Potential Factors Affecting the Spatiotemporal Features of Sunshine Duration in Saudi Arabia Between 1983 and 2022

Abstract

Renewable energy has gained increasing attention and support due to its potential to reduce environmental impacts and address concerns about fossil fuel use.Solar energy can help to mitigate the effects of climate change by reducing the carbon footprint and supporting the transition to a low-carbon economy.Saudi Arabia has experienced an average SD of 283 ± 18 hm^{-1} and has been trending upward at a rate of 1.48 hy^{-1} with a 95% confidence level. The region experienced the highest level of trend in SD at a rate of 7.15 hy^{-1} from 1983 to 1990.In winter, the region has the SD in a range of 215-279 $hm^{-1}$with the lowest mean monthly SD of 244 ± 38 hm^{-1}, and there has been an upward trend in SD at a rate of 0.26 hy^{-1} with a 95% confidence level.In summer, the region has the SD in a range of 239-367 $hm^{-1}$with the highest mean monthly SD of 318 ± 39 hm^{-1}, and there has been a downward trend in SD at a rate of -0.22 hy^{-1} with a 90% confidence level.In spring, the mean monthly SD of 289 ± 24 hm^{-1}, and there has been anupward trend in SD at a rate of 0.62 hy^{-1} with a 99% confidence level.In autumn, the region has an SD in a range of 269-315 $hm^{-1}$with a mean monthly SD of 289 ± 24 hm^{-1}, and there has been anupward trend in SD at a rate of 0.03 hy^{-1} with statistically nonsignificant. There was a decline in SD across the country between 1983 and 1998, whereas from 2000 onward the country experienced an upward trend in SD. Relative humidity ($R = -0.53$, $p < 0.01$) and cloud cover($R = -0.42$, $p < 0.05$) as potential factors have a strong negative correlation with SD, whereas temperature ($R = 0.12$, $p > 0.1$) has a positive correlation with SD in the region.

Keywords: Sunshine Duration, Solar Energy, M-K Mutation, Hurst Exponent, Empirical Orthogonal Function, Trend, and Variability.

1. Introduction

Renewable energy has gained increasing attention and support due to its potential to reduce environmental impacts and address concerns about fossil fuel use, which is the leading contributor (about 90%) of world energy consumption[1]. Renewable energy sources, such as solar energy, is a clean and renewable energy source that does not produce greenhouse gas emissions or contribute to air pollution, unlike fossil fuels[2]. Moreover, solar energy does not require the extraction and combustion of finite resources like fossil fuels, leading to reduced land and water pollution associated with mining and drilling operations. Solar energy is also considered a more sustainable option as it does not deplete natural resources and has virtually unlimited potential. Furthermore, solar energy can help to mitigate the effects of climate change by reducing the carbon footprint and supporting the transition to a low-carbon economy.

The potential of sunshine duration (SD) as solar energy depends on the accurate assessment of availableand variation of the solar resource. To ensure the efficient utilization of solar energy, support the growth of renewable energy systems, and contribute to a sustainable future,accurate assessment and forecast of solar resources are required.The amount of energy that can be harnessed from the sun in a given area is crucial for viable locations for solar plant installation and optimizing the design of solar panels (size and placement).

Various methods are used to measure the available duration of sunlight during whichthe sun irradiates on the earth's surface above the threshold level at 120 W m-2 according to the World Metrological Organization [3], [4]. To obtain a reliable and accurate measurement of available radiation, the ground station method is the best available one but it covers only a specific area. Therefore, to obtain a metrological time series dataset for determining the trend and variability on a regional scale a large number of ground stations are required to be installed which is expensive and time-consuming.On the other hand, satellite data has become more popular among scientists as a tool to study climate change remotely, being used in spatiotemporal distribution mapping on regional and global scales.

The present study aimed to explore the variability and availability of SD on the spatiotemporal scale at different seasons across the country over the period, as well as the influence of the potential factors on SD change, different statistical approaches, such as the linear regression, Hurst Exponent, M-K mutation test, Empirical Orthogonal Function, Correlation, and Partial correlation methods, were adopted.

The orientation of the paper is as follows. The first section describes the geography of the study area. Next, it describes the availability and variation of SD at different seasons in the country based on time and space. Afterward, the results are discussed and concluded.

2. Materials and Methods

2.1. Study Area

Saudi Arabia is the largest country onthe Arabian Peninsula which occupies almost 80% of the peninsula. It is bordered by the Persian Gulf to the east, Yemen to the south, the Gulf of Aqaba, and the Red Sea to the west. The country is situated between latitudes 16°21’58”N and 32°9’57”N and longitudes 34°33’48”E and 55°41’29”E, as demonstrated in Figure 1.In the Asir region, inland mountains rise to over 2,700 m in elevation[5]. The Eastern Province is a region located along the Persian Gulf.Based on the findings of the Food and Agriculture Organization (FAO), the northern regions of the country have a subtropical climate, while the southern areas have a tropical climate.The world's largest continuous sand desert, Al-Rub al-Khali, is located in the southern region of the country.Apart from the western coast of Asirprovince, the region is predominantly arid with sweltering temperatures during the day and a sharp dip in temperature at night. In summer, the average temperature of the country is 45°C, whereas some parts of the northern region hardly ever exceed 0°C in winter.Generally, dry winds blowover the country and consequently,almost all of the area is arid especiallydue to subtropical high-pressure systems and minimal cloud cover, temperatures vary widely by region and season[5]. The Asir region confidently receives about sixty (60) percent of its annual precipitation from the Indian Ocean monsoons between October and March, resulting in approximately 300 millimeters of rainfall[6]. Rainfall in other parts of the country is low and erratic due to its location in the Sun Belt and the abundance of desert land and clear skies year-round. It is worth noting that it is among the biggest producers of solar photovoltaic (PV) energy[7].

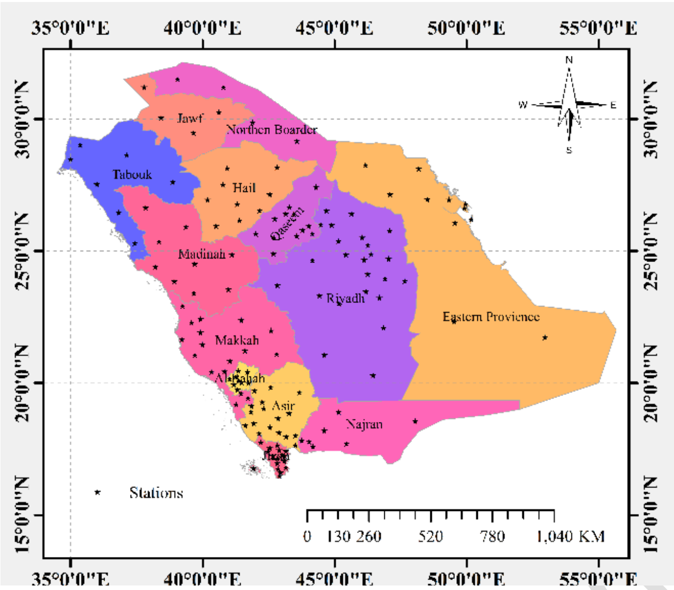


Figure 1. Maps of Saudi Arabia

There are four distinct seasons, such as spring, summer, autumn, and winter, in the country, ranging from chilly winter breezes in January to high desert temperatures in August. The spring season commences in March and concludes in April. The summer season spans nearly four months,commencing in May and culminating in August. Autumn commences after summer, spanning until October, while winter concludes before spring.

2.2 Data

EUMETSAT provides the SARAH-2.1 climate data record for solar radiation, which encompasses cloud, irradiance, and sunshine duration parameters [8]. Satellite-based Sunshine Duration (SD) is calculated by extracting the duration during which the Direct Normal Irradiance (DNI) exceeds 120 W m-2 from the SARAH-2-1 instantaneous DNI dataset with 0.5-degree spatial resolution [8], [9]. The monthly data of SD and Cloud Cover (in percent)for the 147 geospatial locations in Saudi Arabia were extracted over a 40-year period,spanning from 1983 to 2022. The influencing factors, such as precipitation, relative humidity, wind speed, and temperature, were extracted from The Prediction of Worldwide Energy Resources (POWER) project initiated by NASA (https://power.larc.nasa.gov/data-access-viewer). After conducting strict quality controls and inspections of all observed data, any missing or abnormal data were eliminated. However, to make the data more reliable and accurate the average values for the same year, same station, and same month will be used to replace some missing data.

2.3 Methodology

2.3.1 Trend Slope and Significance

The linear trend method stands out as a widely accepted statistical technique in metrological time series analysis. It offers a high level of confidence in determining the magnitude of environmental parameter changes over time. The **M-K mutation** test is a reliable method used to detect shifts in climate data from one state to another in a time series dataset [10]. At a specified significance level (α), the test statistics, for instance, **UF** and **UB,** are calculated and plotted on a graph. A clear indication of an upward trend is when the test statistics, UF is greater than 0, while a downward trend is indicated when this condition isn't met. [11]–[13]. Whenever a trend rises (or falls), the value above the critical line indicates its significance. The mutation time zone refers to the range beyond the critical line[10]. A point at which the UF and UB curves cross between the critical lines will determine when mutation begins if the intersection point is between the critical lines[14].

2.3.2 Hurst Exponent

Long-term memory plays a crucial role in the predictability of time series, and so it requires a scientific method to determine whether such a property exists in a time series dataset.An eminent British hydrologist named H.E. Hurst published a scientific paper in 1951 that proposed a statistical approach to identifying the randomness of a series of time series datasets, as well as characterizing their trends using a Rescaled Range Analysis or R/S Analysis, without making assumptions about stationaryness[15]–[17]. Currently, the most well-recognized method for assessing whether a long-term memory exists in a time series dataset and also characterizes the nature of the time series. For example, the Hurst exponent (H) of a time series is 0.5, which suggests that the time series is Brownian, meaning that there is no meaningful association between observed historical data and anticipated future data[17]. A negative autocorrelation behavior in the time series is implied by a Hurst exponent value when it is less than 0.5. Stated otherwise, it is highly probable that a fall in this time series will be followed by an increase, or vice versa [18]. The time series has a significant propensity to return to its long-term mean value when the value is closer to zero. In contrast, a persistent time series will most likely show a correlation between increases in values and short-term increases or decreases in values and lead to subsequent short-term decreases[16], [19]. The trend is stronger the higher the H value. A Hurst exponent of 0.5 to 1.0 indicates persistent behavior of the time series[18], [19].

2.3.3 Empirical Orthogonal Function

The Empirical Orthogonal Function (EOF), also commonly referred to as Principal Component Analysis (PCA), is an incredibly effective statistical approach widely used in atmospheric, oceanic, and climate science for compressing data and reducing dimensionality[20]. In other words, possible spatial modes of variability (patterns of variability) in climate studies can often be studied by EOF analysis. This technique decomposes the time series dataset into spatial and temporal components, to get a better understanding of the variability with minimal modes required[21]. In a space function, the eigenvectors are composed of several orthogonal space modes, each of which is mutually independent.[22]. A time coefficient defines the projection space modes over time as a time function.[22]. The variance contribution rate reveals the characteristics of spatial and temporal variability.

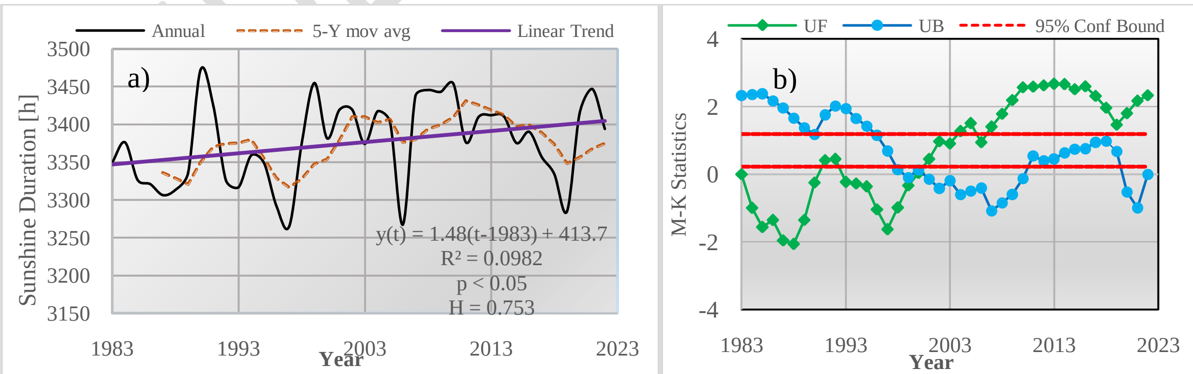
2.3.4 Correlation and Partial Correlation Analysis

Correlation analysis is a statistical technique that determines whether there is a relationship between two different datasets/variables, as well as the strength of the relationship [22]. For the present study, the Pearson correlation coefficient was calculated to identify whether different metrological time series datasets were correlated and how strong the correlation might be. If there is a linear association between a metrological element and different influencing factors, then the partial correlation analysis method can be used to determine whether the two different metrological elements are correlated by excluding the mutual interference of other influencing factors. Hence, the partial correlation analysis method was used to determine the degree of linear association between the sunshine duration and different influencing environmental parameters, such as wind speed, temperature, precipitation, relative humidity, and cloud cover.

2.4 Results and Analysis

2.4.1 Spatiotemporal Characteristics of Annual Variation of Sunshine Duration

Variation of SD across the kingdom between 1983 and 2022is shown in Figure 2. Using linear regression and the M-K mutation test, this study examined the characteristics of annual trends and mutation tests of the SD over the past 40 years. The Hurst index (H) was also computed to determine whether the annual trend will be persistent in the future. During the past forty years, SD has been trending upward at a rate of 1.48 hy^{-1}, with a 95% confidence level. Based on the Hurst exponent (H = 0.753), the trend willcontinue in the future, as shown in Figure 2(a). The UF curve was below zero between 1991 and 2001, suggesting there was a statistically significant downward trend in SD during that time period as they were below confidence levels as shown in Figure 2(b). The UF curve remained positive from 2001 to 2022, indicating an upward trend in SD, and remained above the confidence level limit from 2007 to 2022, indicating statistical significance. In 2000, there was only one point of intersection between the UF and UB, and it was outside the confidence level limit, indicating no obvious but suspected mutation. Over the past forty years, Saudi Arabia has experienced an average monthly SD of 283 ± 18 hm^{-1}, according to SD data analysis. The spatial distribution of yearly mean SD has been shown in Figure 2(c). Based on the Figure, it is evident that most of the regions experienced an annual mean of SD between 3375 and 3754 hy^{-1}, with the exception of the southwest (the hilly regions of Asir, Jizan, and Al Bahah) and the middle-eastern part, such as the southern side of the Northern border; the eastern side of Riyadh; the Hail and Qassim regions; as well as the northern part of Eastern Province, where SD were between 3072 and 3375 hours in a year. To examine the presence of a trend and its magnitude at the spatiotemporal scale in Saudi Arabia, linear regression analysis was adopted for the present study. As is seen in Figure 2(d), there was the presence of a rising trend in SD in Saudi Arabia in various degrees. In general, most of the regions experienced an upward trend in SD in a range of 14.36 - 31.29 h/10a with a 95% confidence level ($p < 0.05$) except the southern part of the country, such as the southern part of Eastern Province; Madinah; Makkah, Al Bahah, Asir, Jizan, and Najran regions, where the decadal trend in SD was rising but statistically nonsignificant. In other words, the duration of sunshine increased at a rate of 1.4 – 3.1 hours every year in most of the regions in Saudi Arabia over the period, but the southern part of the country experienced a much lower rate in SD with only 5 minutes to 1 hour per year.



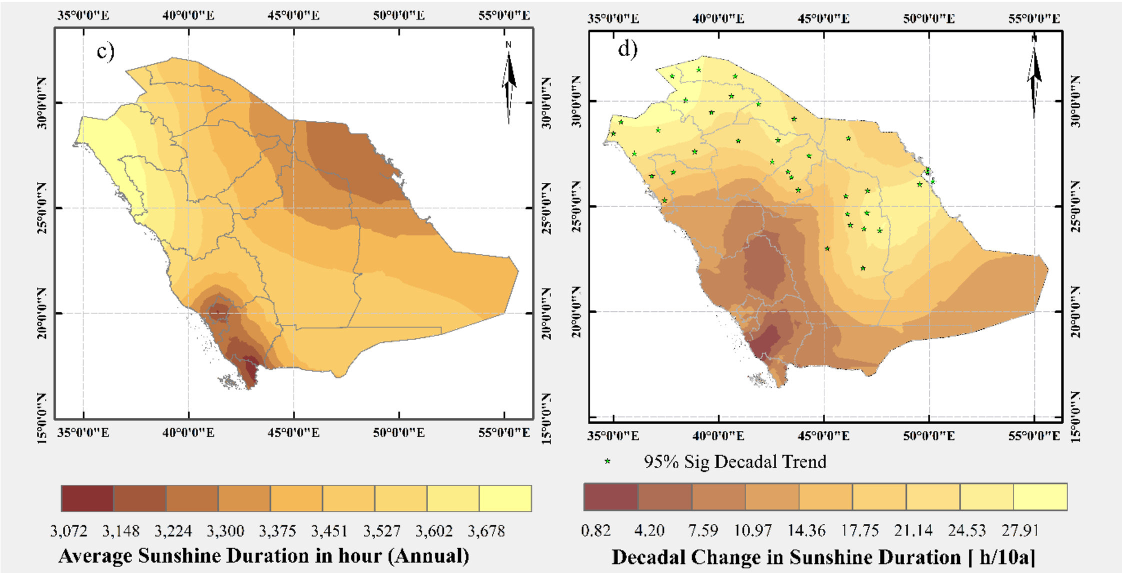


Figure 2: Annual Variation of SD in Saudi Arabia

2.4.2 Seasonal Variation of Sunshine Duration in Spring

The result obtained from the linear regression analysis of SD in Saudi Arabia during the past forty years in spring indicates that SD has been trending upward with 0.62 hy^{-1}in the country, with a 99% confidence level. Based on the Hurst exponent (H = 0.886), the trend willcontinue in the future, as shown in Figure 3(a). The UF curve stayednegative between 1985 and 1990, suggesting there was a statistically significant downward trend in SD during that period since they were below confidence levels as shown in Figure 3(b). The UF curve remained positive from 1990 onward, indicating an upward trend in SD, and remained above the confidence level limit from 2003 to 2022, indicatingstatistical significance. In 2000, there was only one point of intersection between the UF and UB, and it was outside the confidence level limit, indicating no obvious but suspected mutation. Over the past forty years, Saudi Arabia has experienced an average SD of 289 ± 24hm^{-1}, according to SD data analysis. The spatial distribution of meanmonthly SD in spring has been shown in Figure 3(c). Based on the Figure, it is evident that most of the regions experienced a mean monthly duration of sunshine between 262 and 314 hours, with the exception of the middle-eastern part (eastern part of Riyadh and northern part of the Eastern Province regions), where a mean monthly duration sunshine was in a range of 236-262 hours. Results obtained from the linear regression analysis are presented in Figure 3(d). From the Figure, it appears that there was a presence of a rising trend in SD in Saudi Arabia in various degrees during the spring over the period. In general, most of the regions experienced an upward trend in SD in a range of 3.94–7.03 h/10a with a 95% confidence level ($p < 0.05$) except the southern part of the country, such as the southern part of Eastern Province; Madinah; Makkah, Al Bahah, Asir, Jizan, and Najran regions, where the decadal trend in SD was also rising at a rate of 7 – 9.5 h/10a. In other words, in spring, the duration of sunshine increased at a rate of 23 – 42 minutes/month every year in most of the regions in Saudi Arabia over the period, but the southern part of the country experienced a much higher rate in SD with 42 minutes to almost 1 hour per month in every year.

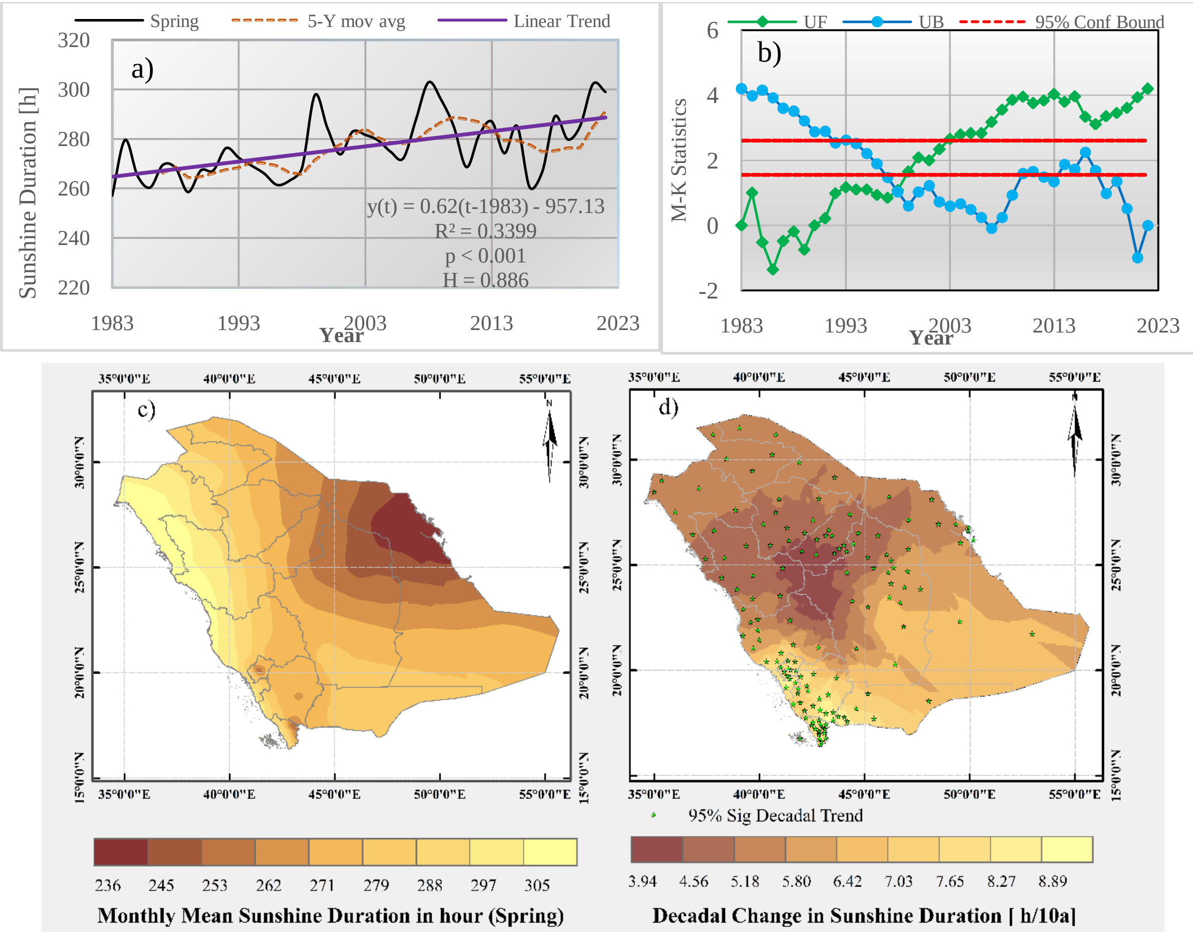


Figure 3: Variation of SDin Saudi Arabia during the Spring Season

2.4.3 Seasonal Variation of Sunshine Duration in Summer

The result obtained from the linear regression analysis of SD in Saudi Arabia during the past forty years in summer indicates that there has been a downward trend in SD with - 0.22 hy^{-1}in the country, with a 90% confidence level. Based on the Hurst exponent (H = 0.896), the trend will continue in the future, as shown in Figure 4(a). The UF curve stayed positive between 1989 and 2006, suggesting there was a statistically significant upward trend in SD during that time period since they were above theconfidence levels as shown in Figure 4(b). The UF curve remained negative from 2008 onward, indicating a downward trend in SD, and remained below the confidence level limit from 2010 to 2022, indicating statistical significance. Between 2008 and 2009, there was only one point of intersection between the UF and UB, and it was within the confidence level limit, indicating mutation occurred at that time. Over the past forty years, Saudi Arabia has experienced an average SD of 318 ± $39hm^{-1}$, according to SD data analysis. The spatial distribution of monthly mean SD in summer has been shown in Figure 4(c). Based on the Figure, it is evident that most of the regions experienced a monthly mean duration of sunshine between 282 and 367 hours, with the exception of the southwestern part (Jizan and Asir regions), where the mean monthly duration of sunshine was in a range of 239-282 hours. Results obtained from the linear regression analysis are presented in Figure 4(d). From the Figure, it appears that there was a presence of a falling trend in SD in Saudi Arabia in various degrees during the summer over the period. In general, most of the regions experienced adownward trend in SD in a range of -6.74 – 0.00 h/10a, except the northwestern part of the country, such as Tabuk andJawf regions, where the decadal trend in SD was rising at a rate of 0.0 – 3.33 h/10awith a 95% confidence level ($p < 0.05$). In other words, in summer, the duration of sunshine decreasedat a rate of 40 – 0.0 minutes/month every year in most of the regions in Saudi Arabia over the period, but the northern part of the country experienced a rising trend in SD with 0-20 minutes per month in every year.

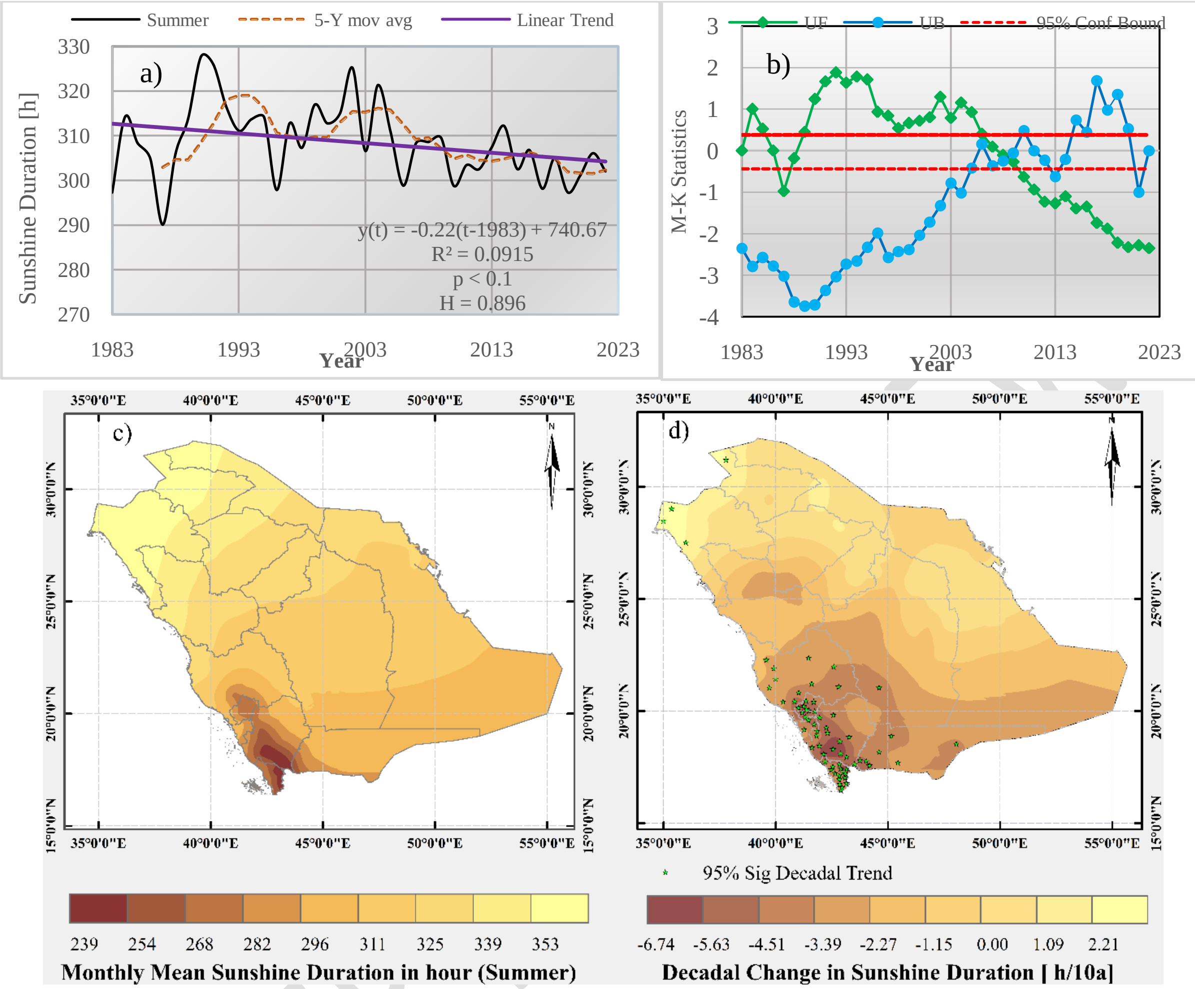


Figure 4: Variation of SD in Saudi Arabia during the Summer Season

2.4.4 Seasonal Variation of Sunshine Duration in Autumn

The result obtained from the linear regression analysis of SD in Saudi Arabia during the past forty years in autumn indicates that there has been anupward trend in SD with 0.03 hy^{-1}in the country, but statistically nonsignificant. Based on the Hurst exponent (H = 0.544), the trend will continue in the future, as shown in Figure 5(a). The UF curve stayed negative between 1993 and 2003, suggesting there was a statistically significant downward trend in SD during that time period since they were below theconfidence levels as shown in Figure 5(b). The UF curve remained positive from 2003 onward, indicating anupward trend in SD, and remained above the confidence level limit from 2008 to 2022, indicating statistical significance. Between 2005 and 2007, there weremultiple points of intersection between the UF and UB, and it was within the confidence level limit, indicating mutation occurred at that time. Whereas other intersection points between the UF and UB curves were found in the years 2003, 2017, 2019, and 2022,indicating no obvious but suspected mutation. Over the past forty years, Saudi Arabia has experienced an average SD of 281 ± 16hm^{-1}, according to SD data analysis. The spatial distribution of monthly mean SD in autumn has been shown in Figure 5(c).Based on the Figure, it is evident that most of the regions experienced a monthly mean duration of sunshine between 290 and 315 hours, with the exception of the southwestern part (Jizan and Asir regions), where the mean monthly duration of sunshine was in a range of 269-290 hours.Results obtained from the linear regression analysis are presented in Figure 5(d).From the Figure, it appears that there was a presence of a falling trend in SD in Saudi Arabia in various degrees during the summer over the period. In general, most of the regions experienced arising trend in SD in a range of 0.0 – 3.75 h/10a, except the southwestern part, such as the Asir andJizan regions, and southeastern part, like the southeastern part of the Eastern Province, where the decadal trend in SD was declining at a rate of -4.34 – 0.0 h/10a. Although the trend in SD in Saudi Arabia during the autumn was not statistically significant ($p > 0.1$), the duration of sunshine increased at a rate of 22 – 0.0 minutes/month every year in most of the regions in Saudi Arabia over the period, but the southeastern and southwestern corners of the country experienced a falling trend in SD with 0-26 minutes per month in every year.

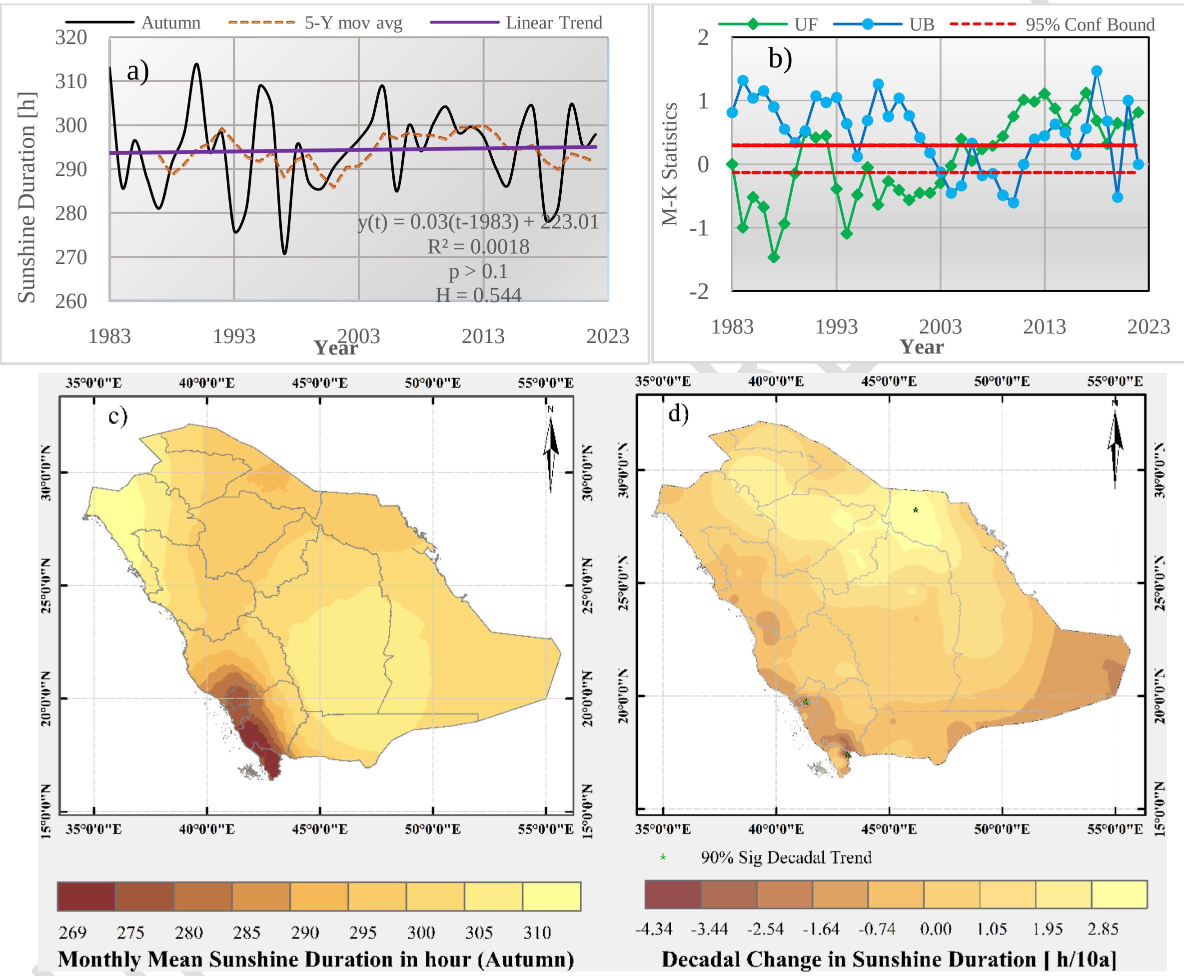


Figure 5: Variation of SD in Saudi Arabia during the Autumn Season

2.4.5 Seasonal Variation of Sunshine Duration in Winter

The result obtained from the linear regression analysis of SD in Saudi Arabia during the past forty years in winter indicates that there has been an upward trend in SD with 0.26 hy^{-1}in the country, with a 95% confidence level. Based on the Hurst exponent (H = 0.866), the trend will continue in the future, as shown in Figure 6(a). The UF curve stayed negative between 1988 and 2006, suggesting there was a statistically significant downward trend in SD during that time period since they were below theconfidence levels as shown in Figure 6(b). The UF curve remained positive from 2007 onward, indicating anupward trend in SD, and remained above the confidence level limit from 2009to 2022, indicating statistical significance. In 2005, there was only one point of intersection between the

UF and UB, and it was beyond the confidence level limit, indicating there was no obvious but suspected mutationthat occurred at that time.Over the past forty years, Saudi Arabia has experienced an average of 244 ± 38 hours of sunshine per month, according to SD data analysis. The spatial distribution of monthly mean SD in autumn has been shown in Figure 6(c). Based on the Figure, it is evident that during the winter, most of the regions experienced a mean monthly duration of sunshine between 243 and 279 hours, with the exception of the middle to the northeastern part, such as Riyadh, Northern Border, Hail, Jawf, and Qassim, where the mean monthly duration of sunshine was in a range of 215-243 hours.Results obtained from the linear regression analysis are presented in Figure 6(d).From the Figure, it appearsthat there was a presence of a rising trend in SD in Saudi Arabia in various degrees during the winter over the period.In general, the middle to the northern part of the country experienced arising trend in SD in a range of 1.14 – 2.58 h/10a,whereasfrom the middle to the southern part, the decadal trend in SD was also rising at a higher rate than the other side with2.58 – 4.35h/10a. In other words, during the winter from the middle to the south-west side of the country experienced a statistically significant rising trend in SD with arange of15.5 – 26.1 minutes/month every year in SaudiArabia over the period, whereas the opposite side experienced a rising trend in SD with 6-15.5 minutes per month every year

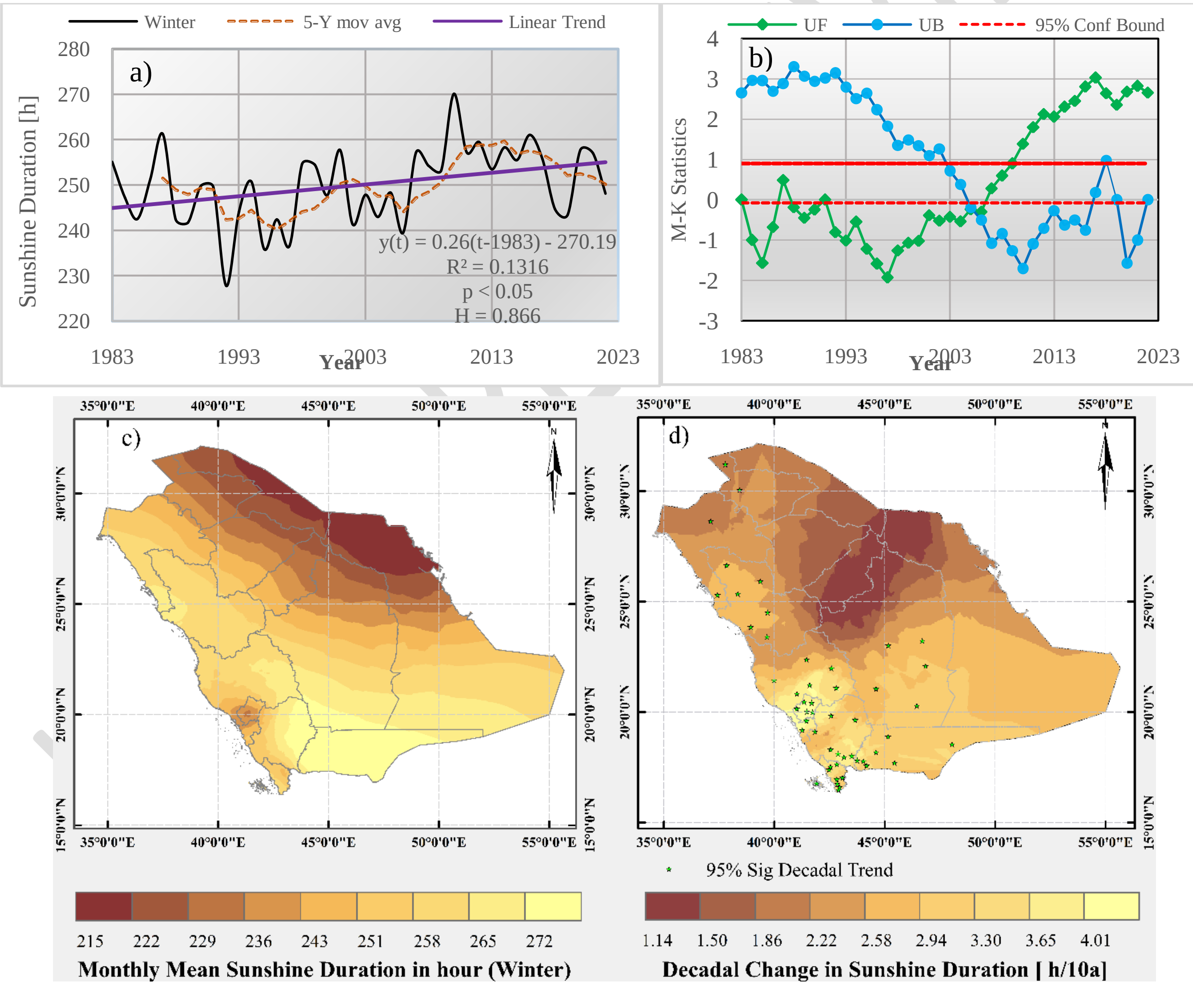


Figure 6: Variation of SD in Saudi Arabia during the Winter Season

2.4.6 EOF Analysis of Sunshine Duration in Saudi Arabia

Anomalies of annual SD are computed by EOF once the decomposition of the dataset is done. Results, such asexplained variance and cumulative variance,obtained from the EOF analysis for different modes are presented in Table 1. It appears from the table that the cumulative sum of the explained variances for the first six EFO modes is 87%. Due to passing the satisfying criteria of the north significance test, the first two modes were considered for analysis in the present study.

Table 1: Variance of Different EOF Modes

EOF Mode	Explained Variance	Cumulative Variance
PC1	58%	58%
PC2	17%	75%
PC3	4%	79%
PC4	4%	83%
PC5	2%	85%
PC6	2%	87%

On the basis of the presented datain the table, it is evident that the experience variance of the first EOF mode is much higher than the other modes with 57%. From Figure 7a, it appears that the eigenvectors are positive for the first EOF mode, which implies that there is either a uniform rising or falling trend insunshine duration across the country. More specifically the trend will follow a consistent pattern.Primarily concentration of the most significant positive centersis located in the Al Bahah, Asir, and Najran regions, which means severe changes are most likely to occur in these areas as compared to the other regions. From Figure 7b it appears that the anomalies (time coefficient) were negative between 1983 and 1998 but the eigenvector from the first EFO mode is positive across the country, which indicates that there was a decline in sunshine duration across the country during that period. Whereas, from 2000 onward the country experienced an upward trend in SD because of the eigenvector as well as the anomalies during that time frame both of them were positive. 1999 and 2015, which implies that during that period there was an increasing trend in SDS radiation across the country. The results obtained from the EOF first mode comply with the spatiotemporal characteristics of the annual variation of SD.

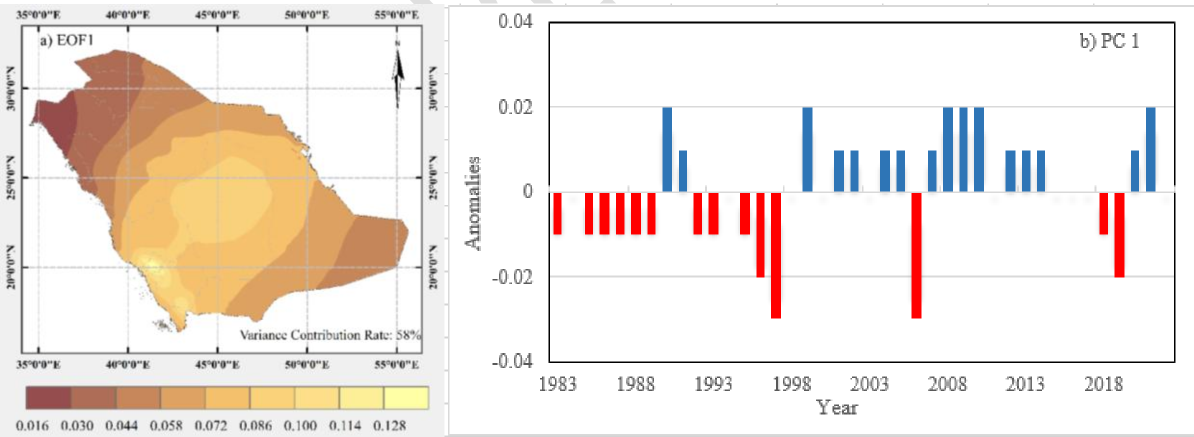


Figure 7: Spatiotemporal Variation of SD in Saudi Arabia for EOF1

Based on the presented data in the table, the experience variance of the second EOF mode is 57%. According to Figure 7(a)space function of the second mode of EOF clearly shows that there was an opposite distribution of eigenvectorfrom north to south direction, and there is an imaginary line in the middle of the country from the Eastern Province to the Makkah region is split the positive and negative eigenvectors.Furthermore, negative eigenvectors located in the northern part of the country, such as the southern part of the Northern Border; Hail; Qassim; Riyadh; Eastern Province; and their adjoining areas, which implies that changes in SD in this part of the country are complex and most likely due to the latitude and terrain. However, positive values are concentrated in the Asir, Jizan, and

Al Bahah and the adjoining regions indicating the severity of changes in SD more in the aforementioned regions than other areas in the southern part. According to Figure 8b, during the years 1983-1996, the time coefficient was positive, which means there was a rising trend in SD in the southern part of the country, whereas the northern part of the countryexperienced a decline in SD during thatperiod.On the other hand, from 1997 onward the time coefficient was negative implying that. There was a rise in SD in the northern part of the country, but the opposite experienced a decrease in SD during that period.

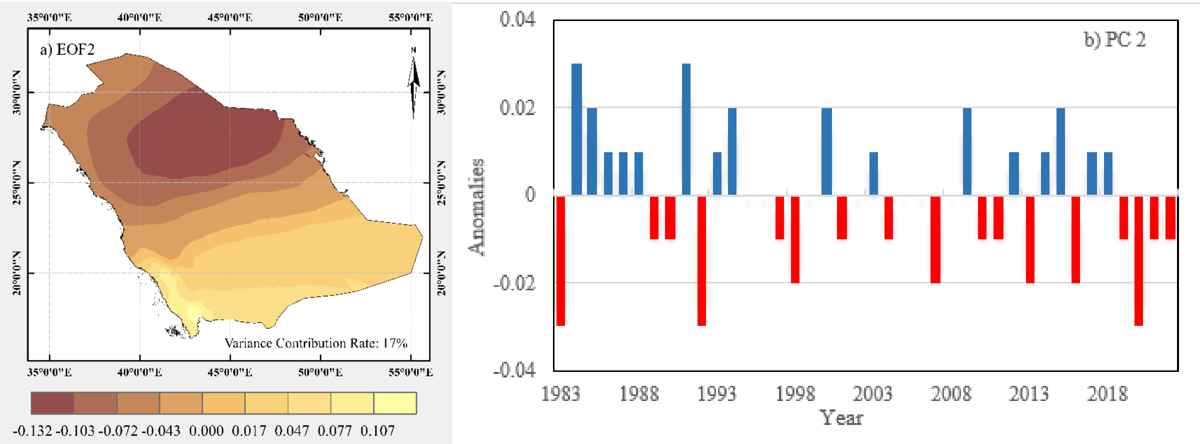


Figure 8: Spatiotemporal Variation of SDS Radiation in Saudi Arabia for EOF2

2.4.7 Influence of Potential Factors on the Variation of Sunshine Duration

Findings from a lot of scientific research conducted by different researchers show that changes in sunshine duration in a region are affected by metrological parameters, such as temperature, relative humidity, precipitation, wind speed, aerosol, cloud cover, and so on. Some of the aforementioned parameters, such as temperature; precipitation; relative humidity; cloud cover; and wind speed, were selected for the present study to analyze how they are acting as potential factors to influence the trend of sunshine duration in Saudia Arabia. Summary of the correlation coefficient between SD and the selected potential factors over the past forty years period across the country in different seasons.

Table 2:Correlation Coefficient between SD and Potential Factors

	Potential Factors				
Season	Temperature	Precipitation	R Humidity	Cloud Cover	Wind Speed
Spring	0.51****	-0.53***	-0.78***	-0.31	0.11
Summer	-0.31	-0.12	-0.48**	-0.70***	0.04
Autumn	-0.26	-0.36*	-0.77***	-0.72	0.26
Winter	0.36*	-0.65***	-0.75***	-0.68***	-0.15
Annual	0.37*	-0.43**	-0.67***	-0.32*	0.13

Note: *** p < 0.01; ** p < 0.05; * p < 0.10; and ns p>= 0.10

Based on the results presented in Table 02, it appears that there are statistically significant negative correlations of potential factors, like precipitation (95% CL); relative humidity (99% CL); and cloud cover (90% CL), with annual SD in Saudi Arabia, whereas there is a positive correlation between annual SD and temperature (90% CL). Relative humidity as a potential factor has a strong negative correlation with SD in all seasons. Precipitation is also another factor that is negatively affecting the changes in SD in all seasons, but the correlation was not statistically significant during the summer. During the summer and winter seasons, there is a statistically significant negative correlation between the SD and cloud cover, but from the statistical point of view, the correlation was not significant in other seasons. On the contrary, wind speed, as an influencing factor, has a positive correlation with SD but is statistically nonsignificant. The temperature has a statistically significant positive correlation with SD during the spring and winter seasons, whereas during the summer and autumn seasons, it has a negative correlation with SD, but is statistically nonsignificant.

Table 3: Partial Correlation Coefficient between SD and Potential Factors

	Potential Factors				
Season	Temperature	Precipitation	R Humidity	Cloud Cover	Wind Speed
Spring	-0.05	-0.03	-0.68***	-0.49***	0.16
Summer	-0.07	0.21	-0.56***	-0.65***	0.24*
Autumn	-0.08	-0.07	-0.55***	-0.37*	-0.05
Winter	0.10	-0.28	-0.55***	-0.27	-0.16
Annual	0.12	-0.12	-0.53***	-0.42**	0.06

Note: *** p < 0.01; ** p < 0.05; * p < 0.10; and ns p>= 0.10

The partial correlation analysis, presented in Table 3, shows that relative humidity and cloud cover have a statistically significant negative correlation with SD, whereas the other factors, such as temperature and wind speed have a positive correlation but are statistically nonsignificant. To have a better understanding of how potential factors, for instance, relative humidity and temperature have negative and positive correlations respectively, with SD, influence the SD across the country. As is seen in Figure 9 (b), there is a statistically significant negative correlation between most of the regions between SD and relative humidity.Almost all of the area is arid especiallydue to subtropical high-pressure systems and minimal cloud cover as a result the relative humidity is comparatively low and the concentration of fine dust in the air is much higher leading to a reduction in the atmospheric transparency, and because of that SD decreases in the middle part of the country. Although there is a positive correlation between SD and temperature, from the statistical point of view that is not significant as seen in Figure 9 (a).

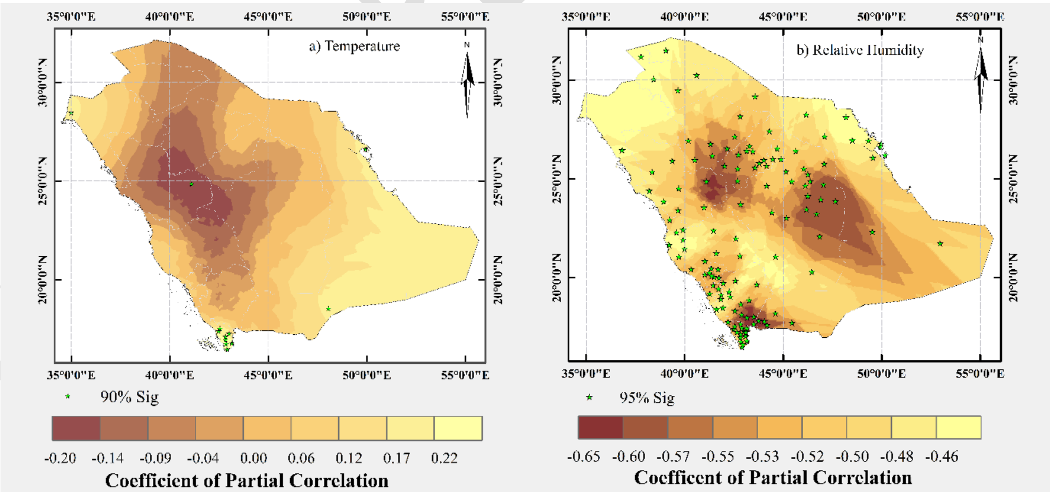


Figure 9: Spatial Distribution of Partial Correlation Between SD and Potential Factors

2.4.8 Temporal Variation of SD in Saudi Arabia

For the present study, Saudi Arabia's SD trend at different seasons as well as in different periods is determined using a linear regression model. A summary of the results obtained from the linear regression model to determine the magnitude and the statistical significance of the trend once the monthly SD was extracted from 1983 to 2022, is presented in Table 4.

Table 4: Temporal Variation of SD in Saudi Arabia

Season	1983-1990	1991-2000	2001-2010	2011-2020	1983-2022
Spring	-0.18	1.59	1.94*	0.62	0.62***
Summer	2.25	-0.93	-1.80**	-0.65	-0.21*
Autumn	0.55	-0.57	0.80	-0.68	0.03
Winter	-0.65	1.13	1.58	-0.94	0.26**
Annual	7.15	2.83	4.60	6.47	1.48**

Note: *** p < 0.01; ** p < 0.05; * p < 0.10; and ns p >= 0.10

During the period 1983-2022, sunshine duration was increased at a rate of 1.48 h $y^{-1}$with a 95% CL (p < 0.05)in Saudi Arabia. Generally, it is quite evident from the periodical analysis that there was a rising trend in SD, and the region experienced thehighest level SD trend in 1983-1990 with 7.15 hy^{-1}. From the table, it appears that during the first decade of the 21^{st} century (2001-2010), the trend in SD was statistically significant, for instance, sunshine duration increased at a rate of 1.94 hy^{-1} with 90% CL in the spring, but there was a decline in SD during the summer with -1.8 hy^{-1}. However, the trend of SD in Saudia Arabia during the last 18 years of the 20^{th} century and the 2^{nd} decade of the 21^{st} century was not significant from the statistical pointof view in the summer.

During the spring, the country experienced a rising trend in SD with 0.62 hy^{-1} which is also statistically significant with 99% CL. More specifically, the trend in SD across the country, increased at various degrees, except there was a downward trend in SD with -0.18hy^{-1} from 1983 to 1990. On the contrary, in general, there was a downward trend in SD at a rate of -0.21 hy^{-1} with 90% CL during the summer. In other words, the country experienced the highest level of statistically nonsignificant upward trend at a rate of 2.25 hy^{-1} in 1983-1990 during the summer, whereas in the next three decades, the region experienced a downward trend in SD. Results obtained from the periodical analysis, it appears that there was a fluctuation in the trend of SD during the autumn season, but overall the region experienced a rising trend in SD with 0.03 hy^{-1} which did not pass the statistical significance (p > 0.10). In winter, SD in the region increased at a rate of 0.26 $hy^{-1}$with 95% CL. From 1991 to 2010, the country experienced an upward trend in SD, but in 1983-1990 and 2011-2022, there was a downward trend in SD.

3. Discussion

Saudi Arabia has experienced an average SD of 283 ± 18 hm^{-1} and has been trending upward at a rate of 1.48 hy^{-1} with a 95% confidence level. Results obtained from the M-K mutation indicate the rising trend in SD and remained statistically significant from 2007 to 2022. From the spatial distribution of the annual mean of SD across the country, it appears that most of the regions experienced annual mean of SD between 3375 and 3754 hy^{-1}, except for the southwest (the hilly regions of Asir, Jizan, and Al Bahah) and the Middle Eastern part, such as the southern side of the Northern border; the eastern side of Riyadh; the Hail and Qassim regions; as well as the northern part of Eastern Province, where SD were between 3072 and 3375 hy^{-1}.Most of the regions experienced an upward trend in SD in a range of 14.36 - 31.29 h/10a with a 95% confidence level (p < 0.05) except the southern part of the country, such as the southern part of Eastern Province; Madinah; Makkah, Al Bahah, Asir, Jizan, and Najran regions, where the decadal trend in SD was rising but statistically nonsignificant.It is quite evident from the periodical analysis that there was a rising trend in SD, and the region experienced the highest level of trend in SD at a rate of 7.15 hy^{-1} from 1983 to 1990.

In winter, the average sunshine duration was 244 ± 38 hm^{-1} which is the lowest as compared to the other seasons, and there has been an upward trend in SD at a rate of 0.26 hy^{-1} with a 95% confidence level. According to the spatial analysis, most of the regions experienced a mean monthly SD between 243 and 279 hours, except for the middle to the northeastern part, such as Riyadh, Northern Border, Hail, Jawf, and Qassim, where the mean monthly sunshine duration was in a range of 215-243 hours. The middle to the northern part of the country experienced a rising trend in SD in a range of 1.14 – 2.58 h/10a, whereas from the middle to the southern part, the decadal trend in SD was also rising at a higher rate than the other side with 2.58 – 4.35 h/10a. According to the periodical analysis, the country experienced an upward trend in SD from 1991 to 2010, but in 1983-1990 and 2011-2022, there was a downward trend in SD.

In spring, the average sunshine duration was 289 ± 24 hm^{-1} which is 18% more than the average SD in winter, and the region experienced an upward trend in SD at a rate of 0.62 hy^{-1} with a 99% confidence level. From the spatial analysis, it is evident that most of the regions experienced mean monthly SD between 262 and 314 hours, except for the middle-eastern part (eastern part of Riyadh and northern part of the Eastern Province regions), where mean monthly sunshine duration was in a range of 236-262 hours. Most of the regions experienced an upward trend in SD in a range of 3.94 – 7.03 h/10a with a 95% confidence level ($p < 0.05$) except the southern part of the country, such as the southern part of Eastern Province; Madinah; Makkah, Al Bahah, Asir, Jizan, and Najran regions, where the decadal trend in SD was also rising at a rate of 7 – 9.5 h/10a.According to the periodical analysis, during the first decade of the 21st century, sunshine duration increased at a rate of 1.94 hy^{-1} with a 90% confidence level in the spring.

In summer, the country has experienced the highest level of SD with an average of 318 ± 39 hm^{-1} which is 30% more than the average SD in winter, and there has been a downward trend in SD at a rate of - 0.22 hm-^{1} in the country, with a 90% confidence level. Based on the periodical analysis,the country experienced a statistically nonsignificant upward trend at a rate of 2.25 hy^{-1} in 1983-1990, whereas in the next three decades, the region experienced a downward trend in SD. According to the spatial analysis, most of the regions experienced a monthly mean duration of sunshine between 282 and 367 hours, except for the southwestern part (Jizan and Asir regions), where the mean monthly sunshine duration was in a range of 239-282 hours. Results obtained from the linear regression analysis, most of the regions experienced a downward trend in SD in a range of -6.74 – 0.00 h/10a, except the northwestern part of the country, such as Tabuk and Jawf regions, where the decadal trend in SD was rising at a rate of 0.0 – 3.33 h/10a with a 95% confidence level ($p < 0.05$).

In autumn, the average SD was 281 ± 16 hm^{-1}, which is 15% higher than the average sunshine duration in winter, and there has been a statistically nonsignificantupward trend in SD with 0.03 hy^{-1}. Based on the result obtained from the periodical analysis, it is clear that there was a fluctuation in the trend of SD but did not pass the statistical significance ($p > 0.10$). based on the spatial distribution, most of the regions experienced a mean monthly sunshine duration between 290 and 315 hours, except for the southwestern part (Jizan and Asir regions), where the mean monthly sunshine duration was in a range of 269-290 hours. Results obtained from the linear regression analysis show that most of the regions experienced a rising trend in SD in a range of 0.0 – 3.75 h/10a, except the southwestern part, such as the Asir and Jizan regions, and southeastern part, like the southeastern part of the Eastern Province, where the decadal trend in SD was declining at a rate of -4.34 – 0.0 h/10a.

Results obtained from the influence of potential factors on SD in Saudi Arabia indicate that relative humidity as a potential factor has a strong negative correlation with SD in all seasons. Precipitation is also another factor that is negatively affecting the changes in SD in all seasons, but the correlation was not statistically significant during the summer. During the summer and winter seasons, there is a statistically significant negative correlation between the SD and cloud cover. On the contrary, wind speed, as an influencing factor, has a positive correlation with SD but is statistically nonsignificant. The temperature has a statistically significant positive correlation with SD during the spring and winter seasons. Almost all of the area is arid especially due to subtropical high-pressure systems and minimal cloud cover as a result the relative humidity is comparatively low and the concentration of fine dust in the air is much higher leading to a reduction in the atmospheric transparency, and because of that SD might decrease in the middle part of the country.

4. Conclusion

For the present study, the monthly data of SD and Cloud Cover (in percent) for the 147 geospatial locations in Saudi Arabia were extracted over 40 years, spanning from 1983 to 2022, from the SARAH-2.1 climate data record for solar radiation provided by the EUMETSAT. The influencing factors, such as precipitation, relative humidity, wind speed, and temperature, were extracted from The Prediction of Worldwide Energy Resources (POWER) project initiated by NASA. The present study aimed to explore the variability and availability of SD on the spatiotemporal scale at different seasons across the country over the period, as well as the influence of the potential factors on SD change, different statistical approaches, such as the linear regression, Hurst Exponent, M-K mutation test, Empirical Orthogonal Function, Correlation, and Partial correlation methods, were adopted. The findings from the study are as follows:Saudi Arabia has experienced an average SD of 283 ± 18 hm^{-1} and has been trending upward at a rate of 1.48 hy^{-1} with a 95% confidence level. The region experienced the highest level of trend in SD at a rate of 7.15 hy^{-1} from 1983 to 1990.In winter, the region has the SD in a range of 215-279 $hm^{-1}$with the lowest mean monthly SD of 244 ± 38 hm^{-1}, and there has been an upward trend in SD at a rate of 0.26 hy^{-1} with a 95% confidence level.In summer, the region has the SD in a range of 239-367 $hm^{-1}$with the highest mean monthly SD of 318 ± 39 hm^{-1}, and there has been a downward trend in SD at a rate of -0.22 hy^{-1} with a 90% confidence level.In spring, the region has the SD in a range of 236-314 $hm^{-1}$with the highest mean monthly SD of 289 ± 24 hm^{-1}, and there has been anupward trend in SD at a rate of 0.62 hy^{-1} with a 99% confidence level.In autumn, the region has an SD in a range of 269-315 $hm^{-1}$with a mean monthly SD of 281 ± 16 hm^{-1}, and there has been anupward trend in SD at a rate of 0.03 hy^{-1} with statistically nonsignificant. There was a decline in SD across the country between 1983 and 1998 according to EOF1, whereas from 2000 onward the country experienced an upward trend in SD. Relative humidity ($R = -0.53$, $p < 0.01$) and cloud cover($R = -0.42$, $p < 0.05$) as potential factors have a strong negative correlation with SD, whereas wind speed ($R = 0.06$, $p > 0.1$) and temperature ($R = 0.12$, $p > 0.1$) have a positive correlation with SD in the region.

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