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Theme

Temporal Assessment of Sunshine Duration Based on Meteosat Satellite Data (CMSAF SARAH-3): Case Study of Ouargla Region

Defended publicly on June 17, 2026 before a jury composed of :

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Dedication

بس الله الرحمن الرحيم

أهدي ثمرة جهدي وتخرجي إلى أعز الناس على قلبي، إلى والديّ الكريمين اللذين كانا سندي ودعمي طوال مسيرتي الدراسية، حفظهما الله وأدامهما تاجًا فوق رأسي.

إلى إخوتي وأفراد عائلتي، الذين أحاطوني بالمحبة والتشجيع في كل خطوة.

إلى أساتذتي الأفاضل الذين أناروا دربي بالعلم والمعرفة.

إلى كل من ساهم من قريب أو بعيد في إنجاز هذا العمل.

أهدي هذا الجهد المتواضع راجيةً من الله أن يجعله بدايةً لمستقبلٍ مليءٍ بالنجاح والتوفيق.

Asma

Thanks and appreciation

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كما أتوجه بجزيل الشكر إلى الأستاذ مساعد المشرف الدكتور **فقيه عبد العالي**، على دعمه وملاحظاته العلمية القيّمة التي ساهمت في إثراء هذا العمل وتحسينه.

وأتقدم بخالص الشكر والتقدير إلى السادة أعضاء لجنة المناقشة، السيد رئيس اللجنة الدكتور **بن بلقاسم خلف الله** والسيد المناقش الأستاذ الدكتور **بن مبروك لزهر**، على تفضلهم بقبول تقييم هذا العمل، وعلى ما سيقدمونه من ملاحظات واقتراحات بنّاءة من شأنها الارتقاء بمستواه العلمي.

ولا يفوتني أن أتوجه بالشكر إلى جميع أساتذتي الكرام الذين أشرفوا على تكويني العلمي والأكاديمي طيلة سنوات الدراسة، وكان لهم الفضل فيما وصلت إليه من معارف وخبرات.

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وفي الأخير، أتقدم بالشكر إلى كل من ساهم من قريب أو بعيد في إنجاز هذا العمل، ولو بكلمة طيبة أو نصيحة نافعة.

والله ولي التوفيق

Asma

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List of acronymes

BWh	: Köppen classification
CDR	: Climate Data Record
CIMO guide	: Guide to Meteorological Instruments and Methods of Observation, WMO-No. 8
CM SAF	: The Satellite Application Facility on Climate Monitoring
DAL	: Daylight
DNI	: Direct Normalised Irradiance
GHI	: Global Horizontal Irradiance
ICDR	: Interim Climate Data Record
MAE	: Mean Absolute Error
MBE	: Mean Bias Error
MFG	: Meteosat First Generation
MSG	: Meteosat Second Generation
MVIRI	: Meteosat Visible Infra-Red Imager.
RMSE	: Root Mean Squared Error
SAL	: Surface Albedo
SARAH-3	: The third edition of the Surface Solar Radiation Data Set - Heliosat
SD	: Sunshine Duration
SEVIRI	: Spinning Enhanced Visible and InfraRed Imager
SID	: Surface Incoming Direct Radiation
SIS	: Surface Incoming Shortwave Radiation
SNL	: Surface Net Longwave Radiation
SNS	: Surface Net Shortwave Radiation
SRB	: Surface Radiation Budget
PAR	: Photosynthetic Active Radiation
WMO	: World Meteorological Organization

General introduction

Accurate knowledge of Sunshine Duration (SD) is fundamental for the design, sizing, and performance assessment of solar thermal and photovoltaic systems. Traditionally, these data are recorded by ground-based meteorological stations using Campbell-Stokes recorders or electronic pyranometers [20]. However, ground networks in arid regions are often sparse, and maintaining them in harsh desert environments presents significant logistical and technical challenges, leading to spatial and temporal gaps in the data.

To overcome these limitations, satellite-derived products have emerged as a robust alternative, providing continuous and high-resolution spatial coverage. Among these, the CM SAF SARAH-3 (Surface Solar Radiation Data Set - Heliosat, Edition 3) represents the latest generation of climate data records. Leveraging observations from the Meteosat fleet, SARAH-3 provides advanced algorithms to estimate surface radiation parameters with improved accuracy in accounting for water vapor, surface albedo, and cloud properties [21].

Sunshine duration (SD) is a precious climatic parameter because it is directly or indirectly used in many studies and applications. For example, Sunshine Duration (SD) is the most frequently used meteorological data for estimating the global solar radiation. Sunshine Duration (SD) over any surface on the earth is strongly related to clouds as well as to solar radiation.

The global shift toward sustainable energy has increased the importance of solar energy, especially in regions with high solar potential. Algeria is among the countries with the greatest solar resources worldwide, while Ouargla, located in the northern Sahara, offers highly favorable conditions for solar energy applications due to its high atmospheric transparency and long sunshine duration [19].

The primary objective of this Master's thesis is to conduct a temporal evaluation of sunshine duration in the Ouargla region by utilizing SARAH-3 satellite data. This study aims to validate the satellite estimates against locally measured ground data, analyzing the variations across different time scales daily, seasonal, and interannual. Furthermore, the research explores the impact of specific Saharan atmospheric conditions, such as high aerosol loads and dust events, on the reliability of satellite observations.

By establishing the precision of SARAH-3 in this specific hyper-arid climate, this work contributes to a better characterization of the Saharan solar resource, providing valuable insights for researchers and engineers involved in the renewable energy sector in Algeria.

The thesis is organized into four chapters:

Chapter I present Sunshine duration and its measurement methods.

Chapter II present the Meteosat CMSAF SARAH-3 satellite data.

Chapter III focus on the climatic study of the study region and the methodology adopted for this study.

Finally, in Chapter IV, we present the results and a comparative analysis between satellite data and in situ observations. Each chapter will draw on different datasets adapted to its specific research objectives. Finally, this work will be summarized in a concluding section outlining the findings and potential directions for future research.

CHAPTER I

Sunshine Duration and Its Measurement Methods

I.1. Introduction

This chapter provides a theoretical and technical foundation for understanding sunshine duration. It begins by defining the physical concepts of solar radiation and the geometric factors influencing its duration. Subsequently, it reviews the standard instrumentation used at meteorological stations—with a particular focus on the Campbell-Stokes heliograph—before transitioning into the modern methodologies of satellite remote sensing. By establishing these measurement principles, this chapter provides the necessary context for the comparative evaluation of ground and satellite data presented in the later stages of this study.

I.2. Definition and Importance

I.2.1. Definition

Sunshine duration (SD) is defined as the cumulative period during which direct solar irradiance at the Earth's surface exceeds a standardized threshold of 120 $W \cdot m^{-2}$, as recommended by the World Meteorological Organization (WMO). Physically, this threshold represents the minimum level of direct solar radiation capable of producing a distinct optical or thermal effect, historically linked to the burning principle of traditional sunshine recorders. Sunshine duration is therefore not a radiometric quantity itself, but a climatological indicator derived from the interaction between solar geometry, atmospheric transmissivity, and cloud cover [1].

From a climatological perspective, sunshine duration provides integrated information on cloudiness, atmospheric clarity, and seasonal solar availability. Unlike instantaneous irradiance measurements, SD reflects the persistence of clear-sky conditions over time, making it particularly relevant for climate classification, solar resource assessment, and agro-meteorological applications [18].

I.2.2. Importance

Sunshine duration is widely used as a key variable in climatological analyses due to its long historical availability and strong linkage to atmospheric conditions. It serves as a proxy for cloud cover variability and is commonly employed in regions where continuous radiometric measurements are scarce. In climate studies, long-term sunshine duration records are used to assess trends related to global dimming and brightening phenomena, which are associated with changes in aerosol loading and cloud properties [24].

In the context of renewable energy, sunshine duration plays a crucial role in estimating solar radiation through empirical and semi-empirical models. It is frequently used in the Angström–Prescott relationship to estimate global horizontal irradiance (GHI) from limited meteorological observations. This makes SD particularly valuable in arid and semi-arid regions, such as the Algerian Sahara, where solar energy potential is high but ground-based radiation measurements are limited [25].

I.3. Traditional measurement methods

Historically, sunshine duration has been measured using the Campbell–Stokes sunshine recorder, one of the oldest meteorological instruments still in use. Additionally, the Jordan sunshine recorders. These basic tools don't need moving parts or electricity.

Modern measurement techniques rely on electronic sunshine sensors and pyrheliometers coupled with data loggers. These instruments determine sunshine duration by continuously monitoring direct normal irradiance and applying the WMO threshold criterion. While these systems offer improved temporal resolution and objectivity, their deployment remains spatially limited, particularly in remote desert environments, due to maintenance requirements and operational costs [3][4].

I.3.1. Campbell-Stokes sunshine recorder

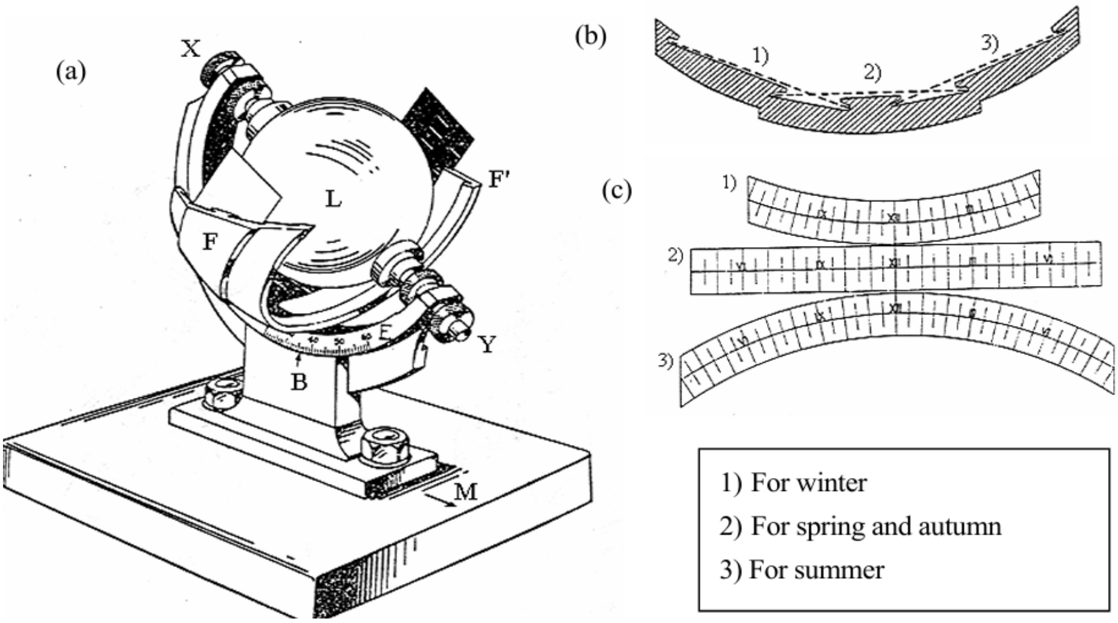
Until 1989, the Campbell-Stokes sunshine recorder has been the common instrument to measure the sunshine duration. The first version of this instrument was built by J.F. Campbell in 1853. Adjustments by G.G. Stokes, in 1879, it remains a standard, passive, and robust instrument for measuring bright sunshine. It works by focusing direct sunlight through a glass sphere to burn a trace onto a card [4][5].

Since the 1950s, the King's Park Observatory has used standard Campbell-Stokes recorders. They have a glass ball in a bowl with a metal groove that holds a recording card. Light from the sun hits the card, leaving burn marks that show how long the sun shines. People find the sunshine duration by measuring the length of these burn marks [5]. Even though it's a simple design, the recorder needs someone to look at the burn marks and change the card every day [4**].**

Figure.1.1. Campbell-Stokes Recorder [26]

(1) Principal and structure

Sunlight goes through the glass ball and hits a card at the focal point. The length of the burn mark tells how long the sun shined. The tool uses three cards for different seasons, placed in grooves in a metal bowl. To measure right, you must adjust for level, alignment, and latitude. The records tell when the sun is out based on its direction and are shown in local time [3][4].



(a) Structure (b) Cross section of bowl and grooves (c) Recording cards

Figure.1.2. Structure of Campbell-Stokes Recorder [26]

(2) Reading the recording card

To obtain uniform results for observation of sunshine duration with a Campbell-Stokes sunshine recorder, the following points should be noted when reading records:

(a) If the burn trace is distinct and rounded at the ends, subtract half of the curvature radius of the trace's ends from the trace length at both ends. Usually, this is equivalent to subtracting 0.1 hours from the length of each burn trace.

(b) If the burn trace has a circular form, take the radius as its length. If there are multiple circular burns, count two or three as a sunshine duration of 0.1 hours, and four, five or six as 0.2 hours. Count sunshine duration this way in increments of 0.1 hours.

(c) If the burn trace is narrow, or if the recording card is only slightly discolored, measure its entire length.

(d) If a distinct burn trace diminishes in width by a third or more, subtract 0.1 hours from the entire length for each place of diminishing width. However, the subtraction should not exceed half the total length of the burn trace [3][4].

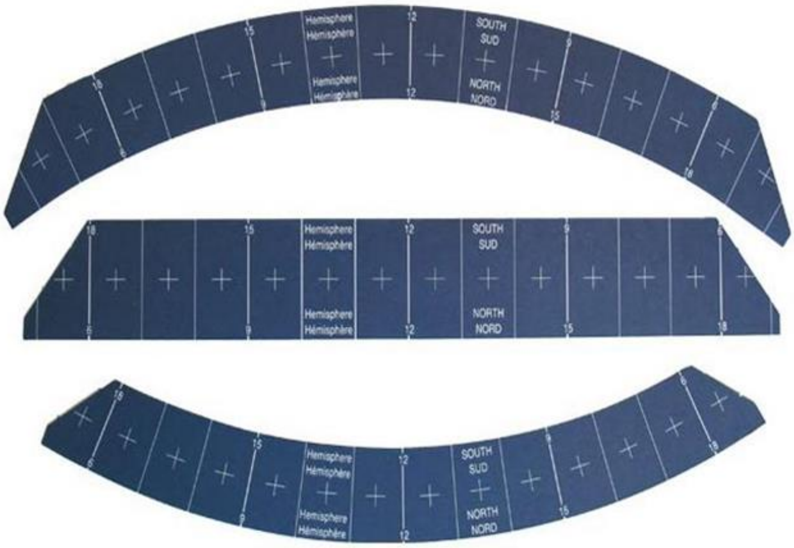


Figure.1.3. Recording cards [26]

Table.1.1. Campbell-Stokes (IRSR grade) specification [26]

Glass sphere	Spherical segment	Record cards
Shape : Uniform **Diameter** : 10cm **Colour** : Very pale or colourless **Refractive index** : 1.52 ± 0.02 **Focal length** : 75 mm for sodium "D"light	**Material** : Gunmetal or equivalent durability **Radius** : 73 mm **Additional specifications** : (a) Central noon line engraved transversely across inner surface. (b) Adjustment for inclination of segment to horizontal according to latitude. (c) Double base with provision for levelling and azimuth setting.	**Material** : Good pasteboard not affected appreciably by moisture **Width** : Accurate to within 0.3 mm **Thickness** : 0.4 ± 0.05 mm **Moisture effect** : Within 2% **Colour** : Dark, homogeneous, no difference detected in diffuse daylight **Graduations** : Hour-lines printed in black

I.3.2. Jordan sunshine recorder

A Jordan sunshine recorder lets in sunlight through a small hole in a cylinder or a semicylinder onto photosensitized paper set inside the cylinder on which traces are recorded. One common type has two hollow semicylinders arranged back to back with their flat surfaces facing east and west (Figure 1.4. (a)).

Each flat surface has a small hole in it. The Jordan sunshine recorder used by JMA is the same in principle, but consists of a hollow cylinder with two holes as shown in Figure 1.4 (b). The instrument has its cylinders inclined to the relevant latitude and their axes set in the meridional direction. Photosensitized paper with a time scale printed on it is set in the cylinders in close contact with the inner surface. When direct solar radiation enters through the hole, the paper records the movement of the sun as a line.

Sunshine duration is ascertained by measuring the length of time the paper was exposed to sunlight [4].

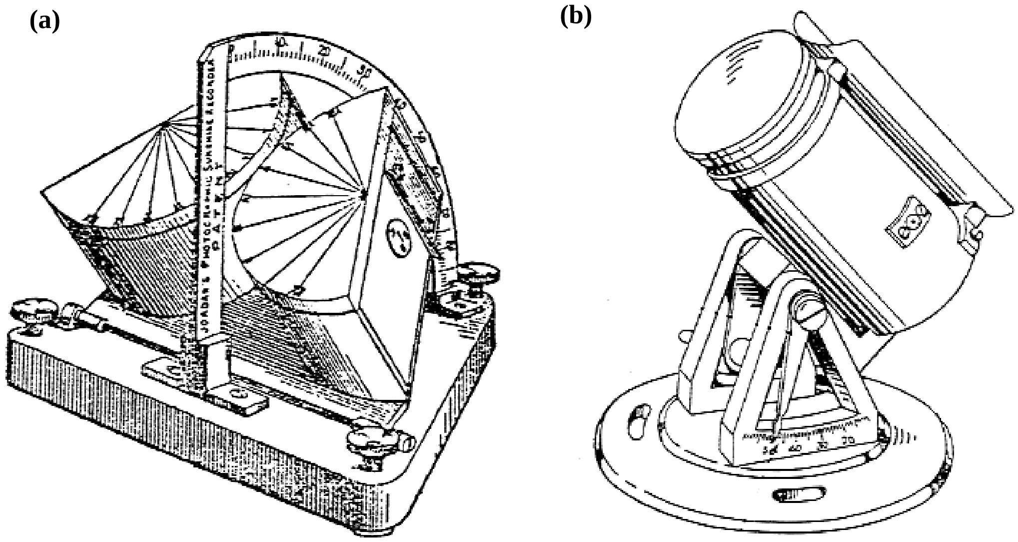


Figure.1.4. Jordan sunshine recorders (a) Common type (b) JMA type [26]

Table.1.2. present a comparison between Campbell-Stokes and Jordan sunshine Recorders:

Table.1.2. Comparison between Campbell-Stokes and Jordan sunshine Recorders [26]

Instrument	Advantages	Disadvantages
Campbell-Stokes Sunshine Recorder	Simple design and easy to use. Low cost. Does not require electrical power. Widely used in traditional meteorological stations.	Affected by thin clouds and fog. Depends on solar radiation intensity (may not record weak sunshine). Requires daily manual card replacement. Limited accuracy.
Jordan Sunshine Recorder	Relatively more sensitive than Campbell-Stokes. Suitable for certain climatic conditions.	Requires periodic maintenance. Can be affected by weather conditions (dust, humidity). Requires manual data reading.

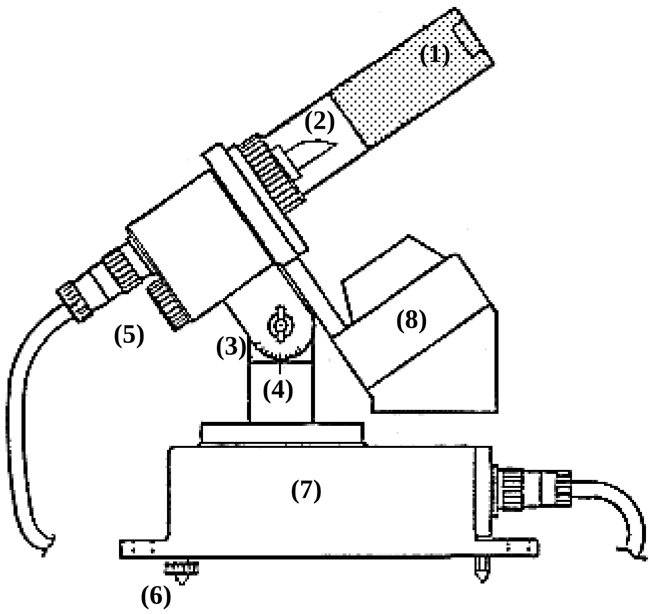
I.3.3. Other sunshine recorders

Since the threshold value for the definition of sunshine is set as a direct solar irradiance of 120 W/m2, sunshine recorders using photosensors as radiation detectors have been developed. By way of example, rotating mirror and solar-cell-type sunshine recorders are described below.

(1) Rotating mirror sunshine recorder

A rotating mirror sunshine recorder is an application of the scanning method presented in the CIMO Guide. A rotating mirror is used to reflect sunlight onto the photosensor, and the occurrence of sunshine is detected by measuring the intensity of the light received. The rotating mirror sunshine recorder used by JMA has a mirror that rotates once every 30 seconds and a photosensor to receive the reflected sunlight.

Once the instrument is set to an angle corresponding to the latitude at the site by adjusting the scale on the body at installation, the double-surfaced mirror reflects sunlight as required throughout the year regardless of changes in the sun’s elevation. Although the radiation received by the photosensor contains both direct solar radiation and diffuse sky radiation, the latter is removed by differentiating the output signal for time electrically, and only direct solar radiation can be detected at the peak of the maximum differential coefficient. The instrument emits a pulse when the signal exceeds the threshold value of 120 W/m^2 corresponding to the definition of direct solar irradiance, and the processing unit counts two minutes of sunshine for every four pulses.



(1) Photosensor
(2) Rotating reflective mirror
(3) Latitude adjusting scale
(4) Latitude adjusting mark
(5) Desiccant container
(6) Level adjusting screw
(7) Converter
(8) Fan

Figure.1.5. Rotating mirror sunshine recorder [26]

(2) Solar-cell-type sunshine recorder

A solar-cell-type sunshine recorder is an application of the contrast method presented in the CIMO Guide. It uses solar cells and determines the occurrence of sunshine from the intensity of their output.

The device is equipped with three solar cells on a triangular prism oriented toward the celestial North Pole –one on top and one on each of the southeast and southwest faces.

The output of the solar cells on each of the southeast and southwest faces includes direct solar irradiance and diffuse sky radiation. As the solar cell on the top is shaded from direct sunlight, its output can be considered equivalent to the level of diffuse sky radiation. By taking the difference between these outputs, an output value equivalent to the level of direct solar irradiance can be obtained. Solar-cell-type sunshine recorders are somewhat inferior in terms of accuracy to rotating mirror sunshine recorders; they are known to underestimate the sunshine duration in the morning and evening, during cloudy weather, and in the summer season when the sun's elevation is high.

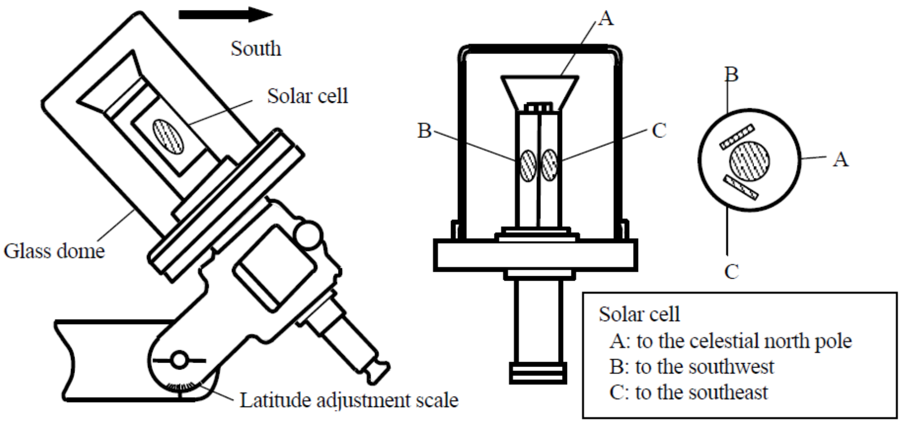


Figure.1.6. Solar-cell-type sunshine recorder [26]

1.4 Relationship between sunshine duration and solar radiation

A strong empirical relationship exists between sunshine duration and surface solar radiation, particularly global horizontal irradiance. One of the most widely used formulations is the Angström–Prescott model, which expresses the ratio of measured to extraterrestrial solar radiation as a linear function of relative sunshine duration[22].

$$\frac{H}{H_0} = a + b\left(\frac{S}{S_0}\right) \tag{1.1}$$

Where:

H: Global solar radiation at the Earth's surface

H_0 : Extraterrestrial solar radiation

S: Actual sunshine duration

S_0: Maximum possible sunshine duration (day length)

a, b: Empirical constants depending on location

This formula is still a common way to estimate solar radiation using sunshine duration [7][8]. And this relationship has been extensively validated across diverse climatic regions and remains a cornerstone of solar radiation estimation in data-scarce areas [7].

From a physical standpoint, sunshine duration primarily reflects the presence or absence of clouds along the solar beam path, whereas solar radiation is additionally influenced by atmospheric absorption and scattering processes involving aerosols and water vapor. Consequently, variations in sunshine duration are generally well correlated with changes in direct solar radiation, while the relationship with diffuse radiation is more complex and climate-dependent [8].

1.5 Temporal Variability of Sunshine Duration

Sunshine duration exhibits variability across multiple temporal scales, driven by both astronomical and meteorological factors. Daily variability is influenced by transient cloud systems and synoptic-scale weather patterns. Monthly and seasonal variations are largely governed by changes in solar declination, day length, and regional circulation regimes. In desert regions, seasonal variability is typically characterized by maximum sunshine duration during summer months, when clear-sky conditions dominate, and slightly reduced values during transitional seasons due to episodic cloudiness and dust events [8].

Long-term variations in sunshine duration provide valuable insight into climate variability and change. Numerous studies have documented multi-decadal trends associated with global dimming (1950s–1980s) and subsequent brightening, highlighting the sensitivity of sunshine duration to changes in atmospheric composition and cloud cover [8].

CHAPTER II

Meteosat Satellite Data: CMSAF SARAH-3

II.1. Introduction

This chapter focuses on the SARAH-3 (Surface Solar Radiation Data Set - Heliosat, Edition 3), a state-of-the-art climate data record provided by the EUMETSAT Climate Monitoring Satellite Application Facility (CM SAF). Based on observations from the MVIRI and SEVIRI sensors aboard the Meteosat series of geostationary satellites, SARAH-3 represents the latest evolution in long-term solar radiation retrieval. It provides a consistent and homogenized time series of surface radiation parameters, including sunshine duration, spanning several decades.

II.2. Geostationary Meteosat Satellites and Solar Observations

The Meteosat series operated by EUMETSAT consists of geostationary meteorological satellites that have offered continuous and reliable observations of the Earth's atmosphere since 1977. Positioned at an altitude near 36,000 kilometers above the equator, these satellites maintain a fixed position relative to the Earth's surface, which allows for sustained observation of approximately one-third of the planet. Meteosat contributes significantly to weather forecasting, nowcasting, and climate surveillance by providing near real-time data on atmospheric parameters such as cloud cover, solar radiation, and other essential meteorological variables [9].

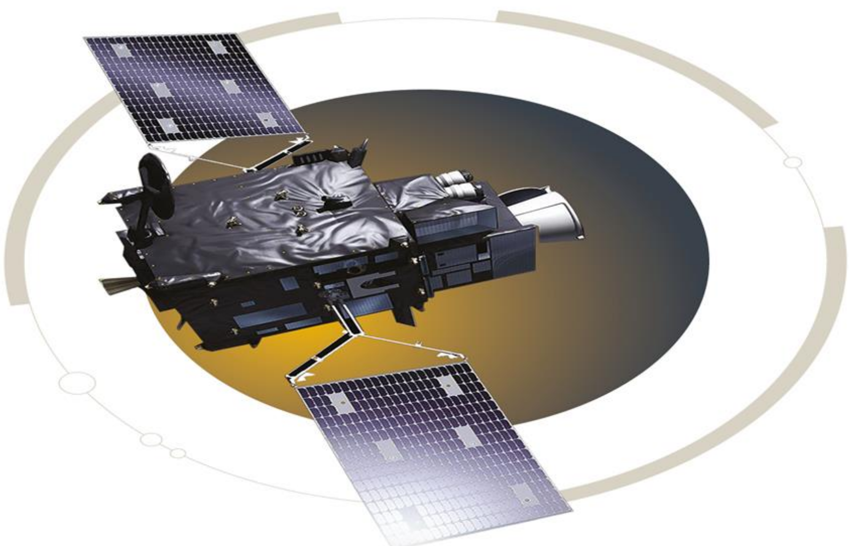


Figure.2.1. Geostationary Meteosat Satellite Model [23]

Meteosat First Generation (MFG) and Meteosat Second Generation (MSG) satellites carry visible and infrared sensors that enable the detection of clouds, surface reflectance, and atmospheric conditions. The visible channels are particularly important for solar applications, as they provide information on top-of-atmosphere reflectance under daylight conditions, which is directly related to cloud optical properties and surface albedo (Cano et al., 1986).

II.3 The SARAH-3 Product

The SARAH-3 (Surface Solar Radiation Data Set - Heliosat) product constitutes a satellite-derived climate data record developed by EUMETSAT under the CM SAF initiative, aimed at providing refined estimates of surface solar radiation. This dataset is generated from visible channel measurements acquired by the MVIRI and SEVIRI instruments on board geostationary Meteosat satellites from the first (MFG) and second (MSG) generations, respectively. Integrating these sources enables SARAH-3 to maintain substantial temporal consistency and high data quality [10][11].

Covering the period from 1 January 1983 to 31 December 2020 as a Climate Data Record (CDR), SARAH-3 is extended operationally to the present as an Interim Climate Data Record (ICDR) with minimal latency, while preserving methodological consistency between the CDR and ICDR products [11] .The dataset encompasses the geographical domain between approximately ±65° latitude and longitude and is provided on a uniform grid with a spatial resolution of 0.05° × 0.05° (approximately 5.5 km x 5.5 km).

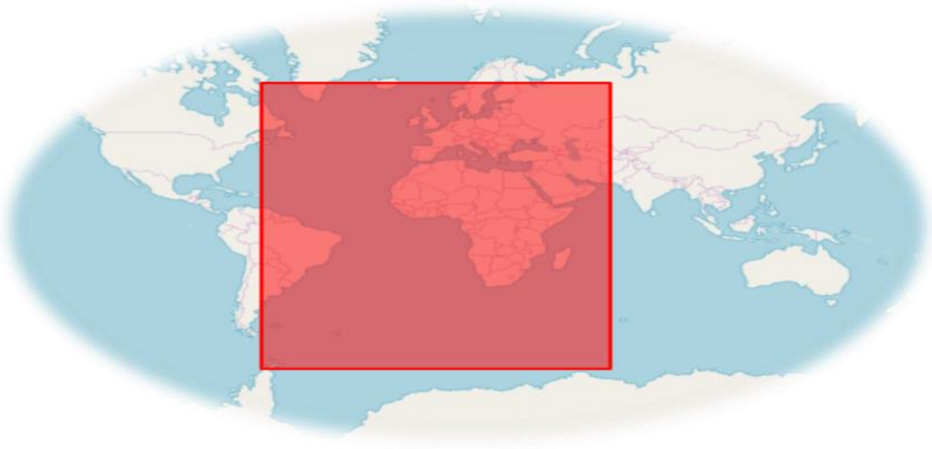


Figure.2.2. Geographical coverage of the SARAH-3 product [11]

SARAH-3 represents the most recent iteration in the SARAH data series, which has progressively evolved since its inception through versions SARAH-1, SARAH-2, and SARAH-2.1, each incorporating enhancements in data quality and temporal stability. Notably, SARAH-3 improves surface solar radiation estimates over snow-covered regions, mitigating the underestimation found in earlier versions [13][11].

Moreover, the dataset is supplemented by detailed documentation of the underlying algorithms, validation assessments, and user guidance, supporting its reliability for climate monitoring and environmental research. Access to the data is facilitated through the CM SAF Web User Interface, with selected products also disseminated via EUMETCast [10].

II.4. Available Parameters and Spatial-Temporal Resolution

The CM SAF SARAH-3 (Surface Solar Radiation Data Set – Heliosat) constitutes an extensive dataset of surface solar radiation parameters. It encompasses multiple variables that facilitate a variety of scientific analyses and practical applications, notably within climate research and the evaluation of solar energy potential. The dataset is distinguished by its enhanced data quality, particularly in snow-affected regions. Furthermore, SARAH-3 provides a long-term time series exceeding four decades, aligning with the current climatological normal period. Continuous updates are performed through near-real-time processing under the Interim Climate Data Record (ICDR) framework, which supports ongoing data continuity and accessibility [10].

II.4.1. Variables and Technical Characteristics

The SARAH-3 dataset incorporates ten principal parameters concerning surface solar irradiance, including:

1. Surface Incoming Shortwave Radiation (SIS)
2. Direct Normalised Irradiance (DNI)
3. Surface Incoming Direct Radiation (SID)
4. Surface Net Longwave Radiation (SNL)
5. Surface Net Shortwave Radiation (SNS)
6. Surface Radiation Budget (SRB)
7. Sunshine Duration (SD)
8. Photosynthetic Active Radiation (PAR)
9. Daylight (DAL)
10. Surface Albedo (SAL)

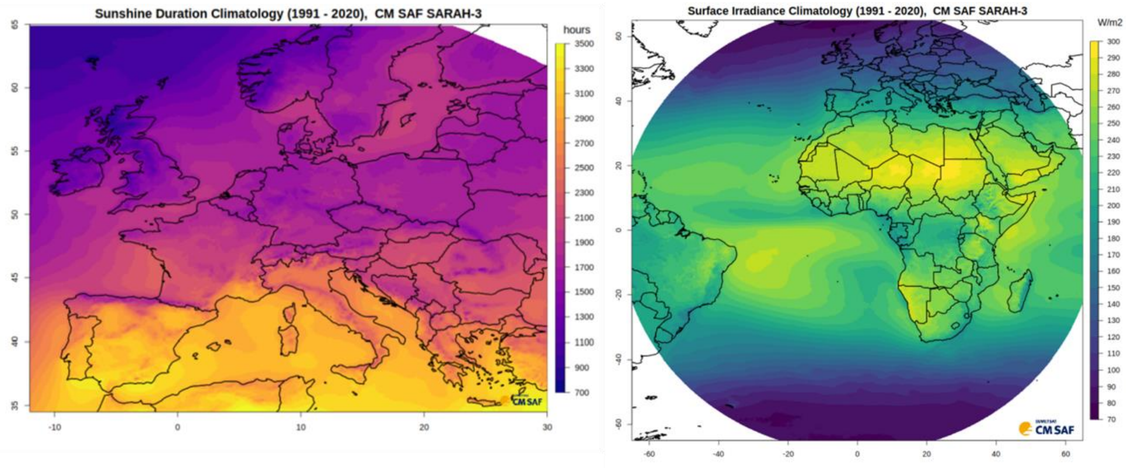


Figure.2.3. Spatial distribution of the climatological surface irradiance and sunshine duration based on SARAH-3 data from 1991 to 2020 [12]

These parameters are derived from observations gathered by geostationary satellite sensors belonging to both the first and second generations of Meteosat satellites—specifically Meteosat First Generation (MVIRI) and Meteosat Second Generation (SEVIRI). This enables the dataset to achieve broad spatial coverage across Africa, Europe, and much of the Atlantic Ocean [14].

II.4.2. Spatial and Temporal Resolution and Coverage

SARAH-3 data are provided on a regular geographic grid with a spatial resolution of 0.05° × 0.05°, resulting in a grid size of approximately 2601 × 2601 pixels. Altitude information is adjusted to correspond with the terrain. Temporally, the dataset offers 30-minute intervals along with daily and monthly averaged values.

The spatial domain extends roughly from 65°S to 65°N latitude and from 65°W to 65°E longitude. Temporally, the record spans from 1983 to 2020 as part of the Climate Data Record (CDR), with subsequent data from 2021 onward incorporated within the Interim Climate Data Record (ICDR)[10][14] .

II.5. Advantages and Limitations of the SARAH-3 Product

II.5.1. Advantages

The SARAH-3 (Surface Solar Radiation Data Set – Heliosat, version 3) constitutes a satellite-derived dataset developed within the CM SAF project, distinguished by several attributes that enhance its suitability for climate research and solar energy applications.

One key feature of SARAH-3 is its provision of a long-term, consistent time series extending over more than forty years. This extensive temporal range facilitates robust analysis of climate variability and the detection of long-term trends in solar radiation [10].

Compared to earlier iterations, the dataset exhibits improved accuracy and data quality. These improvements are particularly evident in the representation of surface conditions, such as those found in snow-covered regions and under complex atmospheric scenarios, thereby yielding more reliable solar radiation estimates [15].

The dataset also offers high spatial and temporal resolution, which enables detailed investigation at regional and local scales. The provision of data in daily, monthly, and near real-time intervals further enhances its versatility for both operational use and scientific inquiry [10].

Geographically, SARAH-3 covers a broad expanse including Europe, Africa, and parts of the Middle East. Such spatial coverage supports extensive large-scale and regional analyses [10].

Data continuity and homogeneity are ensured through observations from Meteosat geostationary satellites, which is particularly beneficial in areas where ground-based measurements are sparse or unavailable.

Additionally, the dataset includes a comprehensive array of solar radiation variables—Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), and Diffuse Horizontal Irradiance (DHI)—which are critical for diverse scientific investigations and practical applications, including the design of solar energy systems and climate modelling [15].

II.5.2. Limitations

SARAH-3 (Surface Solar Radiation Data Set – Heliosat, Edition 3) is a satellite-derived dataset that provides climate records of surface solar radiation from 1983 to the present, serving purposes in climate monitoring and renewable energy research [10].

- Variable Accuracy Depending on Temporal Resolution, although improvements have been made compared to earlier versions, accuracy varies with the temporal resolution of the measurements (instantaneous, daily, or monthly). Monthly surface radiation estimates demonstrate a mean deviation of approximately 5 W/m² relative to reference observations, while deviations increase for daily and instantaneous data. This suggests that uncertainty grows as temporal resolution becomes finer, which may have implications for studies requiring precise temporal characterization or seasonal assessments. Challenges in Snow and Cloud Detection, the dataset employs an internal algorithm for identifying snow and cloud cover. However, during the early period of the record (1980s–1990s), the lower quality of satellite inputs limited the algorithm's performance in correctly detecting snow cover. This limitation can result in misclassifying snow as cloud, thereby compromising the accuracy of solar radiation retrievals in snowy environments.

- Biases in Long-Term Climate Metrics, Analysis of long-term solar radiation trends reveals several concerns. There exist minor temporal biases when comparing SARAH-3 data with ground-based observations, such as a negative deviation around 0.6 W/m^2 over certain intervals. Consequently, long-term trend estimates may not be entirely free from systematic bias. Additionally, the dataset does not explicitly incorporate major climatic events—for example, the 1991 eruption of Mount Pinatubo—potentially influencing the interpretation of short- to medium-term climate variability.

- Geographic Coverage and Instrument Limitations, SARAH-3 utilizes data from geostationary Meteosat satellites, which provide coverage primarily between 65°W to 65°E longitude and 65°S to 65°N latitude. This limited spatial extent means that certain applications requiring global data may encounter gaps. Furthermore, data accuracy may degrade in regions characterized by complex meteorological conditions, such as high-altitude terrain or polar zones.

CHAPTER III

Study Area and Research Methodology

III.1. Introduction

The chapter is divided into two primary sections. The first section characterizes the geographical and climatological profile of Ouargla, highlighting the geographic position of Ouargla city and climatological parameters such as Temperatures, precipitation, Wind, Sunshine duration and solar radiation that influence measurement accuracy. The second section details the research methodology, describing the statistical validation strategy, including the data cleaning procedures, the temporal alignment of satellite and in-situ time series, and the mathematical formulations of the performance indicators (MAE, MBE, RMSE, and R2).

III.2. Presentation of the study area

III.2.1. Geographical Description

Ouargla region, often referred to as the "Capital of the Oases," is located in the south-eastern part of Algeria. Geographically, it is situated at 31°56’ North latitude, at 5°24’ East longitude, and at an elevation of approximately 144 meters above sea level. . It serves as a vital hub in the Northern Sahara, characterised by its strategic importance in energy production and its historical role in trans-Saharan trade.

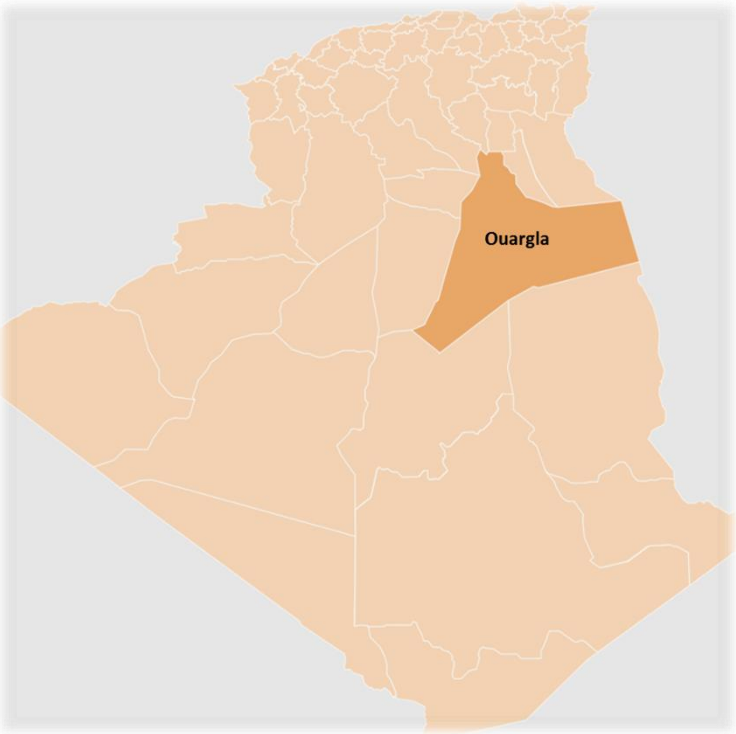


Figure.3.1. The study area location map [27]

According to updated geographic data following the 2019-2021 administrative reorganization, Ouargla is bordered to the:

North: Touggourt, El M'Ghair, Ouled Djellal, and Djelfa.

East: Tunisia.

West: Ghardaïa, El Menia, and Laghouat.

South: In Salah and Illizi.

III.2.2. Climate Characteristics

Ouargla is characterised by a hyper-arid Saharan climate, according to the Köppen classification (BWh). This climate is defined by extreme thermal amplitudes and a chronic deficit in precipitation.

1. Temperatures

Ouargla is characterized by significant temperature variations between day and night, as well as between winter and summer. The maximum temperature can reach 50°C, while in December it drops below freezing.

An analysis of monthly temperature data for the Ouargla region during the period 2016-2025, as shown in Figure 3.2, reveals that the average maximum temperature is 43.3°C in July, making it one of the hottest months in the region. The lowest temperatures are recorded in January, at 4.9°C, making it one of the coldest months.

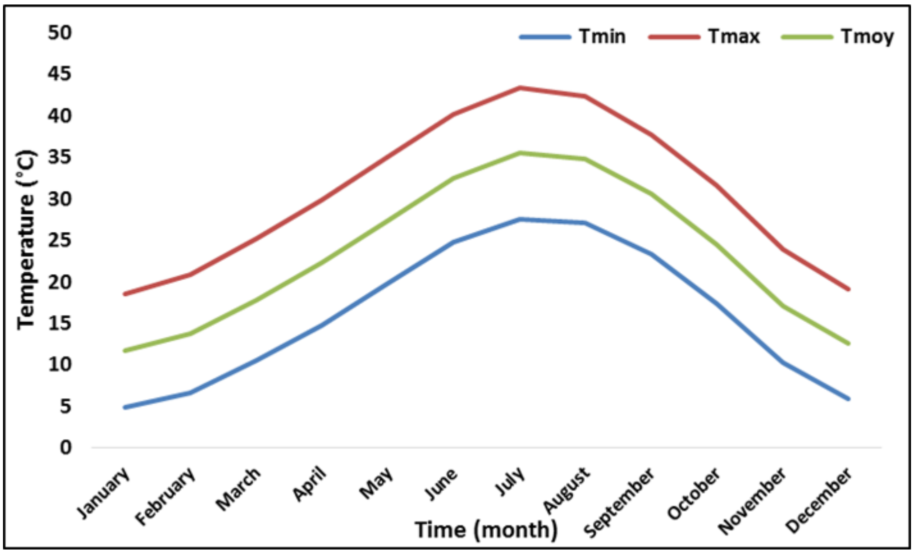


Figure.3.2. Variation of temperatures in the Ouargla region (2016-2025)

2. Precipitation

The Ouargla region experiences some fluctuations in rainfall, with no clearly defined rainy season. Climatologists attribute this to the climate change affecting the region. Despite this, as shown in Figure 3.3, the average annual rainfall is approximately 96.4 mm. Rainfall is concentrated during the winter months, with the highest amount recorded in January at around 17.7 mm. Rainfall decreases significantly during the remaining months of the year. The lowest amounts are recorded during the summer, with rainfall being almost non-existent, particularly in July (0.4 mm) and June (0.1 mm).

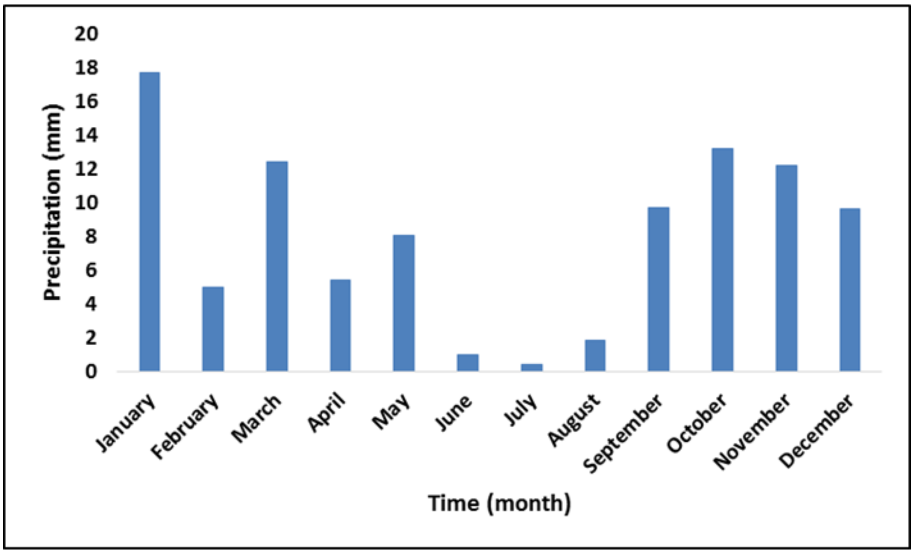


Figure.3.3. Variation of precipitation in the Ouargla region (2016-2025)

3. Winds

Figure 3.4 shows the change in wind speed, revealing a clear seasonal fluctuation throughout the year. Wind speed gradually increases from January to May, reaching 10.7 m/s in May, which represents the annual peak. Wind speed then decreases relatively from June to August. Thus, it is evident that the Ouargla region experiences its highest wind speeds during the spring season. The city of Ouargla is exposed to two types of winds:

- Cold winds: blowing from the east and northeast.
- Hot winds: blowing from the south and southwest.

These winds are accompanied by blowing sand, which forms sandstorms.

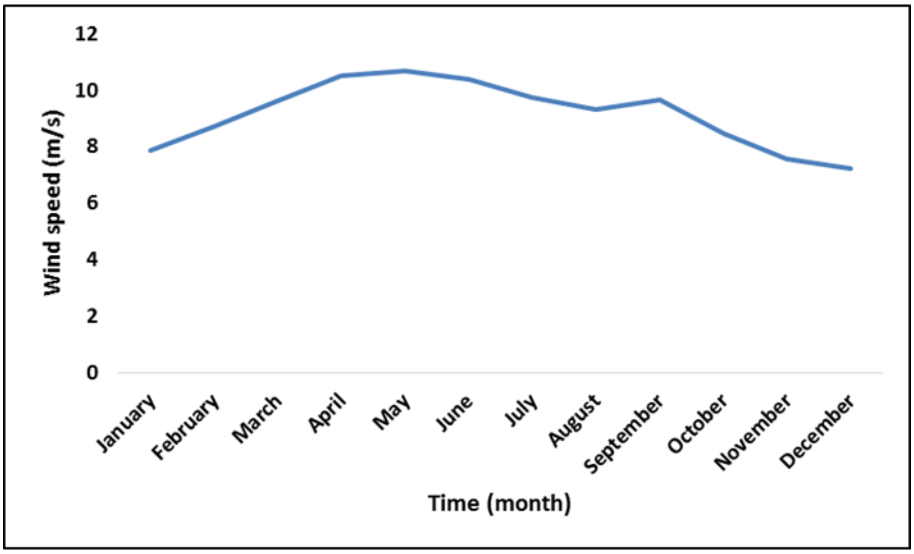


Figure.3.4. Variation of Wind speed in the Ouargla region (2016-2025)

4. Sunshine duration

Sunshine duration refers to the number of hours a region receives direct sunlight. It is linked to clear skies and day length, and is particularly long in the absence of cloud cover. Ouargla is characterized by considerable sunshine duration.

The maximum sunshine duration is recorded in July at approximately 322.1 hours, followed by 319.2 hours in August, and reaches its minimum in December at approximately 210 hours. The annual sunshine duration reaches approximately 3157.8 hours, averaging 8.6 hours per day. (See Figure 3.5).

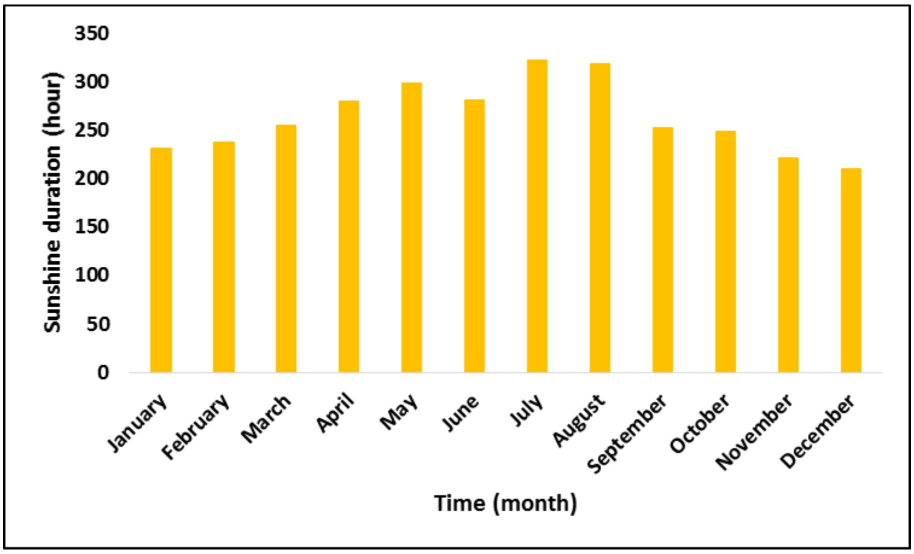


Figure.3.5. Variation of Sunshine duration in the Ouargla region (2016-2025)

5. Solar radiation

Figure (3.6) indicates the change in total solar radiation in the Ouargla region during the period (2016-2025), where we note that the intensity of total solar radiation peaks around midday, exceeding 800 W/m^2, where we note a great correlation between the duration of sunshine and the amount of solar radiation reaching the Earth's surface.

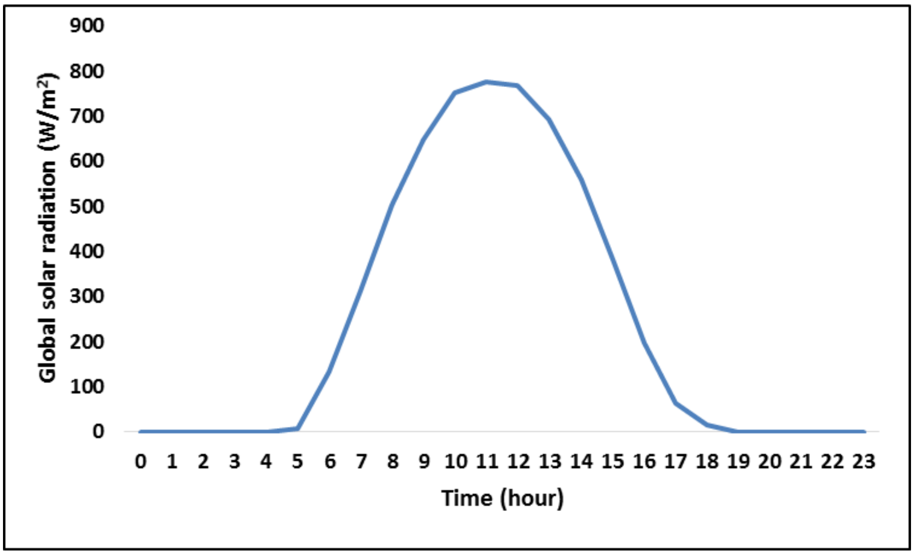


Figure.3.6. Variation of Global solar radiation in the Ouargla region (2016-2025)

III.3. Research Methodology

III.3.1 Data Acquisition and Selection

III.3.1.1. Satellite Data

The primary data source for this study is the Surface Solar Radiation Data Set - Heliosat, Edition 3 (SARAH-3).

Source: The data was retrieved from the EUMETSAT Climate Monitoring Satellite Application Facility (CM SAF) web portal.

Format: The files are provided in NetCDF-4 (Network Common Data Form), which is the standard for multidimensional climate data.

Selection Criteria: To ensure a robust temporal assessment, the period from [2001] to [2017] was selected. This provides a sufficiently long time series to capture inter-annual variability and seasonal cycles in the Ouargla region.

Variables Extracted: While SARAH-3 provides several radiation parameters, the focus was strictly on SD (Sunshine Duration), which is provided as monthly sums and averages [16].

III.3.1.2. In-situ Data

Ground-based measurements were obtained from National Meteorological Office (ONM) of Ouargla city.

Station Details: Ouargla station (WMO ID: 60580, Latitude: 31.56° N, Longitude: 5.24° E, Elevation: 144 m).

Instrumentation: The data reflects measurements from Campbell-Stokes recorders.

Temporal Resolution: Daily sunshine duration totals were compiled to match the temporal scale of the SARAH-3 monthly product.

III.3.2. Evaluation metrics

Based on common methodology for time-series forecasting, climate modeling, and environmental analysis, particularly when separating performance by months and seasons, the following validation metrics are typically calculated:

III.3.2.1. Mean Absolute Error (MAE)

The MAE is the sum of absolute values of the errors divided by the number of observations. This quantity is often used in statistics as measure how close calculated values are to measured values [17]. In authors pointed out some advantages of MAE over the root mean squared error (RMSE) in dimensioned evaluations and inter-comparisons of average model performance error:

$$MAE = \frac{1}{N}\sum\left|H_{Observed} - H_{Calculated}\right| \qquad (1.3)$$

III.3.2.2. Mean Bias Error (MBE)

This indicator expresses a tendency of model to underestimate (negative value) or overestimate (positive value) sunshine duration, while the MBE values closest to zero are desirable [17]. The drawback of this test is that it does not show the correct performance when the model presents overestimated and underestimated values at the same time, since overestimation and underestimation values cancel each other.

$$MBE = \frac{1}{N}\sum\left(H_{Observed} - H_{Calculated}\right) \qquad (2.3)$$

III.3.2.3. Root Mean Squared Error (RMSE)

The RMSE is a frequently used measure to compare forecasting errors of different models. The lower the RMSE value the better the predictive capability of a model in terms of its absolute deviation [17]. However, presence of few large errors can result in greater value of RMSE:

$$RMSE = \sqrt{\frac{1}{N}\sum(H_{Observed} - H_{Calculated})^{2}} \quad (3.3)$$

III.3.2.4. Coefficient of determination (R^2)

This indicator is often used in statistics for estimating the performance of the models. It depicts the fraction of the calculated values that are the closest to the line of measurement data [17]. While the ideal values of all other statistical indicators used in this study are 0, values of the coefficient of determination close to 1 indicate more efficient models:

$$R^2 = 1 - \frac{\sum(H_{Observed} - H_{Calculated})^{2}}{\sum(H_{Observed} - \overline{H}_{Observed})^{2}} \quad (4.3)$$

CHAPTER IV

Results and Analysis

IV.1. Introduction

This chapter presents a comprehensive evaluation of the SARAH-3 satellite-derived sunshine duration against in-situ observations recorded at the Ouargla meteorological station over a 17-year period (2001–2017). This specific period was selected based on the availability and quality of reliable ground-based data from the Ouargla meteorological station during that timeframe. The analysis is structured into two main levels: (1) An assessment of the overall performance using standard indicators such as MAE, MBE, RMSE, and R^2 and (2) an investigation into the daily, monthly, seasonal and yearly fluctuations of errors to identify the impact of Saharan climatic cycles.

IV.2. Comparison of observed and calculated sunshine duration

According to the WMO recommendations, the basic period for which sums of sunshine duration are reported is a day (24 h), a month, or a year. Such information is crucial in theoretical and applied sciences, and in the next part of the study, we concentrate on the accuracy of daily, monthly, seasonal and yearly sums of sunshine duration.

IV.2.1. Daily sunshine duration

Figure 4.1 shows the daily observed sunshine duration versus the daily calculated sunshine duration for Ouargla region.

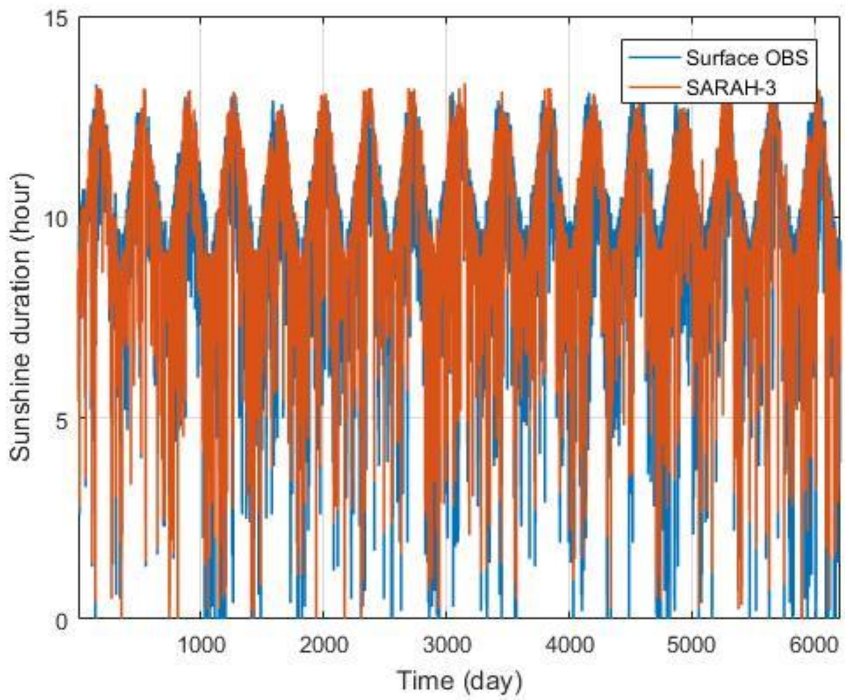


Figure.4.1. Daily observed and calculated sunshine duration for Ouargla region (2001 – 2017)

The analysis of the diagram shows excellent global agreement between in-situ measurements and SARAH-3 data. However, low values on days when the sunshine duration is lower than 5 hours. This is often where the gap is largest. These points usually correspond to cloudy days or dust episodes where the satellite struggles to distinguish thin clouds from dense aerosol layers. In addition, high frequency around 10 to 13 hours/day. This is the signature of the desert climate.

IV.2.2. Monthly sunshine duration

Based on the comparative analysis presented in Figure 4.2, the monthly sunshine duration (SD) shows an excellent seasonal correlation between the two datasets, with both datasets successfully capturing a typical Northern Hemisphere cycle that peaks in July and reaches its minimum in December and January. However, a clear systematic positive bias is evident, as the satellite-derived SD_SARAH3 overestimates the ground-based SD_Surface OBS measurements during every month of the year. This discrepancy is particularly pronounced during the summer months (May through August), when regional atmospheric turbidity, such as suspended dust and sandstorms, frequently causes ground sensors to record lower direct irradiance while the satellite pixel average overmodels clear skies, whereas the data converge more closely during the more stable winter months.

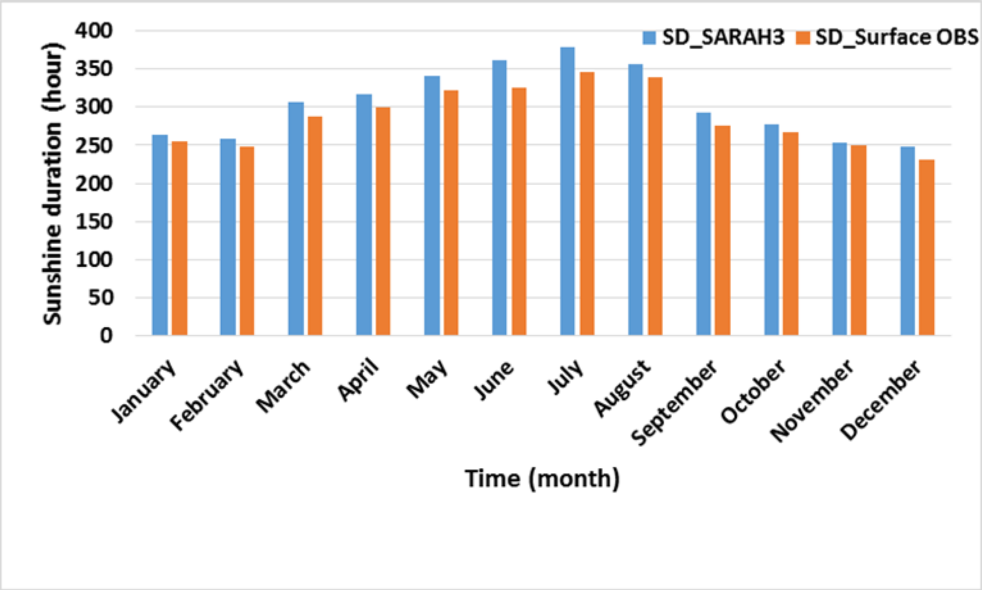


Figure.4.2. Monthly observed and calculated sunshine duration for Ouargla region (2001 – 2017)

IV.2.3. Seasonal sunshine duration

Based on the seasonal comparative data presented in Figure 4.3, the seasonal sunshine duration exhibits a highly consistent macro-trend across both datasets, with maximum values expectedly occurring during the summer and minimum values during the winter. A persistent systematic overestimation by the satellite product remains clear, as SD_SARAH3 exceeds the ground-truth SD_Surface OBS across all four seasons. This positive bias reaches its largest absolute magnitude during the summer, driven by the challenge of satellite retrieval algorithms to fully capture localized, heavy atmospheric dust and sandstorm dynamics that reduce ground-sensor exposure. Conversely, the discrepancy visibly narrows during autumn and winter, revealing an improved alignment between satellite clear-sky index modeling and the more stable seasonal ground conditions.

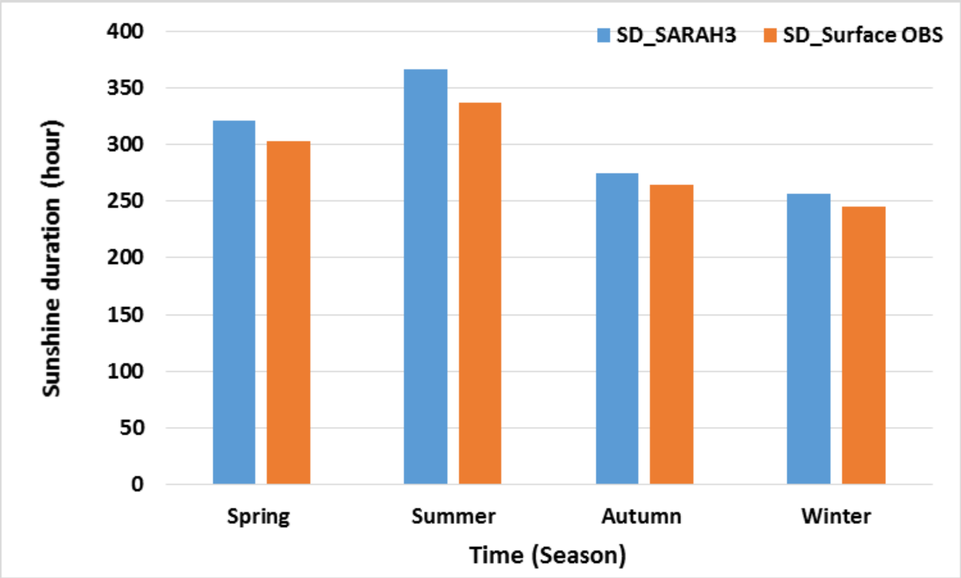


Figure.4.3. Seasonal observed and calculated sunshine duration for Ouargla region (2001 – 2017)

IV.2.4. Yearly sunshine duration

Based on the long-term annual comparative data spanning from 2001 to 2017 in Figure 4.4, the annual sunshine duration consistently tracks a similar interannual variability between the two datasets, with both capturing distinct multi-year fluctuations and peaks, such as the high sunshine periods around 2011–2012. However, mirroring the shorter-term trends, a stark and permanent systematic positive bias is apparent, with the satellite-derived SD_SARAH3 values continuously overestimating the ground truth SD_Surface OBS observations for every single year of the 17-year study period. The annual gap between the data series varies dynamically over the years—widening significantly in certain years (such as 2004, 2005, and 2008) and narrowing in others (such as 2002 and 2011)—which demonstrates how interannual variations in regional climate factors, like changing dust-storm frequencies and atmospheric aerosol loading, continuously influence the precision of satellite clear-sky retrieval models over time.

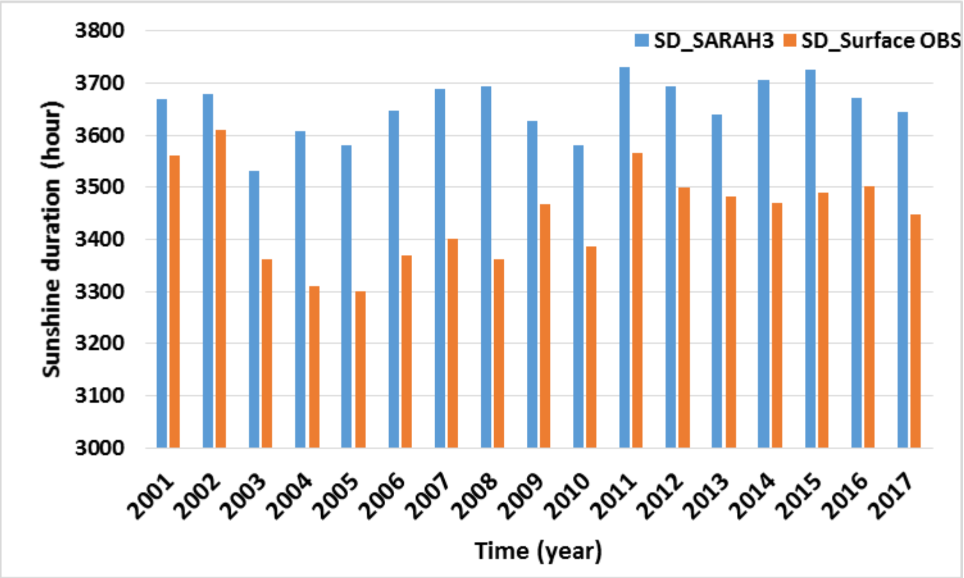


Figure.4.4. Yearly observed and calculated sunshine duration for Ouargla region (2001 – 2017)

IV.3. Statistical evaluation

Figure 4.5 presents scatterplots between the daily sunshine duration values of Ouargla station against SARAH-3. The agreement between the surface database and SRAH-3 is good, suggesting that the spatial distribution of sunshine duration is comparable between the two databases.

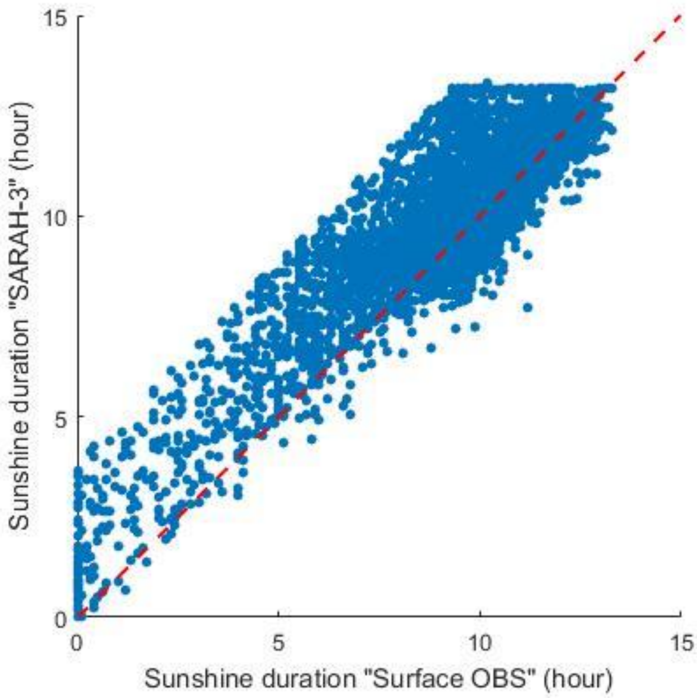


Figure.4.5. Scatterplots between the daily sunshine duration values of Ouargla station against SARAH-3

In this study, four statistical quantitative indicators were used to evaluate observed and calculated sunshine duration for Ouargla region. These quantitative indicators are :

1. Mean Absolute Error (MAE)
2. Mean Bias Error (MBE)
3. Root Mean Squared Error (RMSE)
4. Coefficient of determination (R^2)

Results of statistical analysis are given in Table 4.1. As it has been already said in the previous section, the lower the absolute values of all statistical indicators except the R^2, the more accurate the estimate. The R^2 value around 1 indicates that there is a perfect linear relationship between the estimated and measured values whereas R^2 around zero shows that there is no linear relationship.

Table.4.1. Statistical evaluation of sunshine duration

OBS number	MAE (hour)	MBE (hour)	RMSE (hour)	R^2
6209	0,872	0,569	1,238	0,808

The statistical evaluation of the SARAH-3 dataset against in-situ observations in Ouargla yields a solid correlation (R^2 = 0.808), confirming its utility for regional solar resource assessment. However, the positive MBE (+0.569 hours) suggest that the satellite model systematically overestimates sunshine duration. This overestimation is likely a signature of the 'high-albedo/high-aerosol' environment of the Algerian Sahara, where mineral dust scattering can prevent ground-based sensors from recording sunshine, while satellite algorithms may still interpret the radiometric signal as clear-sky conditions.

The RMSE (1.238 hours) is significantly higher than the MAE (0.827 hours). The gap between RMSE and MAE indicates the presence of outliers or large occasional errors. There are certain days where the error is much larger (exceeds 3 hours). These exceptional days likely occur during sandstorms or complex partial cloud cover, where the satellite's 5km pixel cannot match the point measurement of the station.

Conclusion

The primary objective of this thesis was to evaluate the reliability of the CM SAF SARAH-3 satellite dataset for estimating sunshine duration (SD) in the hyper-arid environment of Ouargla over a long-term 17-year period (2001–2017). This specific period was selected based on the availability and quality of reliable ground-based data from the Ouargla meteorological station during that timeframe.

Based on the empirical findings, the results of this study conclude that:

- SARAH-3 is a highly robust tool for tracking solar dynamics in the Algerian Sahara, proving its strong viability for remote-sensing-based solar resource assessments.
- A strong linear relationship exists between the satellite estimates and ground truth observations, as confirmed by a high coefficient of determination (R^2 = 0.808).
- The satellite product maintains a reliable level of precision for daily climatological applications, yielding a Mean Absolute Error (MAE = 0.827 hours) and a Root Mean Square Error (RMSE = 1.238 hours).
- A persistent positive bias is present (MBE = +0.569 hours), revealing that the satellite systematically overestimates sunshine duration by approximately 34 minutes per day.
- This overestimation is highly seasonal and epoch-dependent, proving most severe during the spring transition months (March–May) and within a distinct, multi-year anomalous window stretching from 2003 to 2011.
- The systematic bias is physically driven by the region's intense atmospheric load of mineral aerosols (desert dust) and the high albedo of the Saharan surface, both of which interfere with the satellite's cloud-detection algorithms and its matching of the WMO 120 W/m^2 direct radiation threshold.

Recommendations

Despite the positive results, the observed seasonal bias suggests that satellite data should not be used "raw" for high-precision engineering projects. We recommend the following for future research:

- Developing a seasonal correction factor based on the Aerosol Optical Depth (AOD) to reduce the bias during sandstorm seasons.
- Combining SARAH-3 with other satellite products (such as MSG-CPP) to improve cloud-shadow detection.

- Expanding this validation to other Saharan stations (e.g., Hassi Messaoud, Touggourt, El Oued, Ghardaia) to create a unified validation framework for the entire Algerian South.

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Annexe

History of Meteosat-based CM SAF Climate Data Records of Surface Radiation parameters

Version	Name	Document code	Time range	Major changes
1		MVIRI_HEL	Jan 1983–Dec 2005	•First version based on modified Heliosat version 1.0 •MAGIC version 0x86
2	SARAH-1	METEOSAT_HEL	Jan 1983–Dec 2013	•Second version of data record covering MFG and MSG time period, hence longer time period covered. •Improved algorithms & accuracy. •Improved aerosol information. •Name of the data record: SARAH
3	SARAH-2	METEOSAT_HEL	Jan 1983–Dec 2015	•Second release of the SARAH CDR •Includes SRI •Includes SDU •Improved treatment of water vapour •Geometry correction for high viewing angles •Improved temporal stability
	SARAH-2.1	METEOSAT_HEL	Jan 1983–Dec 2017	•Extension of SARAH-2 in time (until 2017) -> SARAH-2.1 consists of SARAH-2 plus 2016, 2017.
4	SARAH-3	METEOSAT_HEL	Jan 1983–Dec 2020	•Improved treatment of snowcovered surfaces •Improved surface albedo for clearsky surface radiation •Includes PAR, DAL data record; SRI data record deleted

ملخص

تهدف هذه الدراسة إل تقييم دقة تقديرات مدة سطوع الشمس المستمدة من قاعدة بيانات SARAH-3 التابعة لـ (CM SAF/EUMETSAT)، وذلك عبر مقارنتها بالقياسات الأرضية لمحطة الرصد الجوي في ورقلة. تمتد فترة الدراسة لـ 17 عاماً (من 2001 إلى2017). تظهر النتائج عن توافق إحصائي مرتفع بين بيانات الأقمار الصناعية والرصد الأرضي، حيث بلغ معامل التحديد (R^2) قيمة 0.808، مع تسجيل متوسط خطأ مطلق (MAE) قدره 0.827 ساعة، وجذر متوسط مربع خطأ (RMSE) قدره 1.238 ساعة. كما أظهرت الدراسة وجود انحياز إيجابي (MBE) بقيمة 0.569+ ساعة، مما يشير إلى ان القمر الصناعي يبالغ بشكل منهجي في تقدير مدة سطوع الشمس حوالي 34 دقيقة؛ ويُعزى ذلك بشكل رئيس إلى تأثير الهباء الجوي والعواصف الرملية التي تميز المناخ الصحراوي. تؤكد الدراسة إلى موثوقية نموذج SARAH-3 كبديل فعال لتقييم موارد الطاقة الشمسية في المناطق التي تعاني من نقص في شبكات الرصد الأرضي.

الكلمات المفتاحية: مدة سطوع الشمس، SARAH-3، المؤشرات الإحصائية، ورقلة

Abstract

This study aims to evaluate the accuracy of sunshine duration estimates derived from the SARAH-3 climate data record (CM SAF/EUMETSAT) by comparing them with ground-based measurements from the Ouargla meteorological station. The study covers a 17-year period (2001–2017). The results reveal a high statistical agreement between satellite data and ground observations, with a coefficient of determination (R^2) of 0.808, a Mean Absolute Error (MAE) of 0.827 hours, and a Root Mean Square Error (RMSE) of 1.238 hours. Additionally, the study identified a positive Mean Bias Error (MBE) of +0.569 hours, indicating that the satellite systematically overestimates sunshine duration by approximately 34 minutes. This is primarily attributed to the effects of aerosols and sandstorms characteristic of the desert climate. The study confirms the reliability of the SARAH-3 model as an effective alternative for assessing solar energy resources in regions with limited ground-based monitoring networks.

Keywords: Sunshine duration, SARAH-3, Statistical indices, Ouargla.

Résumé

Cette étude vise à évaluer la précision des estimations de la durée d'insolation issues de la base de données SARAH-3 (CM SAF/EUMETSAT), en les comparant aux mesures au sol de la station météorologique d'Ouargla. La période d'étude s'étend sur 17 ans (de 2001 à 2017). Les résultats révèlent une forte concordance statistique entre les données satellitaires et les observations au sol, avec un coefficient de détermination (R^2) de 0.808, une erreur absolue moyenne (MAE) de 0.827 heures, et une erreur quadratique moyenne (RMSE) de 1.238 heures. De plus, l'étude a identifié un biais moyen (MBE) positif de +0.569 heures, indiquant que le satellite surestime systematiquement la durèe d`ensoleillement d`environ 34 minutes. Cela est principalement attribué aux effets des aérosols et des tempêtes de sable caractéristiques du climat saharien. L'étude confirme la fiabilité du modèle SARAH-3 comme alternative efficace pour l'évaluation des ressources en énergie solaire dans les régions souffrant d'un manque de réseaux de mesure au sol.

Mots-clés : Durée d'insolation, SARAH-3, Indices statistiques, Ouargla.