Original Research Article

Determination of the Availability and Variation ofSurface Downwelling Shortwave Radiationin Saudi Arabia using EUMETSAT Satellite Imagery

Abstract

Solar energy is expected to be a viable alternative sustainable energy source in the near future due to diminishing fossil fuel resources and escalating changes in the climate. Surface Downwelling Shortwave (SDS) radiation is an important component for the characterisation of energy deposition of the earth’s surface.The monthly means of SDS radiation for Saudi Arabia were extracted from EUMETSAT(SARAH-2.1 climate data record)between 1983 and 2022. The country experienced the lowest level (188 ± 40 W m-2) of SDS radiation in the winter season with a range of 67-271 W m-2.The summer season in Saudi Arabia has the highest level of radiation with a mean value of 304± 27 W m-2, which is 1.62 times the mean of the winter season.The region experienced the highest(10.6 W m-2/10y) and lowest (-10.80 W m-2/10y)levels of a statistically significant upward and downward trend in SDS radiation during the spring and summer seasons respectively in the first decade of the 21st century (2001-2010).During the spring season, there was an upward trend in the availability of SDS radiation across the region, with a magnitude of 3.8 W m-2/10y with a 99% confidence level. In contrast, there was a downward trend in SDS radiation in the summer with a magnitude of 1.0 W m-2/10y with a 90% confidence level followed by the autumn season when the trend was lowest (-0.45 W m-2/10y) and statistically non-significant.

Keywords: Surface Downwelling Shortwave Radiation; EUMETSAT; spatiotemporal variation;trend analysis

1. Introduction

In recent times, the number of climate catastrophe events on this planet has increased. Droughts, heatwaves, floods, and other extreme weather events are becoming more common as a result of the rapid rise in energy usage and CO_2 emissions(Li, Wang, and Ho, 2011) caused by the major infrastructure programs underway in differentareas of the world to meet increasing population demand.Furthermore, abnormal weather variations have been found to have deleterious effects on plants and wildlife, such as lowering annual crop yields, rising sea levels and flooding low-lying land, rendering ocean water more acidic due to CO_2 absorption, and so on[2]. Fossil fuels account for almost 90% of the energy used in construction activities, contributing to global warming and climate change. The scientific community is focused on seeking alternate sources of energy that are more pure and renewable, such as solar; thermal energy, and so on, due to escalating climate change and dwindling fossil fuel supplies[3].The amount of energy that radiates from the Sun approaching the Earth’s surface every day is over three hundred times more energy used by the world in a year[2]. About 17.300 GW of electricity can be generated with 10% efficiency from 0.1% of the radiation from the Sun thatis received by the earth’s surface is more than five times the global electricity usage in 2016[4], [5].

Surface Downwelling Shortwave (SDS) radiation is the flux that reaches the earth's surface in the band range of 0.2-4 microns[6]. It is one of the most important components of the Surface Radiation Budget[3]. It is also describedby different terms such as solar surface irradiance, incoming shortwave radiation, surface incident shortwave radiation, etc.[7].It is not only critical for solar energy as a renewable source, but also for environmental studies such as computing the energy deposition of the earth's surface and designing prediction models for climate change and different land surface processes[3].Information on SDS radiation availability and variance over time in aspecific region can be obtained from different sources, such as ground stations; numerical estimation models, weather satellites, etc.[8]. The most accurate and reliable source for obtaining available radiation is a ground station that covers a specific area.Measuring the trend and availability of radiation requires a large number of stations to be installed in the region, which is both costly and time-consuming. As a result, obtaining data for climate change studies remotely from satellites has increasingly become more popular among scientists.Since 1960,the estimation ofSDS from satellites has been started to map the spatiotemporal distributions on regional and global scales.

Saudi Arabia is the world's second-largest oil producer which accounts for 12.4% of the entire global production in 2019[9]. Over the last three decades, the country's economy has increased significantly because of having natural resources. It is predicted that there will be over 120GW of electricity required to maintain the demand by 2030[9].The government has already taken several strategies to find suitable and available renewable energy resources for power generation and reduce the dependence on fossil fuels.However, it is one of the biggest solar photovoltaic (PV) power-producing countries because of its huge desert land and open sky all year round in most areas. [10]–[12].

Over the past several decades, trend detection of hydro-metrological time series data has become popular among scientific researchers. Parametric or nonparametric approaches, such as linear regression analysis, cumulative sum, Mann-Kendall trend test, Sen's slope and so on, have been used to investigate the different types of hydro-metrological time series data across the globe. Especially, the Mann-Kendall trend test and Sen's slope methods have become popular and used in much scientific research in different parts of the world. Although these aforementioned methods are widely used in trend detection, have certain limitations.

The novelty of this paper was to investigate the availability and seasonal variation of the SDS radiation on a spatiotemporal scale over the past forty years (1983-2022) by using the monthly data of 147 stations across the country. Results obtained from this study can be used as a reference for solar energy resource development and utilization, climate change studies, and crop production.

2. Study Area

Saudi Arabia is the Middle East's largest nation, with a total area of about 2.25 million km^2 that covers roughly 80percent of the Arabian Peninsula. It is located between 16°21'58" N - 32°9'57" N and 34°33'48" E - 55°41'29" E. In this nation, there are 13 administrative regions, which are depicted in Figure 1a. Figure 1.b shows the 147 metrological stations that were selected to examine the availability and variability of SDS across the country over the past forty (1983-2022) years.

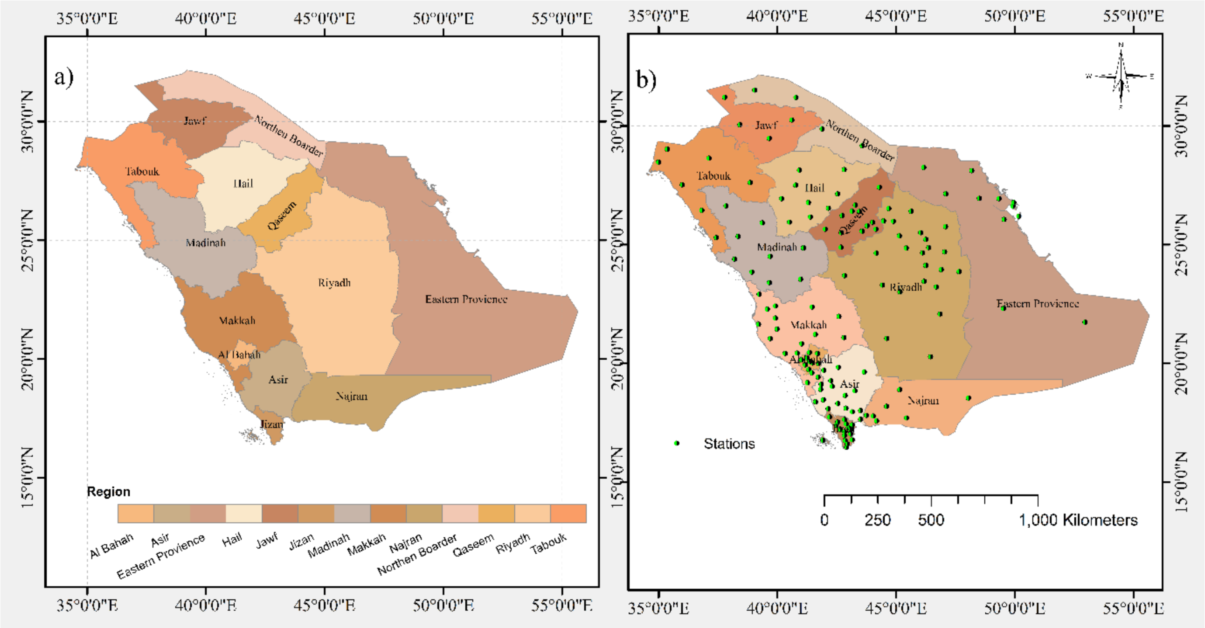

Figure 1:Administrative Regions of Saudi Arabia

While Saudi Arabia is often portrayed as a hot country, it is not always so.There are four distinct seasons, such as spring, summer, autumn and winter, that can be found throughout the country - from chilly winter breezes in January to peak desert heat in August. Spring season is from March to April. Summer is the biggest season which comprises almost four months between May and August. The Autumn season starts after the summer season and extends up to October, and the winter ends before the spring.

3. DataSource

Since 1983, the "European Organization for the Exploitation of Meteorological Satellites" (EUMETSAT) SARAH-2.1 climate data record for Surface Downwelling Shortwave (SDS) radiation has been available with a 0.05-degree spatial resolution [13]. For this investigation, the monthly means of SDS radiation for Saudi Arabia were extracted for the years 1983 to 2022 and analyzed information by using the CM-SAF application.

4. Methodology

4.1 Trend Slope and Significance

In metrological time series analysis, the linear trend method is one of the commonly used statistical techniques to determine the magnitude of environmental parameter changes over time. The **Mann-Kendall (MK)** test is a non-parametric test to detectwhether there is enough statistical evidence of the presence of a monotonic trend in a time series[14], [15]. When there is sufficient statistical evidence, the MK test rejects the null hypothesis, which is the absence of monotonic trends in the data set. However, time series data are often not random and influenced by autocorrelation, Yue and Wang (2004) have proposed a variance correction approach in the Mann-Kendall tests known as the **modified Mann-Kendall** (**mMK**) tests,which may be used for trend detection to address the issue of serial correlation in the data set has been adopted for the present study. A negative value of Mann-Kendall test statistics (Zc) indicates the presence of a downward trend over time and vice-versa. There is a statistically significant indication of the exitance of a trend at a 90% confidence interval when the absolute value of Zc is more than 1.65 but less than 1.96 [16]. For the case of $2.58 > |Zc| > 1.96$, there is a significant trend present in the data series at the 95% confidence interval [16]. If the absolute value of the test statistics (Zc) is greater than 2.58, there will be a 99% probability of having a significant trend in the temporal data set [16]. **Sen's Slope** is a simple non-parametric approach used to determine the magnitude of the trend slope of a time series[17].

The **M-K mutation** test is used to determine whether or when climate data changes from one state to another in a time series data set [18]. At a given significance level (α), test statistics (**UF** and **UB**) are calculated and plotted on a graph. An upward trend is indicated if UF and UB values are greater than 0, otherwise a downward trend is indicated [19]–[21]. In the case of a rising (or falling) trend, the value over the critical line indicates its significance. The range beyond the critical line is defined as the mutation time zone [18]. If the *UF* and *UB* curves cross at an intersection point, and the intersection point is between the critical lines, then the intersection point corresponds to the time the mutation begins [22].

4.2 Hurst Exponent

Time series predictability heavily relies on long-term memory, so a scientific method is required to identify whether the long-term memory property exists in a time series. In 1951, a renowned British hydrologist named H.E[23], [24]. Hurst proposed a statistical approach in his published scientific paper to identify the randomness of a time series data set and also characterize the trend of time series by Rescaled Range analysis or R/S analysis without making assumptions about stationarity[25]. At present time, the Hurst exponent (H) is the most widely accepted and used to measure long-term memory properties of a time series data set at different industries. For instance, if the Hurst exponent of a time series is 0.5 it implies that the time series is a Brownian time series which means there isn't any significant correlation between the past and predicted future observations[25]. The Hurst exponent value is less than 0.5 implying that the time series shows a negative autocorrelation behaviour. In other words, any decrease in this time series will most likely be followed by an increase or the other way around[26]. A value closer to 0 indicates that the time series has a stronger tendency to return to its long-term means value. Whereas, in a persistent time series an increase in values will most likely be followed by an increase in the short term and a decrease in values will most likely be followed by another decrease in the short term[24], [27]. The greater the H value, the stronger the trend. Persistent behaviour is defined by a Hurst exponent between 0.5 and 1.0[26], [27].

4.3 Empirical Orthogonal Function

The **Empirical Orthogonal Function** (**EOF**) also known as Principle Component Analysis (PCA) is an effective statistical approach for compressing data and reducing dimensionality in atmospheric, oceanic, and climate science [28]. In other words, possible spatial modes of variability (patterns of variability) in climate studies can often be studied by EOF analysis. It is used for decomposing the time series data set into mutually independent spatial and temporal function parts to explain the spatiotemporal variability with the least possible modes [29]. The eigenvectors are the space function part which is composed of several mutually independent and orthogonal space modes [30]. Whereas, the projection space modes over time are the time function part is defined as a time coefficient [30]. The characteristics of spatial and temporal variability are reflected by the variance contribution rate.

5. Result and Analysis

5.1 Spatial Variation of SDS Radiation in Saudi Arabia

Figure 2shows the annual variation of SDS radiation across the kingdom during the aforementioned period. Linear regressional analysis and M-K mutation test were used in this study to examine the characteristics of annual trend and mutation test of SDS radiation. The Hurst index (H) was also computed to determine whether the annual trend will be persistent in the future.From Figure 2.a, it appeared that there was an upward trend in SDS radiation with a 90% confidence interval in the country during the past forty-year period, with a trend of 0.6 W m-2/10y. Results obtained from the Hurst exponent (H = 0.857) indicated that the trend was present in the past and will continue in the future as shown in Figure 2.b.According to Figure 2.c, the UF curve stayed below the zero line between 1991 and 2001 which implies that during that period there was a downward trend in SDS radiation that existed but was statistically nonsignificant because it lay within the confidence interval limit.In contrast, an upward trend in SDS radiation was present from2001onward as the UF curve stayed in the positive zone and the trend was statistically nonsignificant as the curve stayed within the confidence interval limit during that period. In addition, there were multiple intersection points between the UF and UB and all of them were within the confidence interval limit, which indicates that decreasing and increasing mutation occurred in 1998 and 2018 & 2019 respectively. According to the SDS radiation data analysis, themean radiation in Saudi Arabia was 252 ± 17 [W m-2] during the past forty years period. The spatial distribution of yearly mean SDS radiation has been shown in Figure 2.d. From the Figure it is seen that most of the regions experienced annual monthly mean SDS radiation in a range of 250 - 284W m-2, except the southwest part (hilly areas of Asir, Jizan and Al Bahah regions) and the northeast part (Northern border, Northern part of Riyadh region, Hail and Qassim regions), where the available SDS radiation was in a range of 210-250 W m-2.

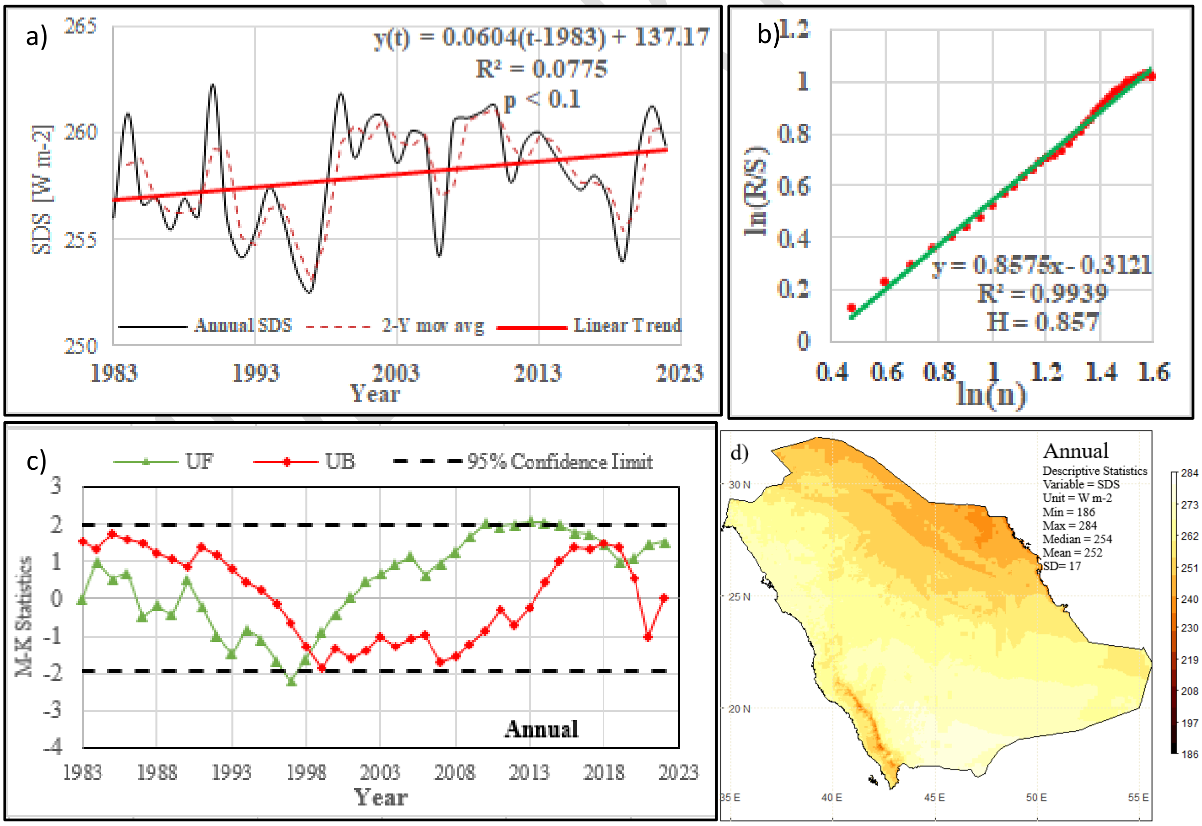

Figure 2: Annual Variation of SDS Radiation in Saudi Arabia

5.2 Variation of SDS Radiation in Saudi Arabia During Spring Season

From Figure 3.a, it appeared that in spring there was an upward trend in SDS radiation with a 99% confidence level in the country during the past forty-year period, with a trend of 3.8 W m-2/10y. Results obtained from the Hurst exponent (H = 0.87) indicated that the trend was present in the past and will continue in the future as shown in Figure 3.b. According to Figure 3.c, in the first seventeen years between 1983 and 1999 the UF curve fluctuated between the 95% confidence limit but after that, there was a statistically significant upward trend in SDS radiation was present for the rest of the period as the curve stayed above the confidence interval. Furthermore, the UF and UB curves intersected in 1999, which implies that there was an increasing mutation that occurred in that year. According to the SDS radiation data analysis, in the spring season, the mean radiation in Saudi Arabia was 279 ± 20 [W m-2] during the past forty years period. The spatial distribution of monthly mean SDS radiation in the spring season has been shown in Figure 3.d. From the Figure it is seen that most of the regions experienced monthly mean SDS radiation in a range of 270 - 318 W m-2, whereas the southwest part (hilly areas of Asir, Jizan and Al Bahah regions) and the northeast part (Northern side of Eastern Province, Riyadh and the southern side of Northern Border regions), where the available SDS radiation was in a range of 230-270 W m-2.

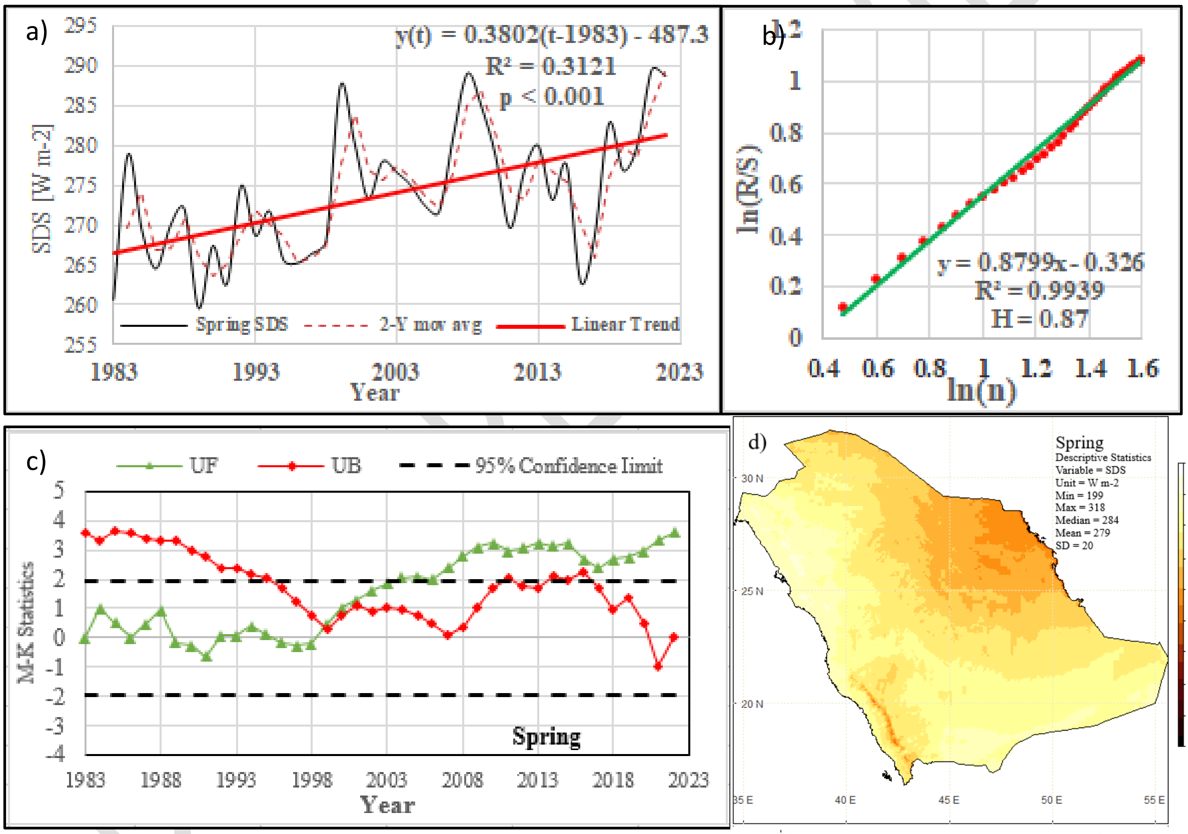

Figure 3: Variation of Surface Downwelling Shortwave Radiation in Saudi Arabia during Spring Season

5.3 Variation of SDS Radiation in Saudi Arabia During Summer Season

From Figure 4.a, it appeared that in the summer season, there was a downward trend in SDS radiation with a 90% confidence level in the country during the past forty-year period, with a trend of 1.0 W m-2/10y. Results obtained from the Hurst exponent (H = 0.817) indicated that the trend was present in the past and will continue in the future as shown in Figure 4.b. According to Figure 4.c, in the first twenty-seven years between 1983 and 2009, the UF curve stayed above the zero value line (remained positive) although the curve remained within the 95% confidence interval limit implies that during that period the region experienced a statistically nonsignificant upward trend in SDS radiation whereas the later part the region experienced a downward trend in the radiation during the summer season.In addition, the only intersection point between the UF and UB curves occurred around 2015 and it was below the zero line and well within the confidence interval limits, which means decreasing mutation occurred in that year. According to the SDS radiation data analysis, in the summer season, the mean radiation in Saudi Arabia was 304 ± 27 [W m-2] during the past forty years period. The spatial distribution of monthly mean SDS radiation in the summer season has been shown in Figure 4.d. From the Figure it is seen that most of the regions experienced monthly mean SDS radiation in a range of 315 - 357 W m-2, whereas the southern part (Eastern province, Al Bahah, Asir, Jizan and Najran) of the country experiencedmean SDS radiation in 170-315 W m-2 during the past period.

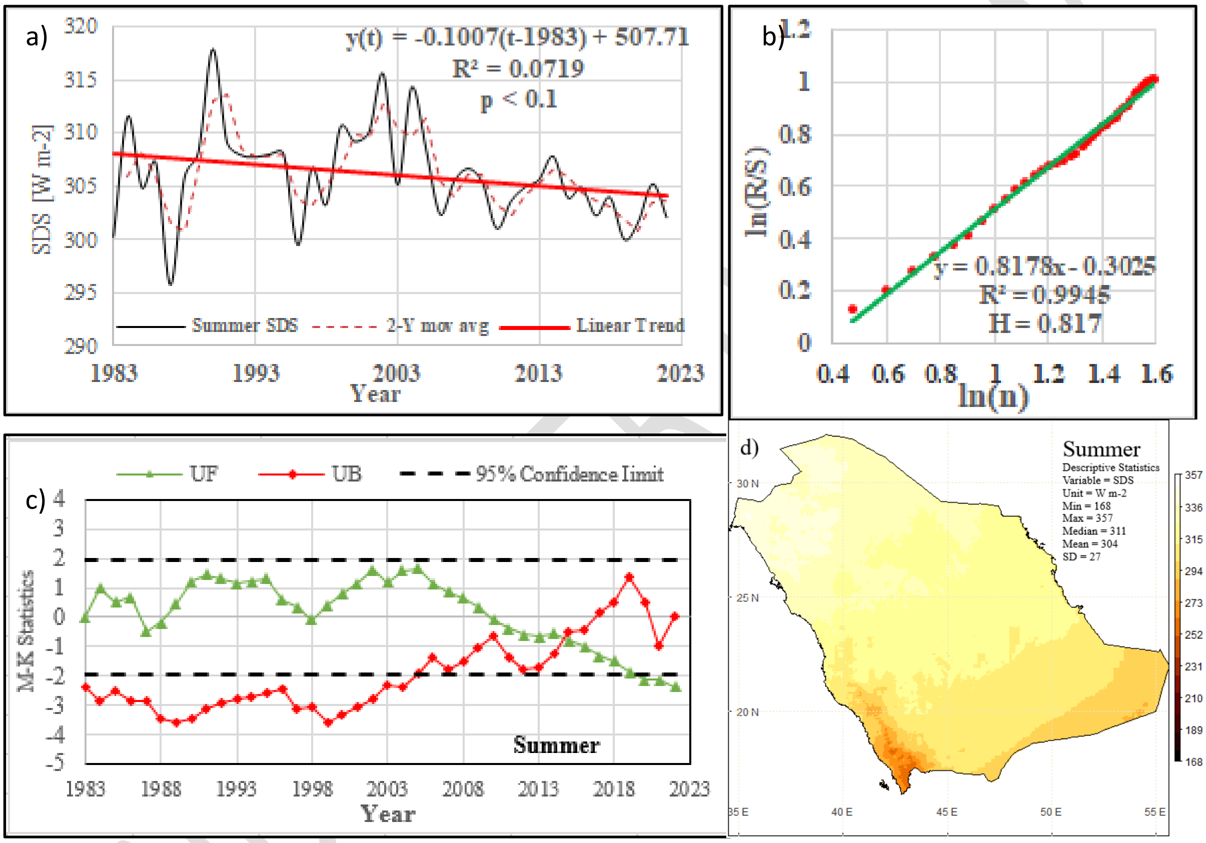

Figure 4: Variation of SDS Radiation in Saudi Arabia during the Summer Season

5.4 Variation of SDS Radiation in Saudi Arabia During Autumn Season

From Figure 5.a, it appeared that there was a downward trend in SDS radiation in the country during the past forty-year period, with a trend of 0.45 W m-2/10y, although the trend wasn't statistically significant ($p > 0.1$). Results obtained from the Hurst exponent ($H = 0.59$) indicated that the trend was present in the past and will continue in the future as shown in Figure 5.b. According to Figure 5.c, throughout the period between 1983 and 2022 the UF curve stayed below the zero value mark line (remained negative) and fluctuated within the 95% confidence line which implies that there was a downward trend existed during the autumn season which wasn't statistically significant. Moreover, there were multiple intersection points where the UF and UB curves intersected, such as 1989, 1990, around 2002 and 2013. In all these years the decreasing mutation occurred except in 2013. According to the SDS radiation data analysis, in the autumn season, the mean radiation in Saudi Arabia was 236

± 23 [W m-2] during the past forty years period. The spatial distribution of monthly mean SDS radiation in the autumn season has been shown in Figure 5.d. From the Figure it is seen that most of the regions experienced monthly mean SDS radiation in a range of 175– 240W m-2, whereas regions in the southern part of the country, such as Eastern Province and Najran regions, experienced mean SDS radiation in 240-286 W m-2 during the past period.

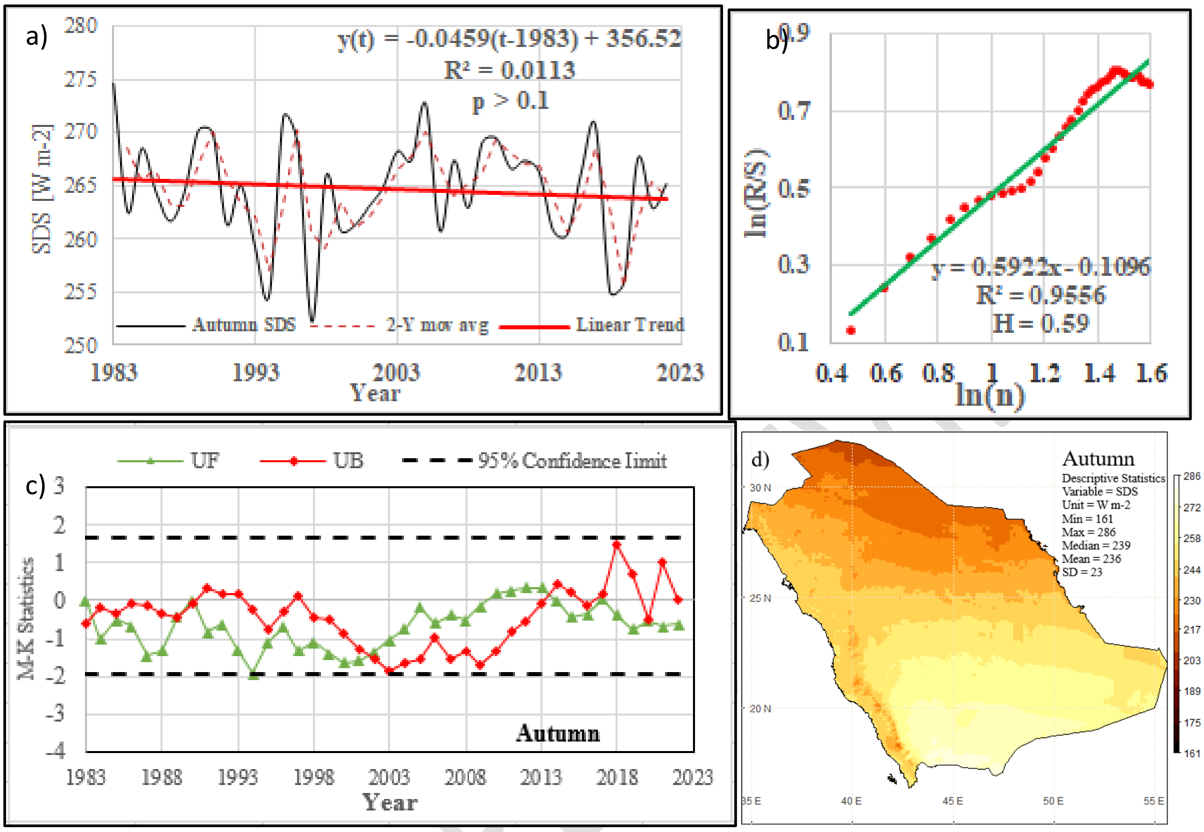

Figure 5: Variation of SDS Radiation in Saudi Arabia during Autumn Season

5.5 Variation of SDS Radiation in Saudi Arabia During Winter Season

From Figure 6.a, it appeared that there was an upward trend in SDS radiation with a 90% confidence level in the country during the past forty-year period, with a trend of 1.1 W m-2/10y. Results obtained from the Hurst exponent (H = 0.838) indicated that the trend was present in the past and will continue in the future as shown in Figure 6.b. According to Figure 6.c, in the first five years between 1983 and 198 the UF curve fluctuated around zero marked line, but after that, there was a statistically nonsignificant downward trend in SDS radiation present till 2009 as the curve stayed within the confidence interval, whereas rest of the period the region experienced an upward trend in SDS radiation during the winter season. Furthermore, in 2007 the UF and UB curves were intersected, and the intersection point was located below the zero line but within the confidence interval limit, which implies that decreasing mutation occurred in that year. According to the SDS radiation data analysis, in the winter season, the mean radiation in Saudi Arabia was 188 ± 40 [W m-2] during the past forty years period. The spatial distribution of monthly mean SDS radiation in the spring season has been shown in Figure 6.d. From the Figure it is seen that most of the regions experienced monthly mean SDS radiation in a range of 180 - 271 W m-2, whereas some parts of the northern side, for instance, Tabuk, Hail, Northern Border and Jawf regionexperienced mean SDS radiation within the range of 80-180 W m-2 during the past period.

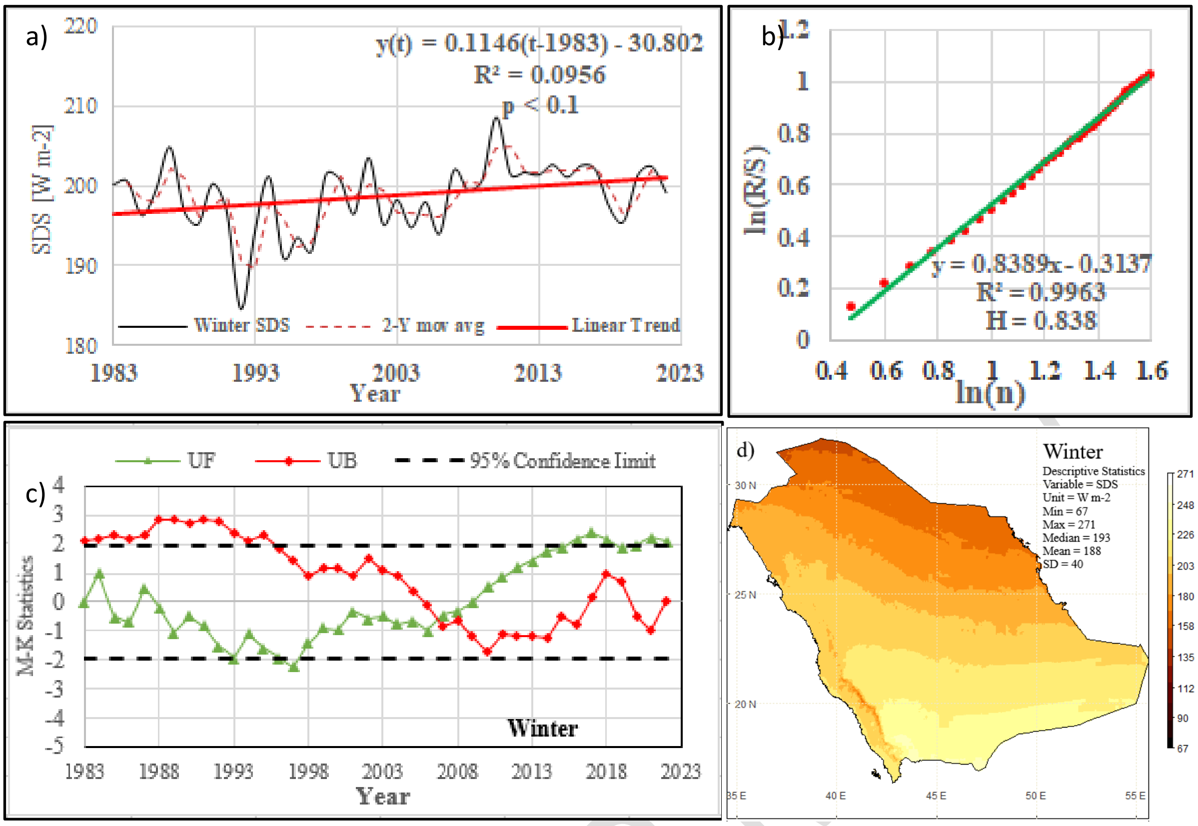

Figure 6: Variation of SDS Radiation in Saudi Arabia during Winter Season

5.6 *Analysis of MonthlyVariation of SDS Radiation in Saudi Arabia*

For the present study, non-parametric trend tests, such as the MK/mMK test and Sen's slope,were used to examine the presence of a trend and its magnitude atthe spatiotemporal scalein Saudi Arabia as shown in Figure 7. In the spring season (March-April), there is a presence of an upward trend in SDS radiation in Saudi Arabia with various degrees.In March, upward trends in SDS radiation in most of the regions were statistically significant ($p < 0.05$) with a 95% confidence level except for stations that fall in the Madinah region. Moreover, from the middle to the south-eastern part of the country, such as Riyadh and the Eastern province region, experienced the highest rate (4.65-7.03 W m-2/ 10y) of upward trend in SDS radiation. The rest of the regions experienced an upward trend in SDS radiation in a range of 2.28-4.65 W m-2/10y. Whereas, in the second month (April) of the season, regions in the northern part of the country, for instance, Tabuk; Hail; Qassim; Madinah and Northern Border regions, and south-western regions, like Asir; Al Bahah and Jizan, experienced statistically significant upward trend in SDS radiation with a range of 3.19-5.03 W m-2/10y.

In the summer season (May-August), most of the regions experienced a downward trend in SDS radiation as it appeared from the past forty-year (1983-2022) data analysis. More specifically, in May, from the Middle to the southern part of the country, like the Eastern province; Riyadh; Al Bahah, Asir, Najran; Jizan and Makkah, statistically nonsignificant ($p > 0.05$) negative changing rate in a range of -4.68 - 0.0 W m-2/10y, whereas, regions (Tabuk, Jawf, Northern Border, Madinah, Qassim and Hail) on the other side of the country experienced statistically significant upward trend in the SDS radiation during that period. However, in June, the spatial pattern of SDS radiation changing rate was quite different than the previous month. In other words, from the middle part of the country to the western side experienced a statistically significant downward trend (-5.03 - 0.0 W m-2/10y) in the changing rate of SDS radiation, while there was an upward trend in SDS radiation, which wasn't statistically significant, on the eastern part of the country. The highest changing rate in SDS radiation was experienced in July. For instance, most parts of the country experienced a statistically significant ($p < 0.05$) downward trend in SDS radiation except the eastern province region, and the changing rates varied in a range of -11.55 – 0.0 W m-2 for every ten years on average. In August, the end part of the summer season, the changing rate of SDS radiation was much lower than the previous month, but still showed a downward trend.

In the autumn season (September-October) downward trend in SDS radiation continued in most of the regions of the country over the past forty years. Lastly, in the winter season (November-February) most parts of Saudi Arabia experienced an upward trend in SDS radiation, except the first month (November) of the season as is seen in Figure 7. The southern part of the country experienced a downward trend (-4.11-0.00 W m-2/10y), whereas the opposite side experienced an upward trend in SDS radiation.

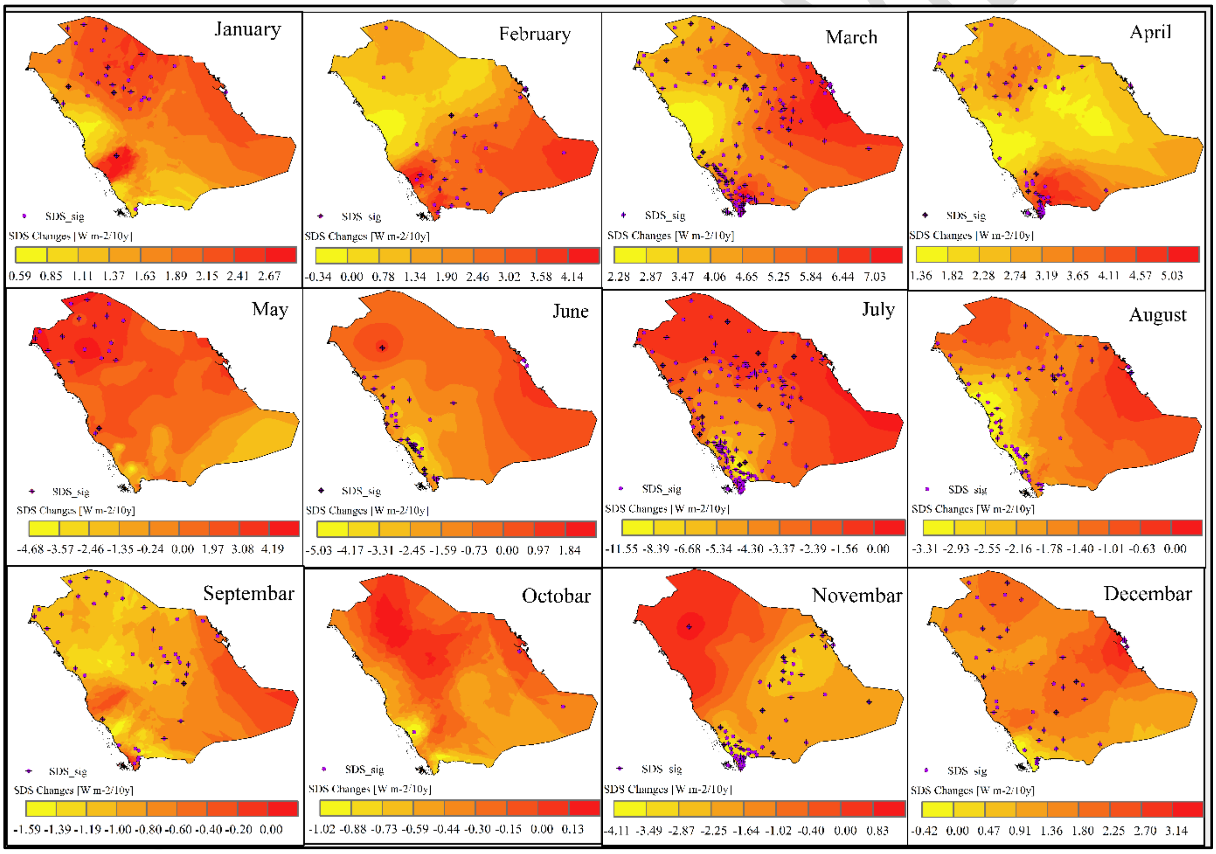

Figure 7: Spatiotemporal Variation of Changing Rate of SDS Radiation in Saudi Arabia

5.7 *EOF Analysis of SDS Radiation in Saudi Arabia*

After the decomposition of annual SDS radiation anomalies by the EOF, the obtained explained variance and cumulative variance of different modes are shown in Table 1. From the table, it is seen that the cumulative variance of the first five modes is 84%. The first two modes are used in the present study because these two modes passed the north significance test.

Table 1: Summary of Explained Variance and Cumulative Variance of Different EOF Modes

EOF Mode	Explained Variance	Cumulative Variance
Mode1	57%	57%
Mode2	16%	73%
Mode3	5%	78%
Mode4	4%	81%
Mode5	3%	84%

Based on the table data, it is evident that the first EOF mode has a much higher experience variance of 57% as compared to the other modes. Furthermore, it is the primary spatial distribution form of SDS radiation in Saudi Arabia. By observing Figure 8a, it is evident that the eigenvectors of the first mode are negative, which indicates that the SDS radiation level across Saudi Arabia shows a consistent pattern of either decreasing or increasing uniformly. The most significant negative centres are primarily concentrated in Riyadh, Makkah, Al Bahah, Asir, and Najran, highlighting the more severe changes occurring in these areas than in others. It can be seen from Figure 8b thatSDS radiation showed a decreasing trend in Saudi Arabia from 1983 to 1998as the first modal eigenvector is negative but the time coefficient was positive during that period. On the contrary, from the figure it appeared that the time coefficient was negative between 1999 and 2015, which implies that during that period there was an increasing trend in SDS radiation across the country. The time coefficient was the smallest in 1984, 1990, 1999, 2009 and 2010, which means that the SDS uniformly increased in these years, whereas, it was the largest in 1997, which means that the SDS uniformly decreased in 1997. The findings are in line with the analysis of the inter-annual variation characteristics.

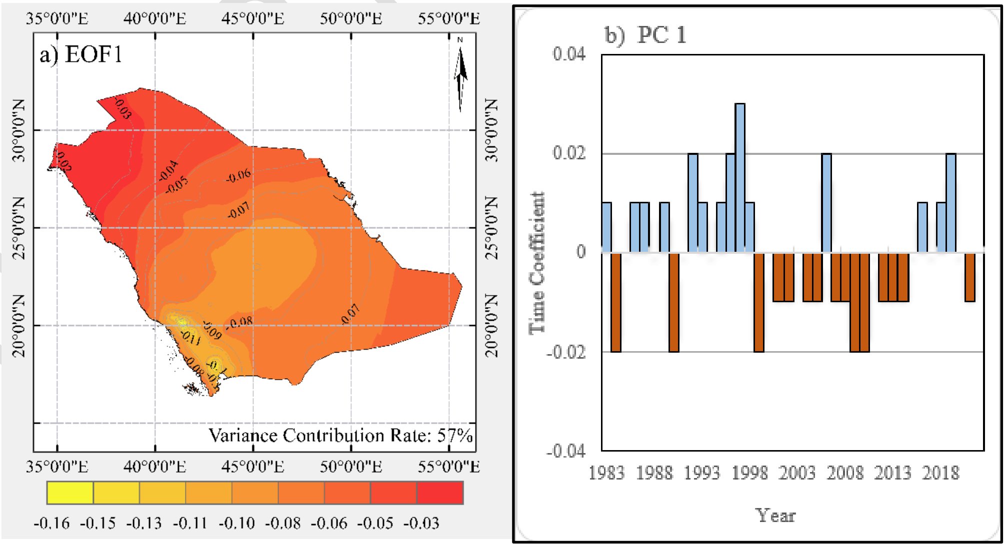

Figure 8: Spatiotemporal Variation of SDS Radiation in Saudi Arabia for EOF1

The experienced variance of the second mode of the eigenvectors is 16%, according to Table 1. Figure 9a clearly illustrates that the eigenvector space of EOF2 exhibits opposite distributions in the north-south direction, and is separated by an imaginary line running from the Eastern Province to the

Makkah region in the middle of the country. Moreover, it is evident that negative values persist in the northern regions of the country, starting from the middle. This indicates that the SDS radiation changes in this region are complex and are potentially influenced by the terrain and latitude. In addition, the centres of negative values are predominantly distributed in the northern part of the Eastern Province, Riyadh, Qassim, along with the southern part of the Northern Border and Hail region, and their adjoining areas. In contrast, the centres of the positive values are primarily concentrated in the southwest region of the country, specifically in the Asir, Jizan, and Al Bahah regions. This strongly indicates that the changes in SDS radiation levels in these areas are significantly more severe than in other regions. According to Figure 9b, the time coefficient was undoubtedly positive during the years 1983-1984 and 1991-1998, which implies that the SDS radiation experienced a decreasing trend in the northern part of the country, while there was an increasing trend in the southern regions. On the contrary, the time coefficient was negative for the periods 1985-1990 and 1999-2015. This suggests that the SDS radiation exhibits an increasing trend in the northern regions while displaying a decreasing trend in the southern areas of the country.

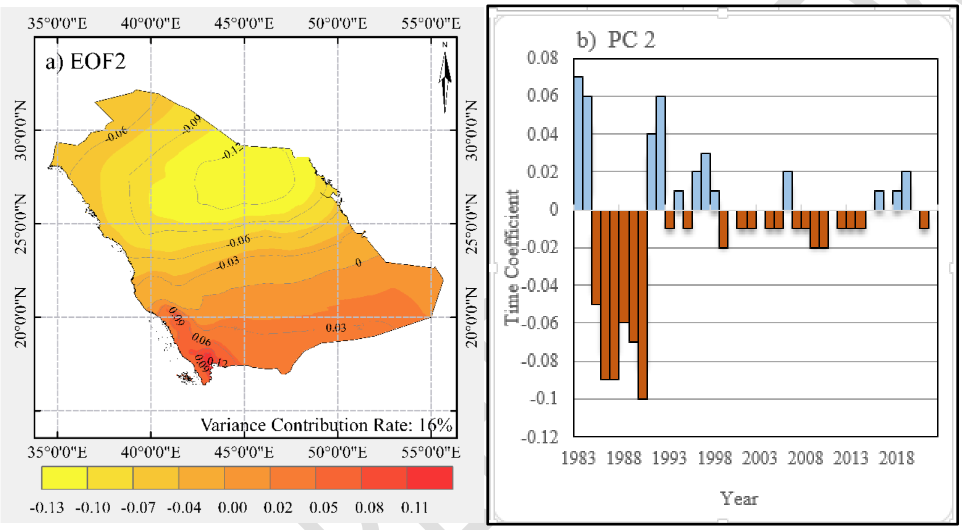

Figure 9: Spatiotemporal Variation of SDS Radiation in Saudi Arabia for EOF2

5.8 *Trends of SDS Radiation in Saudi Arabia*

The linear regressional model is used to determine the magnitude and statistical significance of the SDS radiation trend in Saudi Arabia at different seasons in different periods. As the monthly means of SDS radiation for Saudi Arabia were extracted between 1983 and 2022, the trend of SDS radiation is presented in Table 2.

Table 2: Seasonal and Annual Trends of SDS Radiation in Saudi Arabia

Season	1983-1990	1991-2000	2001-2010	2011-2020	1983-2022
Spring	-4.24	13.85	10.60*	4.88	3.80***
Summer	11.72	-0.95	-10.80**	-4.54*	-1.00*
Autumn	-1.08	-0.42	2.97	-5.59	-0.45
Winter	-2.24	7.33	6.52	-3.91	1.14*

Annual	2.27	4.36	0.84	-2.93	0.60*

Note: * 90% Confidence level, ** 95% Confidence level, * 99% Confidence level**

From the table, it appears that there was an upward trend in SDS radiation in Saudi Arabia during the past forty-year period (1983-2022). In 1983-2000, the trend in SDS radiation across the country in different seasons was statistically non-significant ($p > 0.1$). During the spring season, there was a downward trend in SDS radiation in the 80s, whereas, in the next decade, an upward trend was exhibited and that was the highest trend (13.85 W m-2), although that was statistically non-significant.In the first decade of the 21st century (2001-2010), the region experienced the highest level (10.6 W m-2) of a statistically significant upward trend in SDS radiation. Overall, the SDS radiation during the spring season increased at a rate of 3.8 W m-2 per decade with a 99% confidence level.

Since 1991, there has been a downward trend in SDS radiation exhibited across the country during the summer season at varied degrees, except in 1983-1990, as it appeared in the table that during that period SDS radiation increased at a rate of 11.72 W m-2/10y but statistically not significant. Whereas, from the analysis, it is evident that SDS radiation in Saudi Arabia decreased during the summer season, except in 1983-1990 when the trend was positive, but from the statistical point of view, the trend in SDS radiation was not significant ($p > 0.1$). However, in the twenty years from 1991 to 2010, there was a positive trend in SDS radiation during the winter season, but before and after this period, the region experienced a downward trend in SDS radiation. Generally, the region experienced a negative trend in SDS radiation with -1.14 W m-2 per decade at a 90% confidence level during the winter season as Table 2. On average, the SDS radiation in this country increased at a rate of 0.60 W m-2 per decade with a 90% confidence level. Since 1983, there has been a positive trend in SDS radiation in Saudi Arabia, except in the 2nd decade of the 21st century the country experienced a downward trend in SDS radiation.

6. Discussion

Incoming solar radiation plays a key in different biological, physical and chemical processes on the earth's surface, as well as being strongly linked to climate and its changes. The variation of solar radiation at any place on the earth’s surface is affected either by astronomical factors, such as positioning; distance between the sun and the point of interest; sun's zenith angle and so on, or human activities; topographic condition[6]. A steady increase in solar energy use, as well as possible implications for global climate change, have enhanced the interest of the scientific community in these changes.

Ground-based stations provide the most reliable and accurate source of radiation, but they have a smaller spatial representativeness, while satellites and/or models provide the greatest level of representativeness. For this investigation, the monthly means of SDS radiation for Saudi Arabia were extracted for the years 1983 to 2022 from the “European Organization for the Exploitation of Meteorological Satellites” (EUMETSAT) of SARAH-2.1 climate data record.With reference to the Baseline Surface Radiation Network (BSRN), the radiation data from SARAH-2.1 has been validated with a mean absolute difference of the monthly mean SDS is 5.2 [W m-2][31].

In the winter season (Novembar-February), the country experienced the lowest level (188 ± 40 W m-2) of SDS radiation with a range of 67-271 W m-2. Between March and April, the mean SDS radiation was 279 ± 20 [W m-2], and minimum and maximum radiation was 199 and 318 W m-2 respectively during the past forty years period. In other words, the mean SDS radiation increased by 48.4% in the spring season as compared to the winter season. The summer season in Saudi Arabia has the highest level of radiation with a mean value of 304± 27 W m-2 and the range was 168-357 W m-2. As compared to the winter season, the radiation increased in this season by about 62%. In the autumn season, the radiation started to reduce as compared to the summer season, although the mean radiation was 236± 23 [W m-2], which is 25% higher than the winter season. Overall, the mean SDS radiation in Saudi Arabia was 252 ± 17 [W m-2] with a range of 186-284 W m-2 during the past forty-year period (1983-2022).

In the spring season, there was an upward trend in SDS radiation with a 99% confidence level in the country during the past forty-year period, with a trend of 3.8 W m-2/10y, and will continue in the future as previously because the Hurst exponent was 0.87 ($H > 0.5$). In contrast, there was a downward trend in SDS radiation with a 90% confidence level in the summer season during the period, with a trend of 1.0 W m-2/10y. From the Hurst exponent analysis, it is evident that the radiation in the summer season might decrease in the future as previously because the Hurst exponent was 0.817 ($H > 0.5$). Moreover, during the autumn there was a downward trend in SDS radiation during the past forty-year period, with a trend of 0.45 W m-2/10y, although the trend wasn't statistically significant ($p > 0.1$). However, there was an upward trend in SDS radiation with a 90% confidence level during 1983-2022, with a trend of 1.1 W m-2/10y. Results obtained from the Hurst exponent ($H = 0.838$) indicate that the rising trend might follow a similar pattern in the future. Overall, there was an upward trend in SDS radiation with a 90% confidence level during the past forty-year period, with a trend of 0.6 W m-2/10y, and the trend will continue in the future as it was present in the past according to the Hurst exponent analysis.

In March, the first month of the spring season, from the middle to the south-eastern part of the country, such as Riyadh and the Eastern province region, experienced the highest rate (4.65-7.03 W m-2/ 10y) of upward trend in SDS radiation with a 95% confidence level. In contrast, most of the regions experienced a downward trend in SDS radiation in the summer season (May-August) as appeared from the past forty-year (1983-2022) data analysis. More specifically, the lowest changing rate in SDS radiation was experienced in July. For instance, most parts of the country experienced a statistically significant ($p < 0.05$) downward trend in SDS radiation with the changing rates varied in a range of -11.55 – 0.0 W m-2 for every ten years on average except the eastern province region. However, during the autumn season (September-October) downward trend in SDS radiation continued in most of the regions of the country. Lastly, in the winter season (November-February) most parts of Saudi Arabia experienced an upward trend in SDS radiation, except the first month (November) of the season when the southern part of the country experienced a downward trend (-4.11-0.00 W m-2/10y), whereas the opposite side experienced an upward trend in SDS radiation.

Results obtained from the EOF analysis, it is seen that the first EOF mode is the primary spatial distribution form of SDS radiation in Saudi Arabia due to having a much higher experience variance of 57% as compared to the other modes. the time coefficient was positive during the years 1983-1998 and 2015-2020 which implies that there was a downward trend in the SDS radiation across the country, while the region experienced a rise in SDS radiation from 1999-2015 and 2021-2022 because the time coefficient was negative during that period. The eigenvector space of EOF2 exhibits opposite distributions in the north-south direction and is separated by an imaginary line running from the Eastern Province to the Makkah region in the middle of the country. Moreover, negative values persist in the northern regions of the country indicating that the SDS radiation changes in this region are complex and are potentially influenced by the terrain and latitude. In addition, the centres of negative values are predominantly distributed in the northern part of the Eastern Province, Riyadh, Qassim, along with the southern part of the Northern Border and Hail region, and their adjoining areas. In contrast, the centres of the positive values are primarily concentrated in the southwest region of the country, specifically in the Asir, Jizan, and Al Bahah regions. This strongly indicates that the changes in SDS radiation levels in these areas are significantly more severe than in other regions.

7. Conclusion

This study has dealt with the characteristics of the seasonal and annual variation in the availability of SDS radiation in Saudi Arabia over the past forty years, 1983-2022. The country experienced the lowest level (188 ± 40 W m-2) of SDS radiation in the winter season with a range of 67-271 W m-2. The mean SDS radiation increased by 48.4% in the spring season as compared to the winter season. The summer season in Saudi Arabia has the highest level of radiation with a mean value of 304± 27 W m-2 and the range was 168-357 W m-2. As compared to the winter season, the radiation increased in this season by about 62%. In the autumn season, the radiation started to reduce as compared to the summer season, although the mean radiation was 236± 23 [W m-2], which is 25% higher than in the winter season.

There was a rising trend in SDS radiation with a 90% confidence interval in the country during the past forty-year period, with a trend of 0.6 W m-2/10y, and the mean radiation was 252 ± 17 [W m-2]. There were suspected multiple mutations that occurred in the years 1998 and 2018 & 2019 respectively. During the spring and winter seasons (Novembar-April), there was an upward trend in the availability of SDS radiation across the region, with a magnitude of 3.8 W m-2/10y with a 99% confidence level and 1.14 W m-2/10y with a 90% confidence level respectively. In contrast, there was a downward trend in SDS radiation in the summer with a magnitude of 1.0 W m-2/10y with a 90% confidence level followed by the autumn season when the trend was lowest (-0.45 W m-2/10y) and statistically non-significant. In the first decade of the 21st century (2001-2010), the region experienced the highest level (10.6 W m-2) of a statistically significant upward trend in SDS radiation during the spring season. However, there was a downward trend in SDS radiation in 1991-2022 during the summer season. More specifically,the region experienced the lowest level of SDS radiation trend with -10.80 W m-2/10y with a 95% confidence level in 2001-2010. Results obtained from the Hurst Exponent analysis for annual and seasonal time series datasets for SDS radiation in Saudi Arabia during the past forty years period show that the value of H was greater than 0.5 but less than 1 which implies that the trend in SDS radiation was present in the past will continue in the future.

The first EOF mode is the primary spatial distribution form of SDS radiation in Saudi Arabia due to having a much higher experience variance as compared to the other modes. The eigenvectors of the first mode are negative, which indicates that the SDS radiation level across Saudi Arabia shows a consistent pattern of either decreasing or increasing uniformly. The more severe changes occurring in Riyadh, Makkah, Al Bahah, Asir, Najran and the surrounding areas than in others because the most significant negative centres are primarily concentrated in these areas. During the years 1983-1998 and 2015-2020, there was a downward trend in the SDS radiation across the country, while the region experienced a rise in SDS radiation from 1999-2015 and 2021-2022.

Future investigations must be carried out to gain a deeper understanding of the impact of influencing factors, for instance, cloudiness and aerosol emissions, on the variability of SDS radiation. It is also crucial to gain a comprehensive understanding of how different types (low, medium or high) of cloud can affect the variations in SDS radiation. By exploring the interactions between aerosols, cloud cover, and SDS radiation, it is possible to gain valuable insights into how they collectively influence climate change on climate change.

Reference

[1] J. Li, M. H. Wang, and Y. S. Ho, “Trends in research on global climate change: A Science Citation Index Expanded-based analysis,” *Glob. Planet. Change*, vol. 77, no. 1–2, pp. 13–20, 2011, doi: 10.1016/j.gloplacha.2011.02.005.

[2] National Education Development Project, “Energy From the Sun Student Guide INTERMEDIATE 2 0 1 7-2 0 1 8,” [Online]. Available: www.NEED.org

[3] N. Samuel Chukwujindu, “A comprehensive review of empirical models for estimating global solar radiation in Africa,” *Renew. Sustain. Energy Rev.*, vol. 78, pp. 955–995, 2017, doi: 10.1016/j.rser.2017.04.101.

[4] S. Nwokolo and J. Ogbulezie, “Performance evaluation of existing sunshine-based computing models for estimating global solar radiation at Lagos, Nigeria,” *Int. J. Adv. Astron.*, vol. 5, no. 2, p. 106, 2017, doi: 10.14419/ijaa.v5i2.8308.

[5] United Nations, *Energy Statistics Pocketbook*. 2019. [Online]. Available: https://unstats.un.org/unsd/energy/pocket/2018/2018pb-web.pdf

[6] A. Carpentieri, D. Folini, M. Wild, L. Vuilleumier, and A. Meyer, “Satellite-derived solar radiation for intra-hour and intra-day applications: biases and uncertainties by season and altitude,” *Sol. Energy*, vol. 255, no. September 2022, pp. 274–284, 2022, doi: 10.1016/j.solener.2023.03.027.

[7] G. Huang *et al.*, “Estimating surface solar irradiance from satellites: Past, present, and future perspectives,” *Remote Sens. Environ.*, vol. 233, no. July, p. 111371, 2019, doi: 10.1016/j.rse.2019.111371.

[8] T. Watanabe, Y. Oishi, and T. Y. Nakajima, “Characterization of surface solar-irradiance variability

using cloud properties based on satellite observations," *Sol. Energy*, vol. 140, pp. 83–92, 2016, doi: 10.1016/j.solener.2016.10.049.

[9] Y. H. A. Amran, Y. H. M. Amran, R. Alyousef, and H. Alabduljabbar, "Renewable and sustainable energy production in Saudi Arabia according to Saudi Vision 2030; Current status and future prospects," *J. Clean. Prod.*, vol. 247, p. 119602, 2020, doi: 10.1016/j.jclepro.2019.119602.

[10] A. K. Al-Sefri and A. M. Al-Shaalan, "Availability, Performance and Reliability Evaluation for PV Distributed Generation," *World J. Eng. Technol.*, vol. 07, no. 03, pp. 429–454, 2019, doi: 10.4236/wjet.2019.73032.

[11] K. O. Daffallah, "Modelling and sizing of a 12 V DC photovoltaic refrigerator," *Int. J. Ambient Energy*, vol. 0, no. 0, pp. 1–5, 2019, doi: 10.1080/01430750.2019.1672580.

[12] A. H. Almasoud and H. M. Gandayh, "Future of solar energy in Saudi Arabia," *J. King Saud Univ. - Eng. Sci.*, vol. 27, no. 2, pp. 153–157, 2015, doi: 10.1016/j.jksues.2014.03.007.

[13] R. Buffat and S. Grassi, "Validation of CM SAF SARAH solar radiation datasets for Switzerland," *Proc. 2015 IEEE Int. Renew. Sustain. Energy Conf. IRSEC 2015*, pp. 16–21, 2016, doi: 10.1109/IRSEC.2015.7455044.

[14] M. G. KENDALL, "A NEW MEASURE OF RANK CORRELATION," *Biometrika*, vol. 30, no. 1–2, pp. 81–93, Jun. 1938, doi: 10.1093/biomet/30.1-2.81.

[15] M. Henry, "Nonparametric Tests Against Trend Author (s): Henry B . Mann Published by : The Econometric Society Stable URL : https://www.jstor.org/stable/1907187 REFERENCES Linked references are available on JSTOR for this article : You may need to log in to JSTOR," *Econometrica*, vol. 13, no. 3, pp. 245–259, 1945.

[16] Y. Alifujiang, J. Abuduwaili, B. Maihemuti, B. Emin, and M. Groll, "Innovative trend analysis of precipitation in the Lake Issyk-Kul Basin, Kyrgyzstan," *Atmosphere (Basel).*, vol. 11, no. 4, pp. 1–16, 2020, doi: 10.3390/atmos11040332.

[17] P. K. Sen, "Estimates of the Regression Coefficient Based on Kendall's Tau," *J. Am. Stat. Assoc.*, vol. 63, no. 324, pp. 1379–1389, Apr. 1968, doi: 10.2307/2285891.

[18] L. Xing, L. Huang, G. Chi, L. Yang, C. Li, and X. Hou, "A dynamic study of a karst spring based on wavelet analysis and the Mann-Kendall trend test," *Water (Switzerland)*, vol. 10, no. 6, 2018, doi: 10.3390/w10060698.

[19] W. Wang, Z. Yi, and D. Chen, "Mann-Kendall Mutation Analysis of Temporal Variation of Apparent Stress in Qinba Mountains and Its Adjacent Areas," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 660, no. 1, 2021, doi: 10.1088/1755-1315/660/1/012112.

[20] S. Tong *et al.*, "Spatial and temporal variability in extreme temperature and precipitation events in Inner Mongolia (China) during 1960-2017.," *Sci. Total Environ.*, vol. 649, pp. 75–89, Feb. 2019, doi: 10.1016/j.scitotenv.2018.08.262.

[21] M. Ay and O. Kisi, "Investigation of trend analysis of monthly total precipitation by an innovative method," *Theor. Appl. Climatol.*, vol. 120, Jun. 2014, doi: 10.1007/s00704-014-1198-8.

[22] W. Qu, Z. Jin, Q. Zhang, Y. Gao, P. Zhang, and P. Chen, "Estimation of Evapotranspiration in the Yellow River Basin from 2002 to 2020 Based on GRACE and GRACE Follow-On Observations," *Remote Sens.*, vol. 14, no. 3, 2022, doi: 10.3390/rs14030730.

[23] H. H. E., "Long-Term Storage Capacity of Reservoirs," *Trans. Am. Soc. Civ. Eng.*, vol. 116, no. 1, pp. 770–799, Jan. 1951, doi: 10.1061/TACEAT.0006518.

[24] Subir Mansukhani, "The Hurst Exponent: Predictability of Time Series," *The Institute for Operations Research and the Management Sciences (INFORMS)*. pp. 1–10, 2012. doi: https://doi.org/10.1287/LYTX.2012.04.05.

[25] A. Gómez-Águila, J. E. Trinidad-Segovia, and M. A. Sánchez-Granero, “Improvement in Hurst exponent estimation and its application to financial markets,” *Financ. Innov.*, vol. 8, no. 1, 2022, doi: 10.1186/s40854-022-00394-x.

[26] A. W. Lo, “Long-Term Memory in Stock Market Prices,” *Econometrica*, vol. 59, no. 5, pp. 1279–1313, Aug. 1991, doi: 10.2307/2938368.

[27] L. Pérez-Sienes, M. Grande, J. C. Losada, and J. Borondo, “The Hurst Exponent as an Indicator to Anticipate Agricultural Commodity Prices,” *Entropy*, vol. 25, no. 4, pp. 1–11, 2023, doi: 10.3390/e25040579.

[28] A. H. Monahan, J. C. Fyfe, M. H. P. Ambaum, D. B. Stephenson, and G. R. North, “Empirical orthogonal functions: The medium is the message,” *J. Clim.*, vol. 22, no. 24, pp. 6501–6514, 2009, doi: 10.1175/2009JCLI3062.1.

[29] Y. Ma, H. Liu, G. Xu, and Z. Lu, “Empirical orthogonal function analysis and modeling of global tropospheric delay spherical harmonic coefficients,” *Remote Sens.*, vol. 13, no. 21, pp. 0–18, 2021, doi: 10.3390/rs13214385.

[30] C. Tang, Y. Zhu, Y. Wei, F. Zhao, X. Wu, and X. Tian, “Spatiotemporal Characteristics and Influencing Factors of Sunshine Duration in China from 1970 to 2019,” *Atmosphere (Basel).*, vol. 13, no. 12, 2022, doi: 10.3390/atmos13122015.

[31] U. Pfeifroth, J. Trentmann, S. Kothe, R. Hollmann, and M. Werscheck, “Validation Report: Meteosat Solar Surface Radiation and Effective Cloud Albedo Climate Data Record SARAH-2 . 1 climate data records,” *EUMETSAT Satell. Appl. Facil. Clim. Monit.*, vol. SAF/CM/DWD, no. 2.3, pp. 1–96, 2019, doi: 10.5676/EUM.