions receives moderate rainfall while southern areas have the highest rainfall. The arid and semi-arid regions have an extreme, continental climate with low annual rainfall, high temperatures, a dry Summer, and a very cold Winter, especially in the central regions of the country (e.g., Almazroui et al., 2012; Edgell, 2006, Maghrabi & Al Dajani, 2013).

In addition to large-scale circulation, local factors such as the geographical position, local surface heating and topography for each individual site play a potential role in determining the spatial distribution and intensity of rainfall in Saudi Arabia (Alyamani, 2001; Al Senafi & Anis, 2015; De Vries et al., 2016). These factors may explain some of the trends in rainfall that are observed during some periods in some regions, but not all of them.

Moreover, the impact of extraterrestrial factors such as meteor showers and solar activity, and their consequential effect on the Earth's climate, are also expected to affect rainfall patterns in several locations around the world including Saudi Arabia (Bowen, 1956; Laurenz et al., 2019; Bhattacharyya & Narasimha, 2005).

For instance, it has been proposed that the El Niño Southern Oscillation (ENSO) significantly affects the global temperature patterns during certain periods, which consequentially, influences rainfall variability through large changes in moisture availability (Kirov & Georgieva, 2002; Emori & Brown, 2005; Foster & Rahmstorf, 2011). It has been found that the ENSO is significantly correlated with sunspots, which, in turn, are considered as solar activity indicators (Kirov & Georgieva, 2002).

Additionally, solar activity and associated magnetic activities may also have a potential role in influencing the pattern of rainfall, or cause severe drought/rainfall episodes observed in Saudi Arabia (Bucha, 1991). This arises from the fact that solar activity and geomagnetic disturbances can modulate the flux of high-energy cosmic rays, which are considered as the main source of ionization in the atmosphere. These variations in the ionization can directly or indirectly affect the physical and chemical properties of the atmosphere; for example, they can change the rate of cloud formation, water vapor content, and atmospheric aerosols (Svensmark & Friis-Christensen, 1997; Carslaw et al., 2002; Svensmark et al., 2009; Maghrabi & Kudela, 2019; Maghrabi, 2019) which, in turn, affect the rate and pattern of rainfall. Research on this subject is ongoing.

4. Conclusion

The longest, historical rainfall data from 19 stations in Saudi Arabia for the period 1985-2019 was used to investigate interannual, monthly, and seasonal rainfall variations and trends.

The mean rainfall in Saudi Arabia was reported to be about 170 mm. The highest rainfall occurred in March and April whereas, the lowest was recorded in

June and September. The monthly rainfall in Spring was about 811 mm which accounted for about 40% of the country's total compared to the other seasons. On the other hand, Summer, the lowest rainfall was about 235 mm, was recorded.

Non-parametric MK tests were performed to detect rainfall magnitude and trends which gave the following results:

1) The mean rainfall in Saudi Arabia showed a decreasing trend during the study period. This decrease was about 2 mm/35 years with a 95% confidence level.

2) The MK analyses for three sub-periods 1985-1996, 1997-2008, and 2009-2019 revealed that rainfall increased by 5.3 mm/12 years and 7.8 mm/11 years for the first and the third periods respectively.

3) Significant decrease of about 11 mm/12 years was detected during the second period.

4) Seasonal trends of rainfall showed that Winter and Spring rainfalls decreased significantly by 2.7 mm/35 years and 5.4 mm/35 years respectively.

5) Three months showed very slight significant decreasing trends in their rainfall. These are February, March and April.

Rainfall trends and distributions are affected by global and regional factors, such as large scale circulations, and local factors such as topography of the sites and geographical positions. However, extraterrestrial factors such as solar activity and their consequential effects on the climate may affect the pattern of rainfall in Saudi Arabia. These factors continue to be subjects research.

Acknowledgements

The authors would like to thank King Abdulaziz University for supporting this work.

Ethical Approval

All research was conducted according to the ethical guidelines provided by the host institutions the authors are affiliated with.

Authors' Contributions

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

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Availability of Data and Materials

The datasets generated and analysed during the current study are not publicly available due the fact that they constitute an excerpt of research in progress but are available from the corresponding author on reasonable request.

Conflicts of Interest

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

References

Al Senafi, F., & Anis, A. (2015). Shamals and Climate Variability in the Northern Arabian/Persian Gulf from 1973 to 2012. *International Journal of Climatology, 35,* 4509-4528. https://doi.org/10.1002/joc.4302

Almazroui, M. (2020). Rainfall Trends and Extremes in Saudi Arabia in Recent Decades. *Atmosphere, 11,* 964. https://doi.org/10.3390/atmos11090964

Almazroui, M., & Saeed, S. (2020). Contribution of Extreme Daily Precipitation to Total Rainfall over the Arabian Peninsula. *Atmospheric Research, 231,* Article ID: 104672. https://doi.org/10.1016/j.atmosres.2019.104672

Almazroui, M., Balkhair, K. S., Islam, M. N., & Şen, Z. (2017a). Climate Change Impact on Monthly Precipitation Wet and Dry Spells in Arid Regions: Case Study over Wadi Al-Lith Basin. *Advances in Meteorology, 2017,* Article ID: 5132895. https://doi.org/10.1155/2017/5132895

Almazroui, M., Islam, M. N., Balkhair, K. S., Şen, Z., & Masood, A. (2017b). Rainwater Harvesting Possibility under Climate Change: A Basin-Scale Case Study over Western Province of Saudi Arabia. *Atmospheric Research, 189,* 11-23. https://doi.org/10.1016/j.atmosres.2017.01.004

Almazroui, M., Nazrul Islam, M., Athar, H., Jones, P., & Rahman, M. A. (2012). Recent Climate Change in the Arabian Peninsula: Annual Rainfall and Temperature Analysis of Saudi Arabia for 1978-2009. *International Journal of Climatology, 32,* 953-966. https://doi.org/10.1002/joc.3446

Alyamani, M. S. (2001). Isotopic Composition of Rainfall and Ground-Water Recharge in the Western Province of Saudi Arabia. *Journal of Arid Environments, 49,* 751-760. https://doi.org/10.1006/jare.2001.0815

Augustine, D. J., & McNaughton, S. J. (2006). Interactive Effects of Ungulate Herbivores, Soil Fertility, and Variable Rainfall on Ecosystem Processes in a Semi-Arid Savanna. *Ecosystems, 9,* 1242-1256. https://doi.org/10.1007/s10021-005-0020-y

Bari, S. H., Rahman, M. T. U., Hoque, M. A., & Hussain, M. M. (2016). Analysis of Seasonal and Annual Rainfall Trends in the Northern Region of Bangladesh. *Atmospheric Research, 176,* 148-158. https://doi.org/10.1016/j.atmosres.2016.02.008

Bell, J. E., Brown, C. L., Conlon, K., Herring, S., Kunkel, K. E., Lawrimore, J., Luber, G., Schreck, C., Smith, A., & Uejio, C. (2018). Changes in Extreme Events and the Potential Impacts on Human Health. *Journal of the Air & Waste Management Association, 68,* 265-287. https://doi.org/10.1080/10962247.2017.1401017

Bhattacharyya, S., & Narasimha, R. (2005). Possible Association between Indian Monsoon Rainfall and Solar Activity. *Geophysical Research Letters, 32.* https://doi.org/10.1029/2004GL021044

Bowen, E. (1956). The Relation between Rainfall and Meteor Showers. *Journal of Meteorology, 13,* 142-151.

https://doi.org/10.1175/1520-0469(1956)013<0142:TRBRAM>2.0.CO;2

Bucha, V. (1991). Solar and Geomagnetic Variability and Changes of Weather and Climate. *Journal of Atmospheric and Terrestrial Physics, 53,* 1161-1172. https://doi.org/10.1016/0021-9169(91)90067-H

Carslaw, K., Harrison, R., & Kirkby, J. (2002). Cosmic Rays, Clouds, and Climate. *Science, 298,* 1732-1737. https://doi.org/10.1126/science.1076964

De Vries, A., Feldstein, S. B., Riemer, M., Tyrlis, E., Sprenger, M., Baumgart, M., Fnais, M., & Lelieveld, J. (2016). Dynamics of Tropical-Extratropical Interactions and Extreme Precipitation Events in Saudi Arabia in Autumn, Winter and Spring. *Quarterly Journal of the Royal Meteorological Society, 142,* 1862-1880. https://doi.org/10.1002/qj.2781

Easterling, D. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R., & Mearns, L. O. (2000). Climate Extremes: Observations, Modeling, and Impacts. *Science, 289,* 2068-2074. https://doi.org/10.1126/science.289.5487.2068

Edgell, H. S. (2006). *Arabian Deserts: Nature, Origin and Evolution*. Springer Science & Business Media. https://doi.org/10.1007/1-4020-3970-0

Emori, S., & Brown, S. (2005). Dynamic and Thermodynamic Changes in Mean and Extreme Precipitation under Changed Climate. *Geophysical Research Letters, 32,* L17706. https://doi.org/10.1029/2005GL023272

Essenwanger, O. M. (1986). *Elements of Statistical Analysis*.

Farnsworth, A., White, E., Williams, C. J., Black, E., & Kniveton, D. R. (2011). Understanding the Large Scale Driving Mechanisms of Rainfall Variability over Central Africa. In D. R. Kniveton, & C. J. R. Williams (Eds.), *African Climate and Climate Change* (pp. 101-122). Springer. https://doi.org/10.1007/978-90-481-3842-5_5

Foster, G., & Rahmstorf, S. (2011). Global Temperature Evolution 1979-2010. *Environmental Research Letters, 6,* Article ID: 044022. https://doi.org/10.1088/1748-9326/6/4/044022

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Rowland, J., Romero, B., Husak, G., Michaelsen, J., & Verdin, A. (2014). *A Quasi-Global Precipitation Time Series for Drought Monitoring* (4 p.). U.S. Geological Survey Data Series 832. https://doi.org/10.3133/ds832

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing Trend of Extreme Rain Events over India in a Warming Environment. *Science, 314,* 1442-1444. https://doi.org/10.1126/science.1132027

Hasanean, H., & Almazroui, M. (2015). Rainfall: Features and Variations over Saudi Arabia, a Review. *Climate, 3,* 578-626. https://doi.org/10.3390/cli3030578

Hunt, B. G. (2000). Natural Climatic Variability and Sahelian Rainfall Trends. *Global and Planetary Change, 24,* 107-131. https://doi.org/10.1016/S0921-8181(99)00064-8

Kirov, B., & Georgieva, K. (2002). Long-Term Variations and Interrelations of ENSO, NAO and Solar Activity. *Physics and Chemistry of the Earth, Parts A/B/C, 27,* 441-448. https://doi.org/10.1016/S1474-7065(02)00024-4

Köppen, W., & Geiger, R. (1930). *Handbuch der klimatologie*. Gebrüder Borntraeger Berlin.

Laurenz, L., Lüdecke, H.-J., & Lüning, S. (2019). Influence of Solar Activity Changes on European Rainfall. *Journal of Atmospheric and Solar-Terrestrial Physics, 185,* 29-42. https://doi.org/10.1016/j.jastp.2019.01.012

Maghrabi, A. (2019). Multi-Decadal Variations and Periodicities of the Precipitable Water Vapour (PWV) and Their Possible Association with Solar Activity: Arabian Peninsula. *Journal of Atmospheric and Solar-Terrestrial Physics, 185,* 22-28. https://doi.org/10.1016/j.jastp.2019.01.011

Maghrabi, A., & Al Dajani, H. (2013). Estimation of Precipitable Water Vapour Using Vapour Pressure and Air Temperature in an Arid Region in Central Saudi Arabia. *Journal of the Association of Arab Universities for Basic and Applied Sciences, 14,* 1-8. https://doi.org/10.1016/j.jaubas.2012.11.001

Maghrabi, A., & Kudela, K. (2019). Relationship between Time Series Cosmic Ray Data and Aerosol Optical Properties: 1999-2015. *Journal Solar Terrestrial Physics, 190,* 36-44. https://doi.org/10.1016/j.jastp.2019.04.014

Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M. et al. (2019). Frequency of Extreme Rainfall Increases Extensively with Event Rareness under Global Warming. *Scientific Reports, 9,* Article No. 16063. https://doi.org/10.1038/s41598-019-52277-4

Olayide, O. E., Tetteh, I. K., & Popoola, L. (2016). Differential Impacts of Rainfall and Irrigation on Agricultural Production in Nigeria: Any Lessons for Climate-Smart Agriculture? *Agricultural Water Management, 178,* 30-36. https://doi.org/10.1016/j.agwat.2016.08.034

Subyani, A. M. (2004). Geostatistical Study of Annual and Seasonal Mean Rainfall Patterns in Southwest Saudi Arabia/Distribution géostatistique de la pluie moyenne annuelle et saisonnière dans le Sud-Ouest de l'Arabie Saoudite. *Hydrological Sciences Journal, 49,* 817. https://doi.org/10.1623/hysj.49.5.803.55137

Sung, J. H., Chung, E. S., Lee, B., & Kim, Y. (2015). Meteorological Hazard Assessment Based on Trends and Abrupt Changes in Rainfall Characteristics on the Korean Peninsula. *Theoretical and Applied Climatology, 127,* 305-326. https://doi.org/10.1007/s00704-015-1581-0

Svensmark, H., & Friis-Christensen, E. (1997). Variation of Cosmic Ray Flux and Global Cloud Coverage—A Missing Link in Solar-Climate Relationships. *Journal of Atmospheric and Solar-Terrestrial Physics, 59,* 1225-1232. https://doi.org/10.1016/S1364-6826(97)00001-1

Svensmark, H., Bondo, T., & Svensmark, J. (2009). Cosmic Ray Decreases Affect Atmospheric Aerosols and Clouds. *Geophysical Research Letters,* 36. https://doi.org/10.1029/2009GL038429

Tan, X., Gan, T. Y., Chen, S., Horton, D. E., Chen, X., Liu, B., & Lin, K. (2019). Trends in Persistent Seasonal-Scale Atmospheric Circulation Patterns Responsible for Seasonal Precipitation Totals and Occurrences of Precipitation Extremes over Canada. *Journal of Climate, 32,* 7105-7126. https://doi.org/10.1175/JCLI-D-18-0408.1

Wang, X.-J., Zhang, J.-Y., Ali, M., Shahid, S., He, R.-M., Xia, X.-H., & Jiang, Z. (2016). Impact of Climate Change on Regional Irrigation Water Demand in Baojixia Irrigation District of China. *Mitigation and Adaptation Strategies for Global Change, 21,* 233-247. https://doi.org/10.1007/s11027-014-9594-z

Yue, S., & Pilon, P. (2004). A Comparison of the Power of the T Test, Mann-Kendall and Bootstrap Tests for Trend Detection/Une comparaison de la puissance des tests t de Student, de Mann-Kendall et du bootstrap pour la détection de tendance. *Hydrological Sciences Journal, 49,* 21-37. https://doi.org/10.1623/hysj.49.1.21.53996

Yue, S., & Wang, C. (2004). The Mann-Kendall Test Modified by Effective Sample Size to Detect Trend in Serially Correlated Hydrological Series. *Water Resources Management, 18,* 201-218. https://doi.org/10.1023/B:WARM.0000043140.61082.60

Zhang, X., Zwiers, F. W., Hegerl, G. C., Lambert, F. H., Gillett, N. P., Solomon, S., Stott, P. A., & Nozawa, T. (2007). Detection of Human Influence on Twentieth-Century Precipitation Trends. *Nature, 448,* 461-465. https://doi.org/10.1038/nature06025