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Assessment of Sunshine Duration Trends in Benin through Polygonal Methods

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Authors' contributions

This work was carried out in collaboration among all authors. Author KH designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors HA and OW managed the analyses of the study. Author HF managed the literature searches. All authors read and approved the final manuscript.

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Abstract

Sunshine duration (SD) is crucial for various natural and human systems, including agriculture and photovoltaic (PV) energy production, as well as numerous environmental outcomes. This study highlights trends in sunshine duration from 1967 to 2017 in Benin. The sunshine duration data was obtained from the Benin Meteorological Agency. The innovative polygon trend analysis (IPTA) and trend polygon star concept (TPSC) methods were applied to the average monthly durations per day. The IPTA test indicates a decrease in sunshine duration in Cotonou and Kandi, while Savè experiences an increase. TPSC reveals that sunshine duration increases by two hours between September and October, while it decreases by about 1.5 hours from June to July. In

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Cotonou specifically, this decline occurs from May to June. As one of the pioneers in Benin, this study paves way for future research that could explore the long-term impacts of changes in sunshine duration on various socio-economic and health sectors in the country. Establishing a continuous sunshine monitoring system would enhance our ability to anticipate and respond to climate variations, thereby ensuring greater resilience against environmental challenges.

Keywords: Sunshine duration; sunshine trend; innovative polygonal trend analysis; trend polygon star concept; Benin; West Africa.

2010 Mathematics Subject Classification. 53C25, 83C05, 57N16.

1 INTRODUCTION

Sunshine duration (SD) is defined as the amount of solar radiation received on a given surface over a specified time interval. It is a crucial climatic parameter that influences many environmental and biological processes (Song et al., 2019). The duration and intensity of insolation are determined by a combination of geographical, climatic, and atmospheric factors. For instance, SD refers to the period during which direct solar irradiance at the Earth's surface exceeds a threshold value of 120 watts per square meter (W/m^2)(WMO, 2023). This level of irradiance occurs shortly after sunrise or just before sunset under clear conditions. The duration of insolation determines the thermal and light regime of a region, reflecting the structure and natural framework of vegetation, soils, geomorphological processes, and more.

Sunshine duration plays a crucial role in climate change and weather patterns on Earth (Nelvi and Nata, 2024). A decrease in sunshine duration may indicate an increase in airborne particles, negatively affecting air quality and local climate Kaiser and Qian (2002). Sunshine duration is also a key input for determining thermal load on buildings (Zhu et al., 2020). It is used to estimate global radiation (Zhu et al., 2015) and is inversely related to cloud cover (Angell, 1990). Periods of high cloud cover often result in a significant reduction in sunshine duration (Sanchez-Lorenzo et al., 2008). The impact of sunshine duration on agriculture is significant, as it is fundamental for plant growth, directly influencing yield and quality. Adequate sunlight and proper sunshine duration are essential for plant development (Farukh et al., 2019). Insufficient intense light can lead to poor crop growth, structural changes, and discoloration. Additionally, sunlight plays a vital role in stomatal opening and the photosynthetic capacity of plants. From an energy perspective, sunshine is the primary energy source for the terrestrial ecosystem and significantly impacts solar energy development (Sen, 2008). With the ongoing depletion of fossil fuels, rising environmental pollution, and the goal of providing universal access to affordable electricity by 2030 as part of SDG 7, the adoption of renewable energy sources is becoming increasingly vital. Consequently, research and utilization of solar radiation must be expanded (Zhou et al., 2021). Hydrologically, variations in sunshine duration can disrupt the water cycle by affecting evaporation and transpiration rates (Li et al., 2016). This disruption can further influence precipitation patterns and water resource availability. Health-wise, a link exists between sunshine duration and mortality rates. In China, for instance, the average daily sunshine duration correlates with increased crude mortality rates. This association extends to maternal mortality as well (Yu and Wang, 2023). Ji et al.(2023)(Ji et al., 2023) suggest that low sunshine duration in China could heighten the risk of mental depression.

Given the above context, any change in sunshine duration could have dramatic consequences for both humans and the environment. Numerous studies have investigated the variability of sunshine duration worldwide, revealing a phenomenon known as global dimming and brightening, characterized by an initial decrease followed by an increase. Consequently, sunshine duration has decreased over the last 60 years. Dong et al.(2013)(Dong et al., 2013) report a decline of -91.3 hours per decade in Shandong, China, from 1970 to 2009. In contrast, Quan et al.(2023) (Quan et al., 2023)found that annual sunshine duration exhibited steady dimming (-67.3 hours per decade) before 2010, followed by brightening (189.9 hours per decade) from 2011 to 2020.

In Japan, sunshine duration from spring to autumn in the northern region decreased at the end of the 1980s and throughout the 1990s, with longer periods of low sunlight in summer since the mid-1980s (Inoue and

Matsumoto, 2003). In Bangladesh, annual sunshine duration decreased from June to September between 1980 and 2010 (Farukh et al., 2019). Western Europe experienced an overall decrease in annual sunshine duration from the 1950s until the early 1980s, followed by recovery in the last two decades (Sanchez-Lorenzo et al., 2008).

In Africa, particularly Chad, studies on sunshine duration variability reveal three major fluctuation periods: 1950 to 1970, 1970 to 1990, and 1990 to 2010, characterized by low, high, and rapid year-to-year fluctuations in sunshine duration (Goni et al., 2019). In West Africa, there has been limited research on sunshine duration trends. Akinpelu and Atteh (2019) (Akinpelu and Atteh, 2019) noted an upward trend in Nigeria, but to our knowledge, no studies have addressed sunshine duration trends in Benin. This research aims to assess the trend of sunshine duration in Benin. The second section presents the data and methods used, followed by results, analysis, and discussion in section three.

2 MATERIALS AND METHODS

2.1 Data and Study Area

In this study, the sunshine duration data used are collected from synoptic stations across Benin over a significant period of time by the agency of meteorology, which is responsible for meteorological data collection in the country. Fig. 1 presents the distribution of stations throughout the territory. The data for this study cover the years 1967-2017, amounting to fifty-one years of collection. The synoptic stations have fewer missing data and play a crucial role in the collection of meteorological data in various regions of the country. In Benin, a country characterized by diverse climatic zones, these stations provide rich datasets that can shed light on local climate patterns and trends, as evidenced by their distribution across the territory.

2.2 Trend Analysis Methods

In this study, the innovative polygonal trend analysis (IPTA) method and the trend polygon star concept (TPSC) method are applied to the average of sunshine duration in each month to highlight the trends at each station. This study employs the same methodology as that developed in (Kougbeagbede et al., 2024), which we will succinctly summarize here as described.

2.2.1 IPTA Method

The IPTA method consists of five points (Patel et al., 2024). However, before detailing each step, the data from each station is organized in a matrix format (Equation 1), where the rows represent the number of years of data collection and the columns represent the periods for which trends are to be evaluated (monthly, dekadal, or seasonal). In this study, the periods are the different months of the year.

$$R = \begin{bmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,12} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,12} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n,1} & x_{n,2} & \cdots & x_{n,12} \end{bmatrix} \tag{1}$$

The resulting matrix is divided into two parts. The first part spans from year 1 to year $\frac{n}{2}$, while the second part covers from year $\frac{n}{2}+1$ to year n. The means of the first sub-matrix are constructed with those of the second sub-matrix in a cartesian coordinate system. The data from the first sub-matrix are plotted on the x-axis, and those from the second on the y-axis (see Fig. 2). The different points are connected to form a polygon as indicated in Fig. 2. Months below the 1:1 line show that the average of sunshine duration of the second period are decreasing compared to those of the first period. Similarly, months above the 1:1 line indicate an upward trend in the sunshine duration of the second period compared to that of the first. Those aligned along the 1:1 line show no noticeable trend. The distribution of sunshine duration affects the shape of the resulting polygon. More complex shapes can be expected to describe the sunshine duration behavior in the region (Sen et al., 2019).

The various steps for analyzing the data are as follows Patel et al. (2024):

1. The average of sunshine duration time series is divided into two equal parts;
2. For each month in both sub-periods, the mean is calculated;
3. On the horizontal (vertical) axis of the scatter plot, the first (second) period is located on the x-axis (y-axis), and 12 points are plotted to represent the 12 months
4. A polygon is created by connecting the points

5. The distance and slope of the line connecting two consecutive points are calculated using the formulas below:

$$d_{AB} = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2} \quad (2)$$

$$S_{AB} = \frac{y_B - y_A}{x_B - x_A} \quad (3)$$

x_A and x_B (y_A and y_B) are derived from the first (second) sub-period and represent the x-coordinates (y-coordinates) of the two consecutive points A and B.

d_{AB} indicates the sunshine duration shift between two successive months, while S_{AB} shows the increase of the second sub-period compared to the first. The steeper the slope, the greater the monthly variation in the second sub-period compared to the first, and vice versa.

When the variability is homogeneous between successive points, the polygon will exhibit a regular shape, meaning that the lengths and slopes will be the same for successive points. Under these conditions, the variability of the sunshine duration is isotropic and uniform Sen et al. (2019). Conversely, the more complex the shape of the polygon, the more complex the variability of the SD will be between successive months at the station considered.

2.2.2 TPSC Method

The TPSC is a star graph that highlights the transition between consecutive points describing the polygon obtained with IPTA Sen (2021). Through this representation, the distance between two successive points and the slope of the line connecting these two points are directly appreciable to the naked eye.

The vectors representing the transition between two successive points are drawn from the origin (0:0) of the cartesian coordinate system. For a vector depicting the transition between two successive points, the x-coordinate (y-coordinate) corresponds to the difference between the values of these two points in the first (second) sub-period. The length of the vector indicates the extent of the transition between the two points. The smaller (larger) the vector length, the smaller (larger) the transition between two successive points will be. The horizontal (vertical) projection of each vector represents the magnitude of the change in the first (second) sub-period. The change in sunshine duration from one month to another is determined by comparing the vertical and horizontal projections of the vector. The slope of the change is obtained by the ratio of the vertical to horizontal projections of the transition vector.

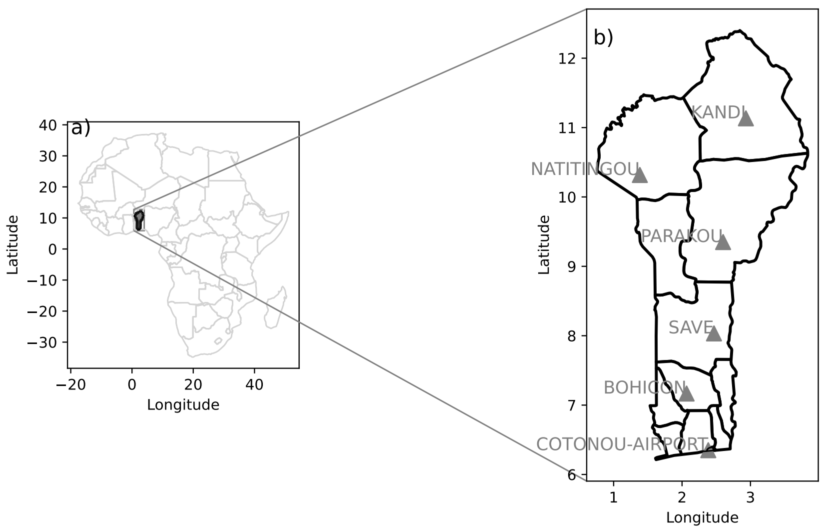

Fig. 1. (a) Benin in Africa and (b) location of synoptic stations on the map of Benin

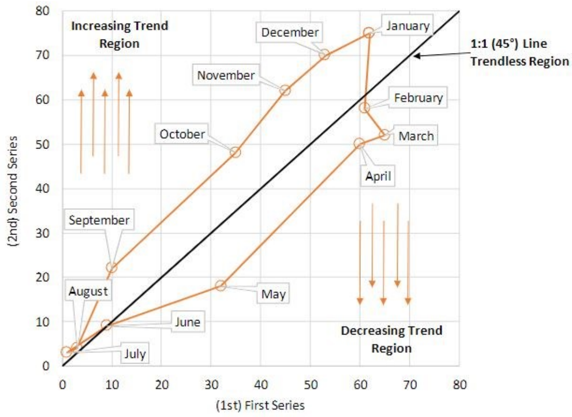

Fig. 2. An innovative polygon trend analysis (IPTA) template Patel et al. (2024)

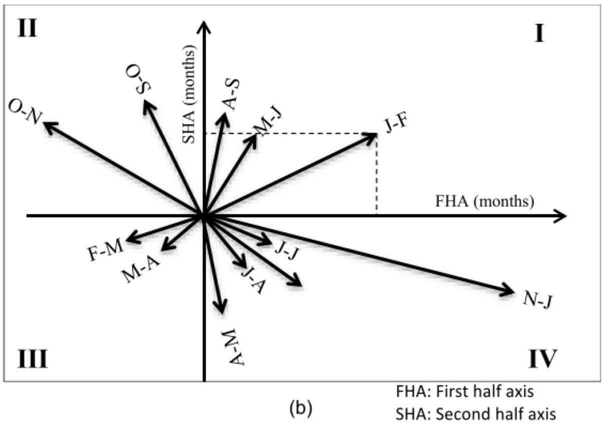

Fig. 3. TPSC example Sen (2021)

Fig. 3 shows an example of TPSC. The vectors in region I (III) indicate an upward (downward) trend in sunshine duration average in both sub-periods. Quadrant II (IV) represents an upward (downward) trend in the second (first) sub-period compared to the first (second) sub-period.

3 RESULTS

Figs. 4 and 5 illustrate the results of the IPTA and TPSC tests applied to monthly data. Table 1 highlights the transitions between successive months and the slope of these changes. Across all stations, July, August, and September consistently show the lowest sunshine durations. These findings align with those reported by (Philippon et al., 2022) in eastern equatorial Africa and (Akinpelu and Atteh, 2019) in Nigeria. The average minimum sunshine durations are less than or equal to 5 hours per day at all stations, except for Kandi, where they range from 5 to 7 hours per day. Conversely, the highest sunshine durations are recorded between November and February, ranging from 7.8 to 9.5 hours per day. The average maximum durations are slightly below 8 hours per day at Bohicon, Cotonou, and Savè stations, while Kandi experiences the longest durations, likely due to its proximity to the Sahelian region. Additionally, the transitions between successive months, as depicted in Fig. 5, occur in a consistent manner across the stations. The vectors indicating these transitions predominantly cluster in zones I and III. To further elucidate the observed changes, we will conduct a detailed trend analysis for each station in the following sections.

3.1 Bohicon Station

With the IPTA test, it is observed that the points representing the months from January to June fall below the 1:1 line, while those for July and August lie on the line, and the points for November and December are above it. This indicates that sunshine durations from January to June are decreasing compared to the first sub-period, whereas those for November and December are increasing. The transitions between successive months occur similarly across both sub-periods, with vectors predominantly located in zones I and III. In zone I, the longest transition happens between September and October, occurring at the same rate (slope = 1.09), with sunshine duration increasing by 2.5 hours per day from September to October. In contrast, the transition in zone III occurs between June and July, with a lower slope of 0.68, suggesting that the transition is more significant in the first sub-period than in the second. The transition between December and January is noteworthy as it is nearly negligible during the first sub-period, which is not the case in the second sub-period, where it increases by approximately 1.20 hours per day, with a slope of 23.88.

3.2 Cotonou Station

Located closer to the Atlantic Ocean, Cotonou Station is situated within the airport. According to the IPTA test, points representing July-August, October, and December lie on the 1:1 line, while the remaining points are below it. Only these months show no trends, while the rest indicate a relative downward trend compared to the first sub-period. Sunshine duration in the second sub-period decreases compared to the first. The TPSC also shows that the vectors are arranged in zones I and III. In Cotonou, sunshine duration increases by about 1.9 hours per day from September to October, as well as between October and November. The transition from September to October experiences a slight increase (slope = 1.24) in the second sub-period compared to the first. Conversely, the October-November transition shows a slight decrease during the second sub-period relative to the first (slope = 0.8). In zone III, the most significant transition is observed between May and June, occurring similarly across both sub-periods (slope = 0.92). The duration decreases by 2.8 hours per day when transitioning from May to June. This reduction may be attributed to June being the month with the highest rainfall, resulting in a cloudier sky Kougbeagbede et al. (2024).

3.3 Savè Station

Located in the Hills department, this area is distinguished by its hilly landscape. According to IPTA, the data points for June, July, and September-December are positioned above the 1:1 line, indicating an upward trend in sunshine duration during these months.

The TPSC test reveals that the vectors representing transitions between consecutive months are predominantly found in Zones I and III. Notably, the December-January and April-May transitions are categorized in Zone IV, indicating contrasting patterns between the two sub-periods. While the norms of these vectors are relatively low (0.56 hours/day for December-January and 0.23 hours/day for April-May), it is significant to note that sunshine duration decreased nearly fourfold during the first sub-period compared to the second for December-January (slope = -3.75) and threefold for April-May (slope = -0.30). In Zone I, the most pronounced transition occurs between September and October, with sunshine duration increasing by over two hours per day during this period. This pattern is consistent across both sub-periods.

3.4 Kandi Station

This station is located further north in the country, closer to the Sahelian zone. The duration of sunshine ranges from 5.6 hours per day to 9.5 hours per day. Aside from the data points for November and December, which are nearly aligned on the 1:1 line, all other points fall below this line. This indicates a decrease in sunshine duration from February to October during the second sub-period compared to the first. This decline can be attributed to increased precipitation at this station (Kougbeagbede et al., 2024). The TPSC test shows that the vectors are mostly clustered in zones I and III. However, the transitions between January and February, as well as between December and January, are located in zone IV. In this zone, the vectors indicate a transition of less than 0.5 hours per day, with a thirteen-fold increase from December to January and a two-fold increase from January to February (see Table 1) during the second sub-period compared to the first. In zone I, sunshine duration increases by 2 hours per day from

September to October. This variation increases by a quarter when moving from the second sub-period to the first. Furthermore, sunshine duration decreases by 1.2 hours per day from June to July (zone III) and follows a similar trend in both sub-periods.

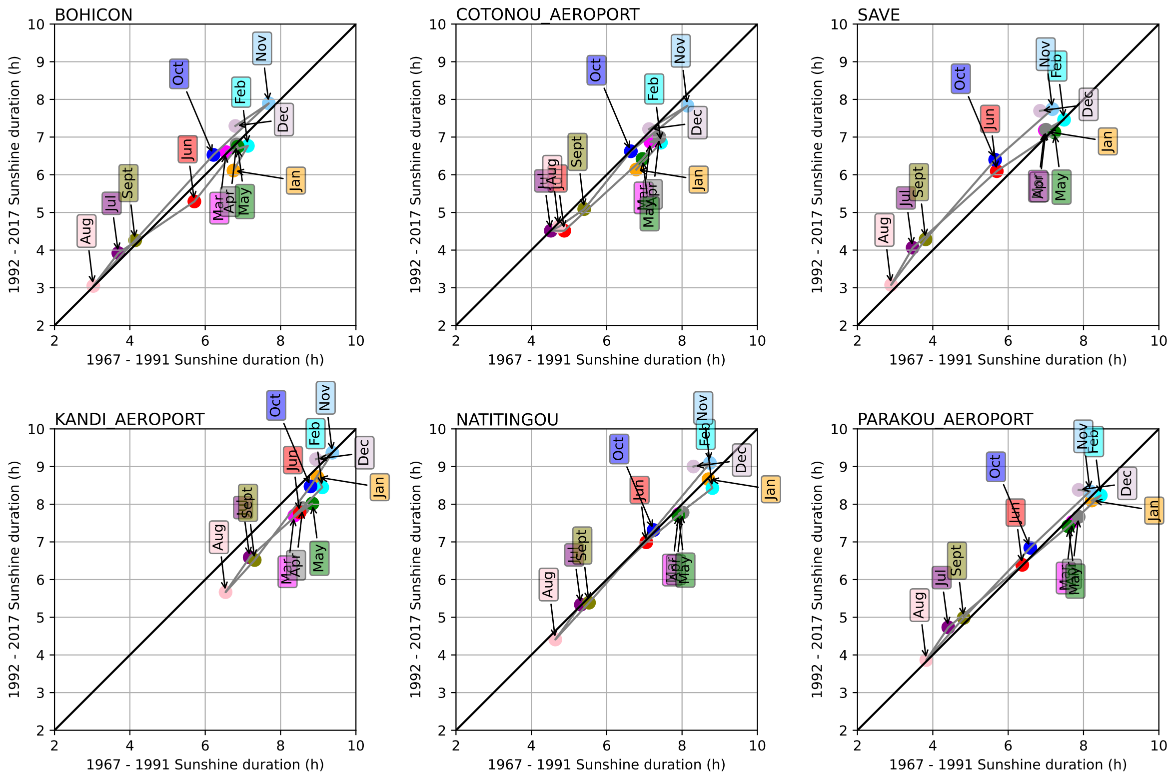

Fig. 4. IPTA test at each station

Table 1. SD distance and trend slope between successive months at each station

		J-F	F-M	M-A	A-M	M-J	J-J	J-A	A-S	S-O	O-N	N-D	D-J
2*BOHICON	TL	0.76	0.60	0.35	0.07	1.85	2.44	1.10	1.64	3.08	2.01	1.07	1.18
	slope	1.72	0.28	0.72	-1.99	1.26	0.68	1.31	1.09	1.09	0.93	0.68	23.88
2*COTONOU-AEROPORT	TL	0.97	0.28	0.27	0.73	2.82	0.36	0.24	0.82	1.97	1.93	1.19	1.13
	slope	1.09	-0.08	0.51	1.28	0.92	-0.00	0.50	0.70	1.24	0.80	0.61	3.16
2*KANDI-AEROPORT	TL	0.30	1.06	0.30	0.28	0.41	1.78	1.12	1.15	2.45	1.07	0.47	0.48
	slope	-2.09	1.01	0.90	0.48	0.70	0.90	1.44	1.10	1.32	1.54	0.39	-12.96
2*NATITINGOU	TL	0.26	1.13	0.11	0.14	1.11	2.40	1.15	1.32	2.58	2.33	0.45	0.52
	slope	-2.27	0.77	0.36	0.63	0.84	0.95	1.36	1.09	1.12	1.19	0.22	-0.84
2*PARAKOU-AEROPORT	TL	0.27	1.03	0.21	0.37	1.59	2.57	1.05	1.50	2.57	2.18	0.30	0.45
	slope	0.58	0.94	0.82	0.91	0.84	0.85	1.48	1.13	1.05	0.95	-0.13	-0.81
2*SAVE	TL	0.58	0.58	0.03	0.23	1.85	3.02	1.14	1.52	2.80	2.03	0.33	0.56
	slope	0.62	0.54	0.35	-0.30	0.67	0.91	1.73	1.32	1.15	0.88	0.13	-3.75

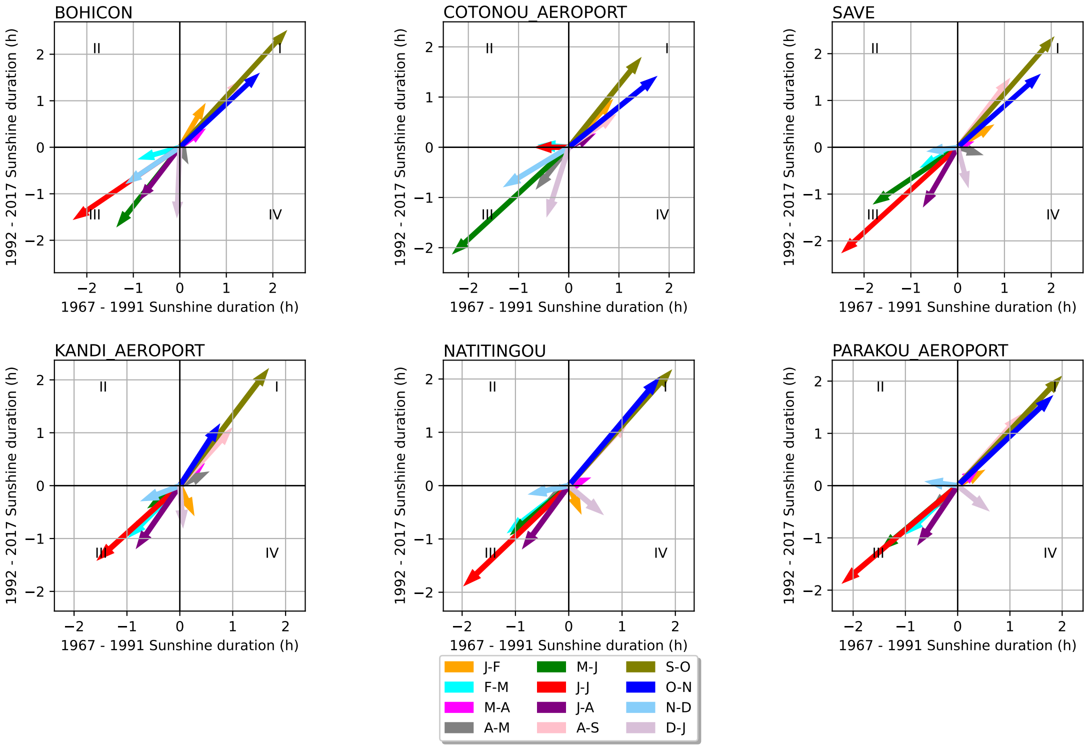

Fig. 5. TPSC test at each station

In Zone III, the June-July transition stands out as the most critical, exhibiting almost no variation (slope = 0.91) between the first and second sub-periods.

3.5 Natitingou Station

The average sunshine duration at this station varies between 4.3 and 9.1 hours per day. Except for February, November, and December, where trends appear more or less significant, the remaining months do not show any noteworthy trends. November and December exhibit an upward trend, while February shows a downward trend. The TPSC test indicates that the vectors representing transitions between consecutive months are mainly concentrated in zones I and III. In zone IV, the January-February and December-January transitions are noted. The presence of these vectors in this zone suggests contrasting transitions between the two sub-periods. According to TPSC, at this station the sunshine duration increases by 2 hours per day when transitioning from September to October and similarly from October to November (Zone I). In contrast, it decreases by the same amount when moving from June to July.

3.6 Parakou Station

The most significant trend observed at this station is during December, in comparison to the other months of the year. Sunshine duration in December experiences a slight increase in the second sub-period compared to the first. The TPSC test indicates that the vectors are mainly positioned in zones I and III. The transition from December to January appears in zone IV, while the transition from November to December is in zone II. At this station, sunshine duration increases by approximately 2 hours per day when moving from September to October (zone I) and decreases by about 2 hours per day from June to July (zone III). These transitions occur at a similar rate in both sub-periods.

4 DISCUSSION

The study of sunshine duration trends is crucial for various applied sectors, including agriculture, tourism, solar energy, transportation, and health. Understanding these trends facilitates effective planning for mitigation measures Lüdecke et al. (2024). While sunshine duration trends appear mixed in Bohicon, Natitingou, and Parakou, there are clear in Cotonou, Savè, and Kandi. Most months show a decreasing trend in Cotonou and Kandi, whereas Savè exhibits an increasing trends. However, in stations with seemingly mixed trends, some months display significant changes, such as January and June in Bohicon, and December in Natitingou and Parakou. Compared to the findings of Akinpelu and Atteh (2019), which indicate a downward trend in Nigeria, similar conclusions cannot be drawn for Benin.

Moreover, the variation in sunshine duration from month to month tends to occur similarly across both sub-periods with notable transitions. There is a marked increase or decrease in sunshine duration when transitioning between certain months. The most significant increase happens between September and October, with an approximate increase of 2 hours per day across all stations. Conversely, a decrease of about 1.5 hours per day occurs between June and July. In Cotonou, this transition happens earlier, specifically between May and June, where sunshine duration decreases by over 2 hours per day.

The observed trends in Cotonou and Kandi, where sunshine duration is decreasing, could have substantial implications for local agriculture and energy independence. For instance, reduced sunlight could lead to lower crop yields (Farukh et al., 2019). In China, Song et al.(2020)(Song and Jin, 2020) found that a reduction in sunshine duration decreased corn yield by 8%, primarily due to limited root growth. They argue that shorter durations significantly impact yield.

In a country like Benin, which faces an energy crisis, the decrease in sunshine duration in Cotonou will not support the implementation of photovoltaic systems for energy production. Therefore, solar sizing studies should take this into account. Conversely, the increasing trend noted in Savè could present opportunities for solar energy technologies, suggesting untapped potential for sustainable development. This increase could moderately enhance crop yield. Nishio et al. (2019) (Nishio et al., 2019) found that an additional hour of sunlight positively affects not only yield but also the number of seeds per square meter. However, excessive increases could jeopardize crop yields.

The pronounced transitions between September and October, where sunshine duration increases by about 2 hours daily, might indicate shifts in seasonal climate patterns, warranting careful planning for harvests and energy supply. The findings of this study have significant practical implications. For farmers, understanding sunlight trends can assist in determining optimal times for planting and harvesting, considering months with particularly high or low sunlight. In the solar energy sector, producers can adjust their solar panel installation strategies based on optimal sunlight periods, maximizing energy production. For tourism operators, this knowledge enables better planning of activities to coincide with peak sunlight periods.

5 CONCLUSION

The examination of sunshine duration trends in Benin reveals a complex interplay with significant repercussions for essential sectors, including agriculture, solar energy, tourism, and public health. Regions such as Cotonou and Kandi are experiencing declining trends, which could adversely affect agricultural productivity and solar energy generation. In contrast, area like Savè are witnessing an upward trend, offering exciting opportunities for sustainable development.

The pronounced monthly fluctuations particularly the surge in sunshine duration from September to October and the noticeable dip from June to July underscore the critical need for adaptive strategies to navigate seasonal changes effectively. Such transitions, coupled with periods of intense sunlight, should be integrated to agricultural planning to booster food security and maximize crop yields.

Implementing strategic adjustments in water resource management and farming techniques can mitigate the adverse impacts of reduced sunshine on agriculture. Furthermore, enhancing collaboration among scientists, policymakers, and economic stakeholders is imperative to develop forward-thinking adaptation and mitigation strategies that address the evolving challenges posed by these trends.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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