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Temporal Variation of Sunshine Duration and Its Potential Affecting Factors with Emphasis on Saudi Arabia for the Period 1983-2022

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The rising trend in fossil fuel prices and the depletion of natural resource reserves in the future force the authority of any country to find a more sustainable option for energy sources, so that future energy demand can be ensured for sustainable development. Assessing the trend and availability of sunshine duration (SD) at a spatiotemporal scale and the effect of different metrological parameters on the SD change is crucial to ensure the efficient utilization of solar energy, support the growth of renewable energy systems, and contribute to a sustainable future. In Saudi Arabia, The average monthly SD is 283 ± 18 hm^{-1}, and there was a rising trend of SD that increased at a rate of 1.48 hy^{-1}

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with a 95% confidence level. Most of the regions experienced an annual mean of SD between 3375 and 3754 hy^{-1}, except for the southwest and the middle-eastern part where SD was between 3072 and 3375 hours in a year. The highest mean monthly SD was 318 ± 39 hm-1 during the summer season, but the trend of SD changes over the years was downward (-0.21 hy^{-1}). The mean monthly SD was lowest (244 ± 38 hm^{-1}) in the winter season, and the changing pattern of SD was on the rise at a rate of 0.26 hy^{-1} with a 95% confidence level. 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 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.

Keywords: Sunshine duration; solar energy; M-K mutation; hurst exponent; empirical orthogonal function; trend; variability.

1. INTRODUCTION

Renewable energy has gained increasing attention and support due to its potential to reduce environmental impacts and address the concern of fossil fuel usage, 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 rising trend in fossil fuel prices and the depletion of natural resource reserves in the future force the authority of any country to find a more sustainable option for energy sources, so that future energy demand can be ensured for sustainable development. In 2021, fossil fuels, especially burning oil, accounted for 60.89% of the total energy contributor to power generation in Saudi Arabia [3]. There was an announcement from the Saudi Arabian authority in March 2018 for the installation of solar power generation plants with a capacity of 200 GW by 2030 [4]. It is crucial to know the amount of energy that can be harnessed from the sun in a given area by installing solar plants and as well as optimizing the solar panel design (size and placement). Assessing the trend and availability of SD at a spatiotemporal scale, the effect of different metrological parameters on the SD change, and forecasting solar resources is crucial to ensure the efficient utilization of solar energy, support the growth of renewable energy systems, and contribute to a sustainable future.

Over the past several decades, many scientific studies have been conducted on the trend and variability of SD and its causes and effects. Findings from those studies, it is evident that there is a rising trend in SD in some parts (Iran [5], Poland [6], and others of the world, whereas a declining trend in SD is witnessed in some other countries, for instance, the USA, Austria [7], Japan [8], Germany [9], Western Europe [10], and so on. This changing pattern of SD may occur due to geographic location, altitude, influencing metrological parameters, climatic phenomena, and so on [11]. Therefore, studying the spatiotemporal characteristics of trend and variability of SD and how the influencing factors affecting its changes have great importance in the efficient utilization of solar energy, supporting the growth of renewable energy systems, climate change studies, and rational distribution of agricultural production.

Various methods are used to measure the available duration of sunlight during which the sun irradiates on the earth's surface above the threshold level of 120 W m^{-2} according to the World Metrological Organization [12,13]. 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, and is also 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 in Saudi Arabia from 1983 to 2022. It was also intended to assess the influence of the potential factors on SD change in the country during the period at different seasons. Different statistical approaches, such as the linear regression, Hurst Exponent, M-K mutation test, Empirical Orthogonal Function, Correlation, and Partial correlation methods, were adopted for the present study.

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 on the 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 Fig. 1. In the Asir region, inland mountains rise to over 2,700 m in elevation [13]. 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 Asir province, 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 blow over the country and consequently, almost all of the area is arid especially due to subtropical high-pressure systems and minimal cloud cover, temperatures vary widely by region and season [14]. 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 [15]. 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 [16].

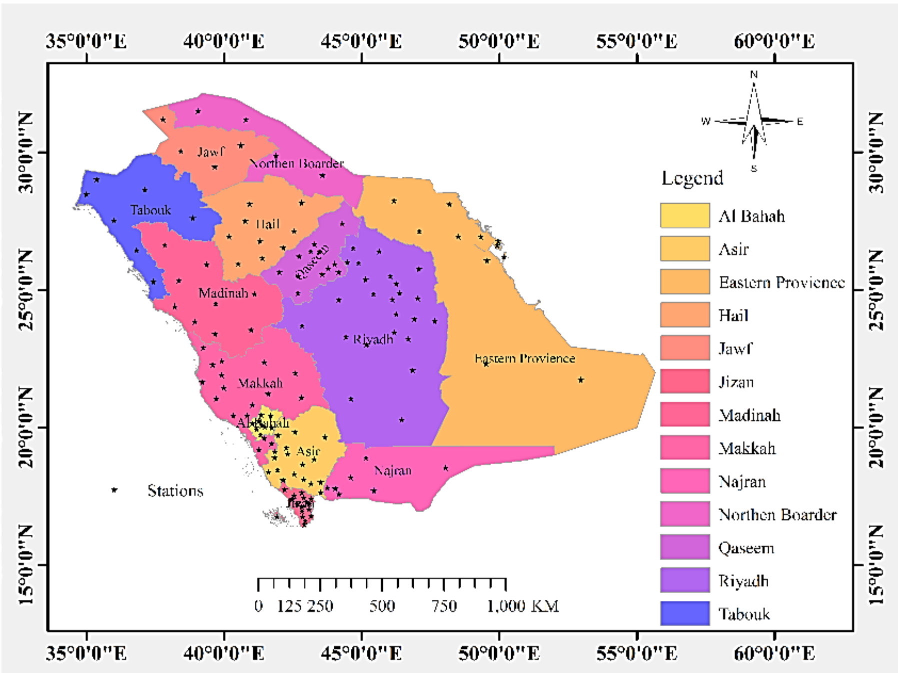

Fig. 1. Maps of Saudi Arabia

2.2 Data

EUMETSAT provides the SARAH-2.1 climate data record for solar radiation, which encompasses cloud, irradiance, and sunshine duration parameters [17]. According to the climate data validation report of CM SAF, the mean absolute difference (MAD) and standard deviation of monthly sum SD were 16.6 and 21.3 hours respectively [18]. 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 [17,19]. 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 metrological factors, such as precipitation, relative humidity, wind speed, and temperature, were derived from MERRA-2, which is a version of the Goddard Earth Observing System (GEOS) of NASA, with a spatial resolution of 0.625º X 0.5º during the period between 1983 and 2021 *("https://power.larc.nasa.gov/data-access-viewer")* [20]. 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 [21]. 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 [22–24]. 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 [21]. 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 [25]. For the present study, the linear regression method was adopted to determine the trend slope of SD at different seasons with statistical significance between 1983 and 2022. Whereas the M-K mutation test was used to examine whether the mutation occurred at different seasons during the period in Saudi Arabia.

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. In 1951, an eminent British hydrologist named H.E. Hurst 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 stationariness [26–28]. Currently, the Hurst exponent (H) is 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, if the H value of a time series is 0.5, it suggests that the time series is Brownian, meaning that there is no meaningful association between observed historical data and anticipated future data [28]. 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 [29]. 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 [27,30]. 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 [29,30]. For the present study, the Hurst index (H) was also computed to determine whether the trend of SD will be persistent in the future.

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 [31]. 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 [32]. In a space function, the eigenvectors are composed of several orthogonal space modes, each of which is mutually independent [11]. A time coefficient defines the projection space modes over time as a time function [11]. 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 [10]. 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.

3. RESULTS

3.1 Spatiotemporal Characteristics of Annual Variation of Sunshine Duration

Using linear regression and the M-K mutation test, this study examined the characteristics of annual trends and mutation tests of the SD in the kingdom between 1983 and 2022. The Hurst index (H) was also computed to determine whether the annual trend will be persistent in the future. As shown in Fig. 2(a), the country experienced an upward trend in SD at a rate of 1.48 hours per year (hy^{-1}), passing the significance test ($p < 0.05$). Moreover, this rising trend will continue in the future, as the result obtained from the Hurst exponent (H = 0.753). From Fig. 2(b), there was a downward trend in SD between 1991 and 2001 as the UF curve was negative and stayed beyond the 95% confidence bound which indicates that the trend was statistically significant. Whereas, the region experienced a statistically significant ($p < 0.05$) rising trend in SD since 2007 as the curve was positive and stayed above the confidence bound. In addition, there was only one intersection point between the UF and UB curves, and it was outside the confidence level limit, which implies that there might be a mutation occurred in 2000.

From the result obtained from the monthly mean SD across the country between 1983 and 2022, the average monthly SD of 283 ± 18 hours/month (hm^{-1}) in Saudi Arabia. The kriging method was adopted for spatial distribution map preparation for the present study. The spatial distribution of yearly mean SD has been shown in Fig. 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}, 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 was 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 Fig. 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/10y 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.

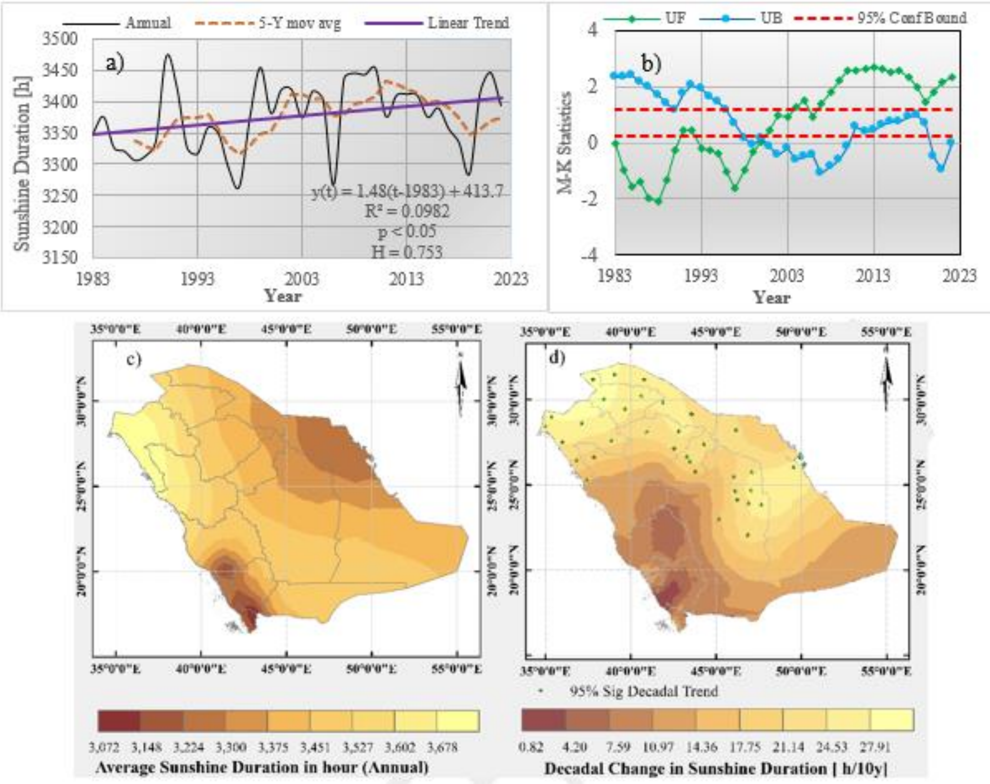

Fig. 2. Annual Variation of SD in Saudi Arabia a) Sunshine duration (h) overlayed with five-year (5 - Y) moving average (red dotted) and linear trend (purple). b) M-K statistics UF (green), UB (blue), and the region between dotted red lines is 95% conf bond. c) Annual mean SD in hour d) Decadal trend in SD (h/10y)

3.2 Seasonal Variation of Sunshine Duration in Spring

The result obtained from the linear regression analysis of SD during the spring season in Saudi Arabia shows that the trend slope of SD was 0.62 hy^{-1} with a 99% confidence level. Based on the Hurst exponent (H = 0.886), the region will experience an inclination in SD changes in the spring season as the past forty years period, as shown in Fig. 3(a). In other words, the country will experience an upward trend in SD during the spring season in the future because the Hurst exponent is greater than 0.5. However, as the result obtained from the M-K mutation test, the region experienced a declining trend in SD and passed the significance test between 1985 and 1990 during the spring season as the UF curve stayed in the negative zone and beyond the confidence levels as shown in Fig. 3(b). Furthermore, SD changes during the spring season from 2003 to 2022 experienced a rising trend and passed the significance test as the UF curve remained positive above the confidence level limit. There might be a mutation that occurred in 2000 as the UF and UB curves intersected outside the confidence level limit in that year.

In spring, the mean monthly SD in Saudi Arabia was 289 ± 24 hm^{-1} between 1983 and 2022 according to SD data analysis. The spatial distribution of the mean monthly SD in spring has been shown in Fig. 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, except 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 Fig. 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/10y 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/10y. 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.

3.3 Seasonal Variation of Sunshine Duration in Summer

As is seen in Fig. 4(a), during the summer season the duration of sunshine in Saudi Arabia reduced at a rate of - 0.22 hy^{-1} over the past forty-year period (1983-2022). From the linear regression analysis, it appears that the downward trend in SD during summer was statistically significant ($p < 0.1$). Moreover, Based on the Hurst exponent analysis for the summer season, it appears that the value of H (H = 0.896) was greater than 0.5 which implies that the changing trend of SD in summer most probably be declining in the future as the past period. Whereas, the results obtained from the M-K mutation test for the summer season were presented in Fig. 4(b). As is seen from the Figure, the changing pattern of SD in summer was rising as the UF curve was positive and stayed above the 95% confidence bound between 1989 and 2006 implying that the changing pattern was statistically significant. However, the changes in SD declined in the summer from 2010 onward as the UF curve remained negative and below the confidence interval limit, indicating the downward trend was statistically significant. Between 2008 and 2009, the UF and UB curves intersected within the confidence level limit, indicating the mutation point.

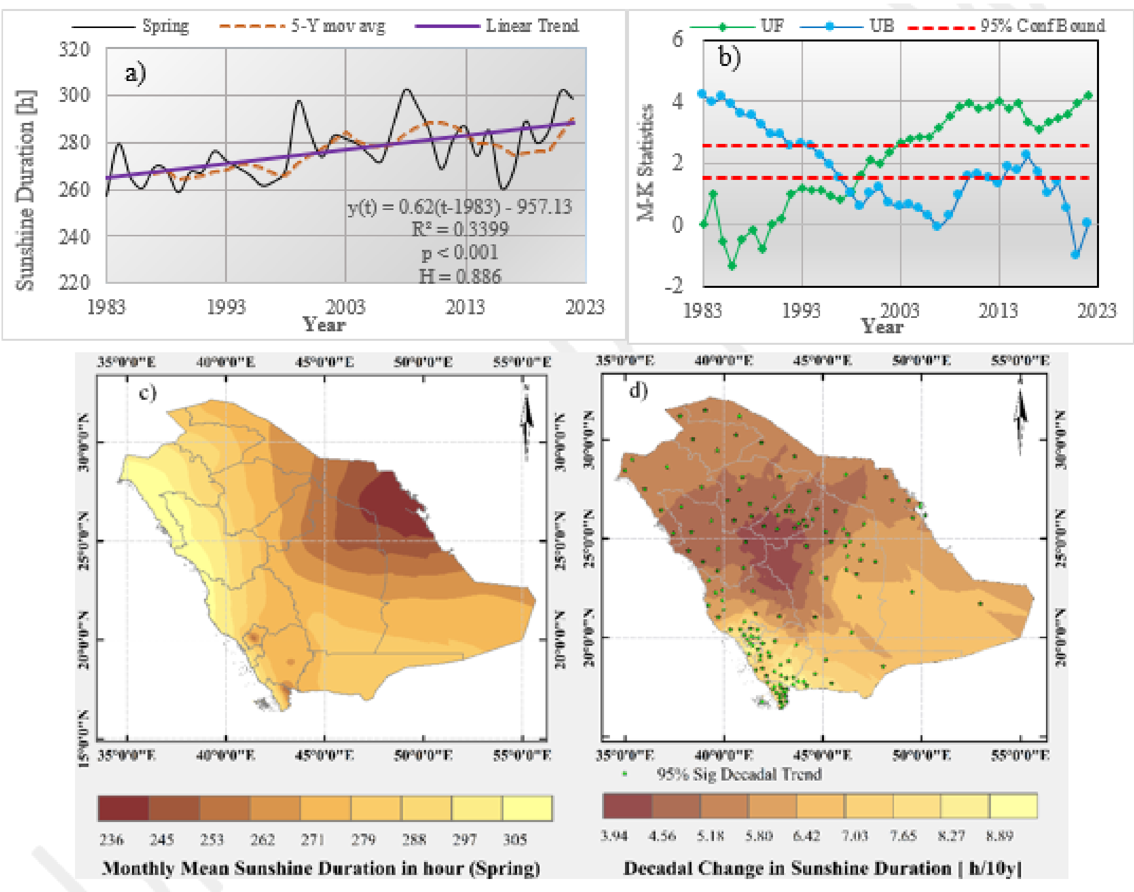

Fig. 3. Variation of SD in Saudi Arabia during the Spring Season a) Sunshine duration (h) overlayed with five-year (5 - Y) moving average (red dotted) and linear trend (purple). b) M-K statistics UF (green), UB (blue) region between dotted red lines is 95% conf bond. c) Monthly mean SD in hours during spring d) Decadal trend in SD (h/10y)

In summer, the monthly mean SD was 318 ± 39 hm^{-1} during the period (1983-2022) from the seasonal data analysis for the period. Due to the lower solar angle, energy received from the sun will be more intense which may cause the longer SD during the summer season. The spatial distribution of monthly mean SD in summer has been shown in Fig. 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, except for 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 Fig 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 season over the period. In general, most of the regions experienced a downward trend in SD in a range of -6.74 – 0.00 h/10y, except the northwestern part of the country, such as the Tabuk and Jawf regions, where the decadal trend in SD was rising at a rate of 0.0 – 3.33 h/10y with a 95% confidence level ($p < 0.05$). In other words, in summer, the duration of sunshine decreased at 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.

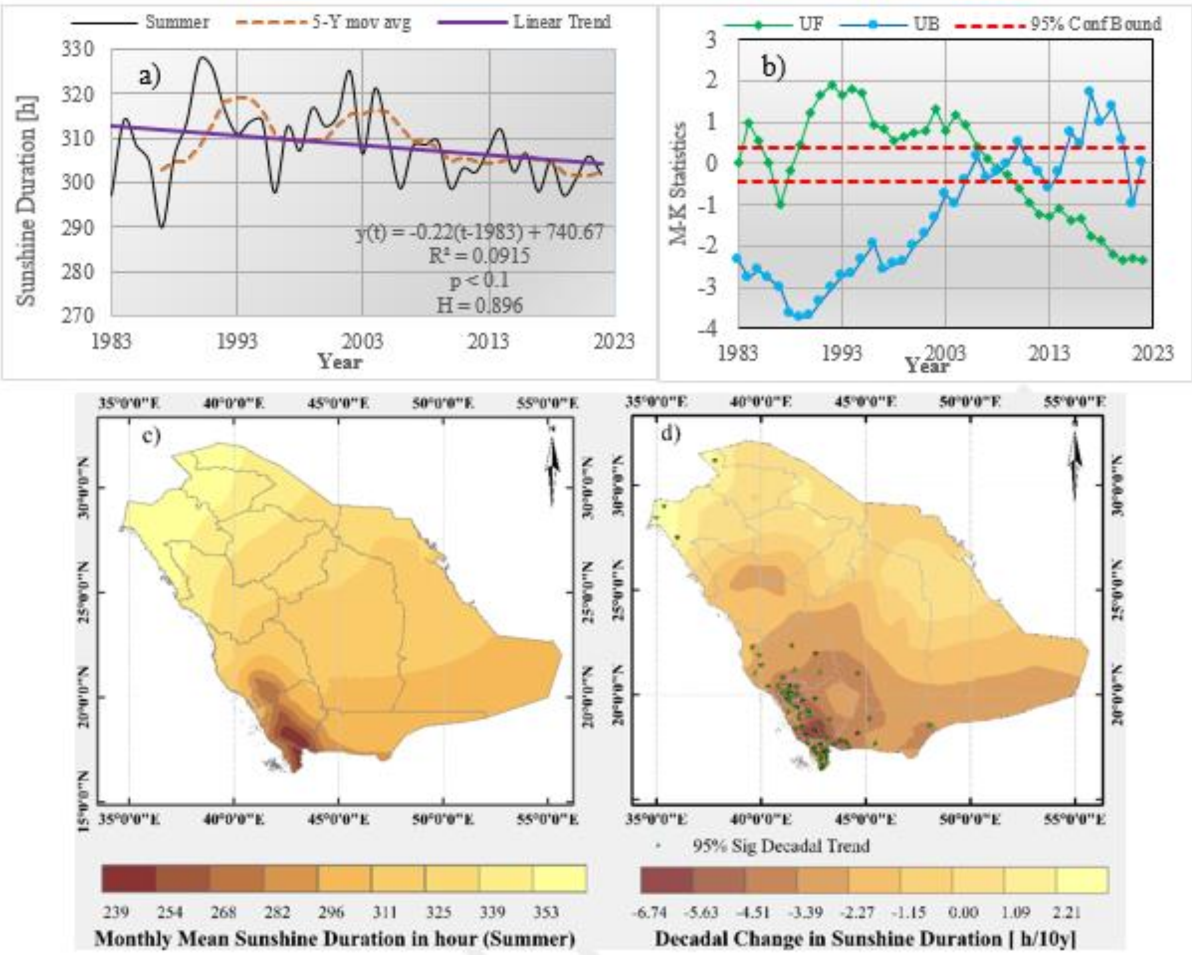

Fig. 4. Variation of SD in Saudi Arabia during the Summer Season a) Sunshine duration (h) overlayed with five-year (5 - Y) moving average (red dotted) and linear trend (purple). b) M-K statistics UF (green), UB (blue) region between dotted red lines is 95% conf bond. c) Monthly mean SD in hours during summer d) Decadal trend in SD (h/10y)

3.4 Seasonal Variation of Sunshine Duration in Autumn

The results obtained from the linear regression and Hurst exponent for the time series data set for autumn are presented in Fig. 5(a). From the figure, it appears that the changing pattern of sunshine duration in the autumn season was not very significant (trend slope 0.03 hm^{-1} and $p > 0.1$) as the results obtained from the linear regression analysis of SD during the past forty years period (1983-2022). The Hurst exponent ($H = 0.544$) was just above 0.5 implying that there is a very weak correlation between the past and future changing pattern of SD in this region during autumn. Results obtained from the M-K mutation test for the autumn season are presented in Fig. 5(b). The changing pattern of SD in the autumn season from 1993 to 2003 was downward and passed the significance test as the UF curve stayed in the negative zone below the confidence limit. Whereas, from 2008 onward, the UF curve remained in the positive zone above the confidence limit implying that there was a rising pattern in the SD change during the summer season in Saudi Arabia. Between 2005 and 2007, there were multiple points of intersection between the UF and UB, and it was within the confidence level limit, indicating mutation occurred during those years. 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.

In Saudi Arabia, the mean monthly SD was 281 ± 16 hm^{-1} in autumn during the period 1983-2022 according to the results obtained from SD analysis. The spatial distribution of monthly mean SD in autumn has been shown in Fig. 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, except for 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 Fig. 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 a rising trend in SD in a range of 0.0 – 3.75 h/10y, 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/10y. 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.

3.5 Seasonal Variation of Sunshine Duration in Winter

The result obtained from the linear regression analysis of SD in Saudi Arabia, depicted in Fig. 6(a), indicates that there was a rising trend (0.26 hy^{-1}) in the changing pattern of SD in the winter season during the period 1983-2022, and passed the significance test ($p < 0.05$). In addition, there is a strong correlation between the past and future trends in SD during the winter season because the Hurst exponent ($H = 0.866$) for SD in the winter season is closer to 1. Whereas, results obtained from the M-K mutation test for the winter season are presented in Fig. 6(b). From the figure it appears that the UF curve stayed in the negative zone below the confidence limit between 1988 and 2006, suggesting that the region experienced a statistically significant trend in SD changes in the winter season during that period. However, from 2009 onward, the changing pattern of SD in the winter season across the country was upward as the UF curve stayed in the positive zone above the confidence level during that period. 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 mutation that occurred at that time.

In winter, Saudi Arabia has experienced a monthly mean SD of 244 ± 38 hours per month, according to SD data analysis. Due to the higher solar angle, energy received from the sun will be less intense this time of the year which may cause the lesser SD during the winter season. The spatial distribution of monthly mean SD in autumn has been shown in Fig. 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, except for 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 Fig. 6(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 winter over the period. In general, the middle to the northern part of the country experienced a rising trend in SD in a range of 1.14 – 2.58 h/10y, 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/10y.

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 a range of 15.5 – 26.1 minutes/month every year in Saudi Arabia over the period, whereas the opposite side experienced a rising trend in SD with 6-15.5 minutes per month every year.

3.6 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 as explained 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 EOF 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.

Based on the presented data in the table, it is evident that the experience variance of the first EOF mode is much higher than the other modes with 58%. From Fig. 7(a), it appears that the eigenvectors are positive for the first EOF mode, which implies that there is either a uniform rising or falling trend in sunshine duration across the country. More specifically the trend will follow a consistent pattern. Primarily concentration of the most significant positive centers is 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 Fig. 7(b) it appears that the anomalies (time coefficient) were negative between 1983 and 1998 but the eigenvector from the first EOF 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 were positive. The results obtained from the EOF first mode comply with the spatiotemporal characteristics of the annual variation of SD.

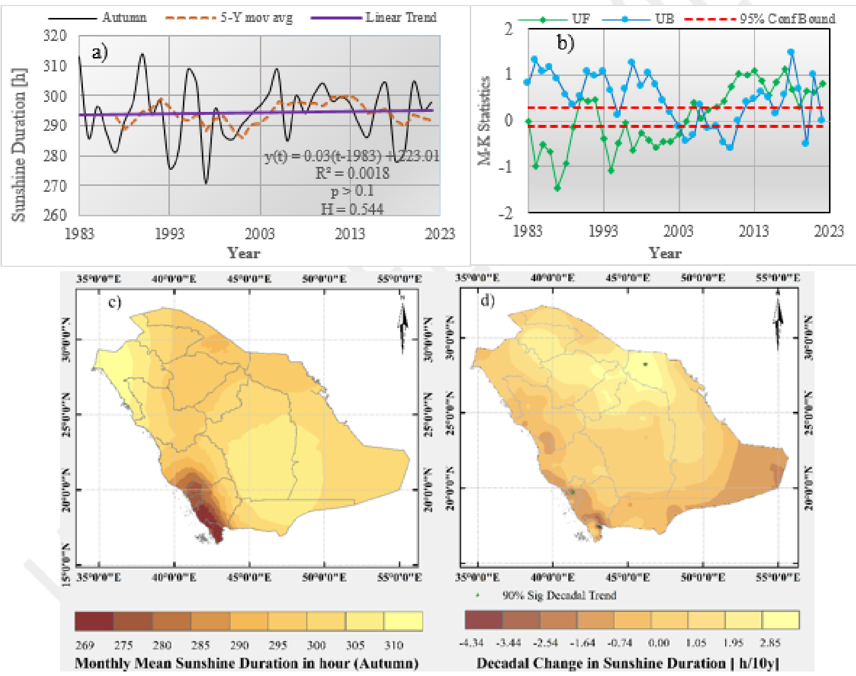

Fig. 5. Variation of SD in Saudi Arabia during the Autumn Season a) Sunshine duration (h) overlayed with five-year (5 - Y) moving average (red dotted) and linear trend (purple). b) M-K statistics UF (green), UB (blue) region between dotted red lines is 95% conf bond. c) Monthly mean SD in hours during autumn d) Decadal trend in SD (h/10y)

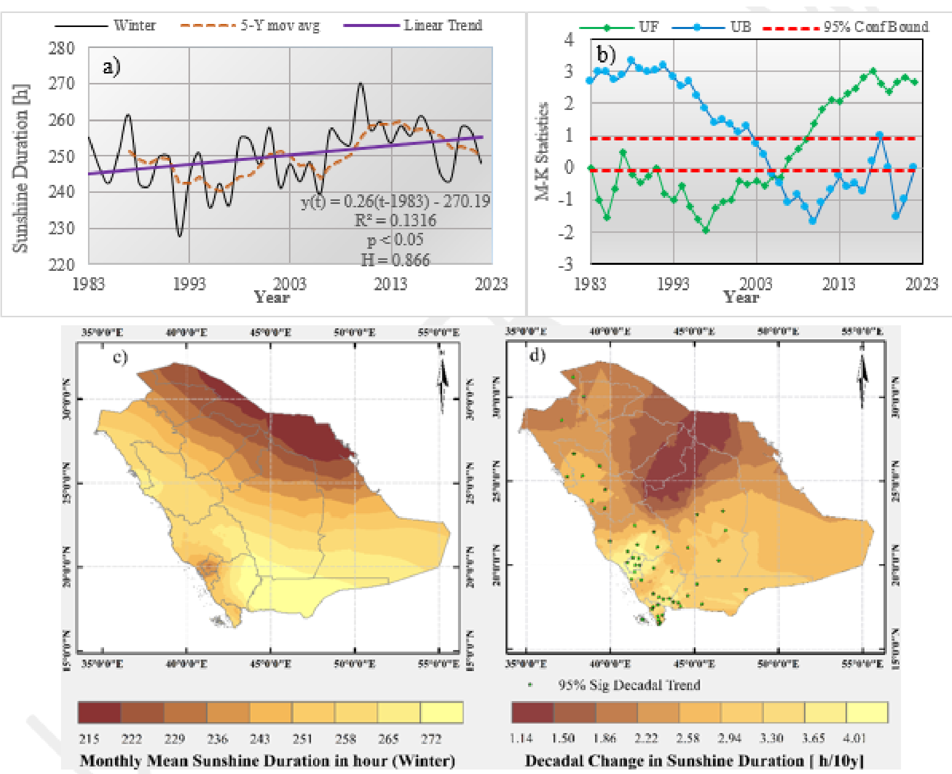

Fig. 6. Variation of SD in Saudi Arabia during the Winter Season a) Sunshine duration (h) overlayed with five-year (5 - Y) moving average (red dotted) and linear trend (purple). b) M-K statistics UF (green), UB (blue) region between dotted red lines is 95% conf bond. c) Monthly mean SD in hours during winter d) Decadal trend in SD (h/10y)

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%

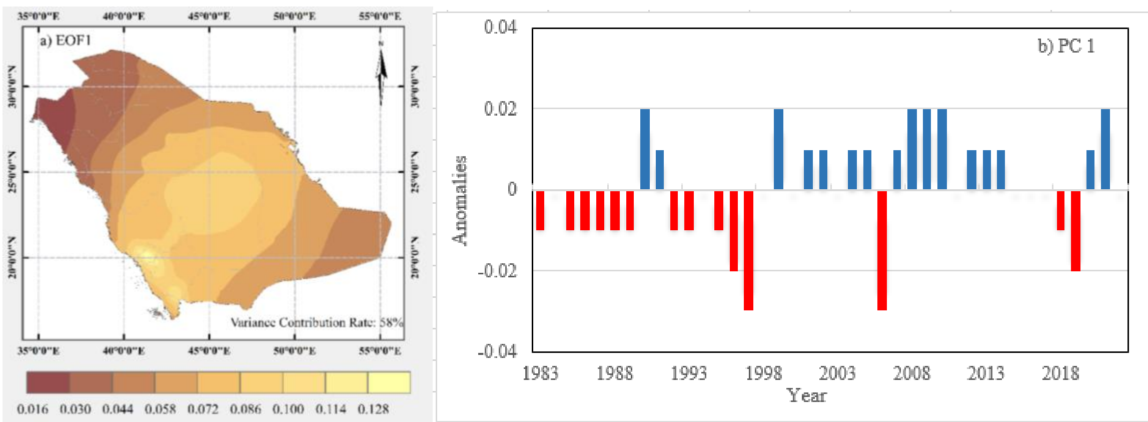

Fig. 7. Spatiotemporal Variation of SD in Saudi Arabia for EOF1

Based on the presented data in the table, the experience variance of the second EOF mode is 17%. According to Fig. 8(a) space function of the second mode of EOF clearly shows that there was an opposite distribution of eigenvector from 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 Fig. 8(b), 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 country experienced a decline in SD during that period. On the other hand, from 1997 onward the time coefficient was negative implying that. There was a rise in the changing pattern of SD in the northern part of the country, but the opposite experienced a decrease in SD during that period.

3.7 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 Saudi 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.

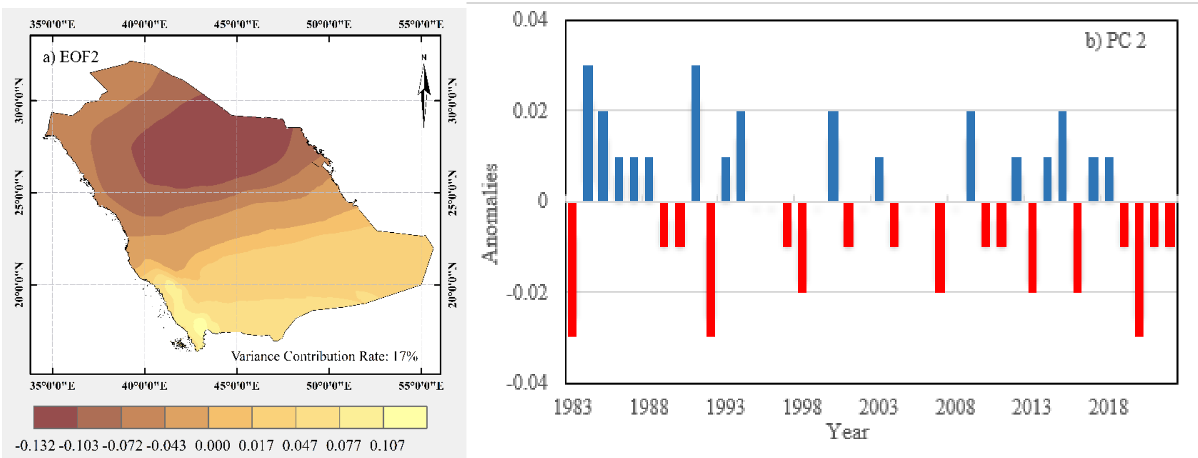

Fig. 8. Spatiotemporal Variation of SD in Saudi Arabia for EOF2

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 2, it appears that there are statistically significant negative Based on the results presented in Table 2, 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.

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 Fig. 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 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 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 Fig. 9 (a).

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*

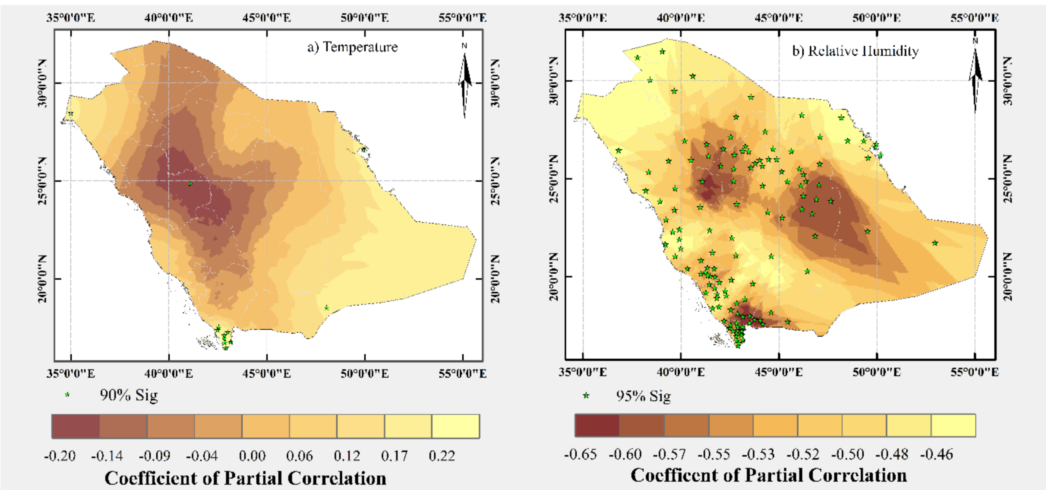

Fig. 9. Spatial Distribution of Partial Correlation Between SD and Potential Factors

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*

3.8 Temporal Variation of SD in Saudi Arabia

The linear regression model method was adopted for the present study to determine the linear trend slope and its statistical significance of changing patterns of SD at the temporal scale for different seasons during the period 1983-2022. A summary of the results obtained from the temporal variation of SD in Saudi Arabia is presented in Table 4.

From the table, it appears that the changing patterns of SD in Saudi Arabia showed a rising trend (1.48 hy^{-1}) during the period 1983-2022, and passed the statistical significance ($p < 0.05$). More specifically, the changing rate of SD was highest at 7.15 hy^{-1} and lowest at 2.83 hy^{-1} during the last two decades of the 20th century (1983-2000) as shown in the table. However, since the beginning of the 21st century, the magnitude of the trend slope started to increase which means the number of available hours of sunshine duration increased from 4.6 hy^{-1} to 6.47 hy^{-1} as shown in the table.

From the periodical seasonal analysis, it appears that the decadal trend of SD in spring was on the rise except in 1983-1990 when the region experienced a downward trend (-0.18 hy^{-1}) in available sunshine duration hours. Whereas, in the summer season, the changing patterns of SD were downward, but there was a rising trend in SD during the period 1983-1990. There was a fluctuation in the changing patterns of SD in the rest of the seasons (autumn and winter).

4. DISCUSSION

In Saudi Arabia, the average monthly SD is 283 ± 18 hm^{-1}, between 1983 and 2022, there was a rising trend of SD that increased at a rate of 1.48 hy^{-1}, passing the significance test ($p < 0.05$). From the spatial distribution, it appears that most of the regions experienced an annual mean of SD between 3375 and 3754 hy^{-1}, except for the southwest and the middle-eastern part where SD was between 3072 and 3375 hours in a year. The highest mean monthly SD was 318 ± 39 hm^{-1} during the summer season, but the trend of SD changes over the years was downward (-0.21 hy^{-1}), whereas the mean monthly SD was lowest (244 ± 38 hm^{-1}) in the winter season, and the changing pattern of SD was on the rise at a rate of 0.26 hy^{-1} with 95% confidence level. According to the Empirical Orthogonal Function (EOF), it appears that between 1983 and 1998 there was a decline in sunshine duration across the country, Whereas, from 2000 onward the country experienced an upward trend in SD. From the spatial distribution of SD, it appears that the highest yearly mean SD was mainly distributed in the northwest part of the country, such as the Tabuk and Madinah regions, with a yearly SD of 3600 hours or more. Whereas, the lowest annual mean SD was distributed in the southwest corner, the Middle-Eastern part, and their surrounding areas, with an annual mean SD of 3200 hours or less. This may be due to the geographic positioning of the region, generally, SD will be longer with higher latitude.

From the results obtained from the correlation analysis, it appears that there are statistically significant negative correlations between the SD and some of the selected potential metrological factors, like precipitation (95% CL); relative humidity (99% CL); and cloud cover (90% CL), whereas there is a positive correlation between the SD and temperature (90% CL). 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 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.

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. For the present study, five potential metrological factors were selected to get an understanding of the influence of SD changes in Saudi Arabia. Other potential factors, such as Air pollution; Aerosol optical depth (AOD); Urban development; Human activities, and Terrien need to be considered in further studies to get a better understanding of SD changes in a region.

5. 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 monthly data of the influencing factors, such as precipitation, relative humidity, wind speed, and temperature, were extracted from MERRA-2, which is a version of the Goddard Earth Observing System (GEOS) of 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 for this study. The findings from the study are as follows: The average monthly SD is 283 ± 18 hm^{-1}, and there was a rising trend of SD that increased at a rate of 1.48 hy^{-1} with a 95% confidence level. Most of the regions experienced an annual mean of SD between 3375 and 3754 hy^{-1}, except for the southwest and the middle-eastern part where SD was between 3072 and 3375 hours in a year. The highest mean monthly SD was 318 ± 39 hm^{-1} during the summer season, but the trend of SD changes over the years was downward (-0.21 hy^{-1}). The mean monthly SD was lowest (244 ± 38 hm^{-1}) in the winter season, and the changing pattern of SD was on the rise at a rate of 0.26 hy^{-1} with a 95% confidence level. 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 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.

COMPETING INTERESTS

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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