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An Empirical Analysis of the Variation of Precipitation Patterns in the Sahara Desert and their Environmental Consequences

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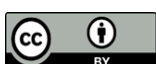
Abstract: The Sahara Desert, in Africa has been known to be part of the hottest regions of the Earth. As a desert it is expected to always have low rainfall, limited vegetation, and high temperatures. Recent observations using satellite images have shown an increase in vegetation cover in some parts of the Sahara Desert. This observation has been attributed to variation in precipitation pattern within the region. In this study, the changed precipitation (rain, snow, sleet, and hail) is the variable of focus. Precipitation data for twenty years (November 2004 to October 2024) was accessed from National Aeronautics and Space Administration's (NASA's) Giovanni data platform. The study shows that the significant change in the precipitation pattern over the two decades was only observable at the twentieth year. This change was attributed to the cause of the greenness observed in a portion of the Sahara Desert as seen by satellite. Hence, the Normalized Difference Vegetation Index (NDVI) data for the selected period is also given to show the new greening areas. The consequences of the observed change in precipitation and the attendant greening were also analyzed in relation to climate change and other factors.

Keywords: precipitation; weather; Giovanni; Sahara Desert; Africa; climate change

1. Introduction

The Sahara Desert, known for its vast sand dunes and harsh climate, spanning over 9,200,000 square kilometers across North Africa, is one of the most extreme and fascinating environments on Earth [1,2]. This vast arid region has long been characterized by its scorching temperatures, limited vegetation (specialized plant life adapted to conserve water), and scarce rainfall, making it one of the most inhospitable places on the planet [3]. The Sahara's harsh climate has shaped the evolution of unique and adapted ecosystems, supporting a diverse range of flora and fauna that have adapted to survive in this unforgiving environment [4].

The climatic condition of the desert is characterized by extreme heat, with daily temperatures often exceeding 40 °C (104 °F) and limited rainfall [5]. The Sahara's climate is influenced by various factors, including Earth's orbital shift and rotation, which impact the distribution of solar radiation and, in turn, affect global climate patterns [6–9]. Changes in Earth's orbit, known as Milankovitch cycles, have been linked to significant climate shifts throughout history, including the formation and disappearance of ice ages [10]. These orbital changes can also influence regional climate patterns, such as the African monsoon, which affects the Sahara's climate [11]. In addition to orbital shifts, Earth's rotation and axial tilt also play a crucial role in shaping the Sahara's climate. The tilt of Earth's axis determines the distribution of solar radiation between the equator and poles, while the rotation rate



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influences global atmospheric circulation patterns [7,8]. These factors, combined with orbital shifts, contribute to the complex and dynamic nature of the Sahara's climate.

The weather as a temporary and local conditions of the atmosphere at a specific place and time, has variables that include temperature, humidity, cloudiness, wind, precipitation (rain, snow, sleet, and hail) and atmospheric pressure. Precipitation is the process where water vapor condenses in the atmosphere to form water droplets that fall to the Earth as rain, sleet, snow, and hail. 'Precipitation' encompasses all the forms of water (liquid or solid) which falls on the Earth's surface from the atmosphere [12].

Recent observations have revealed a notable shift in the Sahara's climate, with changes in precipitation patterns and temperature regimes [13]. These changes have significant implications for the region's ecosystems, biodiversity, and human populations [14]. Precipitation is a complex and multifaceted phenomenon that has been extensively studied by researchers across various disciplines. The works of notable authors such as Trenberth et al. [15] have shed light on the dynamics of precipitation formation and its relationship with atmospheric circulation patterns [16]. Lack of precipitation in a particular region often leads to intense drought and disaster. Drought is usually recognized as an abnormal climatic event caused by a shortage of precipitation over an extended period, especially in the Sahara region [17]. As one of the more serious natural disasters, drought impacts negatively on the environment and human activities [18].

Precipitation plays a fundamental role in the Earth's climate system by linking atmospheric processes with the hydrological cycle, thereby regulating water availability and ecosystem dynamics [15,19,20]. With advances in remote sensing, satellite-based precipitation datasets such as TRMM and GPM-IMERG have become essential tools for monitoring global rainfall patterns, particularly in data-sparse regions, and are widely applied in hydrological and climate studies [21–23]. These satellite products are especially valuable in regions with limited ground observations, where traditional rain gauge networks are sparse or inadequate, thereby providing critical insights into precipitation variability and climate processes [24]. However, satellite-derived precipitation estimates are subject to uncertainties due to the complex nature of precipitation processes and limitations in ground validation data, particularly in regions with challenging environmental conditions [25,26]. To enhance accuracy, the integration of satellite observations with ground-based measurements has been identified as a critical approach for improving precipitation datasets and advancing the understanding of regional climate dynamics. In data-scarce environments such as desert and dryland regions, the use of satellite-derived precipitation datasets provides an indispensable means of assessing long-term variability in rainfall patterns and their impacts on ecosystem processes, including vegetation dynamics and desert greening.

In the Earth's atmosphere, water vapour represents the most abundant greenhouse gas and plays a fundamental role in regulating the global climate system. It controls the Earth's energy balance through processes such as radiative feedback mechanisms, cloud formation, and the greenhouse effect [19]. With approximately 99% of atmospheric water vapour concentrated in the troposphere, it serves as a key driver of weather processes and extreme events, including convective storms and large-scale atmospheric circulation patterns [27].

In arid and semi-arid regions, where precipitation is inherently limited, atmospheric moisture availability becomes a critical controlling factor for hydrological processes and ecosystem dynamics. Drylands, which currently cover nearly 45% of the global land surface and support a substantial proportion of the world's population and vegetation, are particularly sensitive to variations in water availability [28–30]. In these regions, water availability largely governed by precipitation and atmospheric moisture is the primary limiting factor for vegetation growth and ecosystem functioning [31]. Small perturbations in moisture balance can therefore trigger significant ecological responses, often amplified by feedback mechanisms within the land-atmosphere system [32,33].

Recent evidence suggests that global warming and atmospheric circulation anomalies have intensified the hydrological cycle, leading to increased evapotranspiration and changes in moisture transport across dryland regions [34]. Rising atmospheric water vapour driven by enhanced moisturized transport has emerged as a key factor influencing regional climate variability in major desert systems, including the Sahara. These processes are closely linked to the concept of desert amplification, whereby arid regions experience enhanced warming relative to more humid regions, further altering precipitation regimes and atmospheric dynamics.

Recent studies have highlighted significant environmental changes occurring in global desert regions, particularly in relation to increasing atmospheric moisture transport and its role in enhancing water availability. Evidence suggests that rising levels of atmospheric water vapour are contributing to improved soil moisture and precipitation patterns. One of the most striking observations in the Sahara is the recent increase in vegetation in certain parts of the desert, particularly in areas that were previously considered barren and lifeless [35]. This phenomenon, often referred to as "greening", has been linked to unusual shift in the weather conditions [36], particularly changes in precipitation patterns, with some studies suggesting that increased rainfall and altered rainfall seasonality are driving the observed changes in vegetation [36,37].

While precipitation is a key driver of ecosystem dynamics in the Sahara Desert, recent studies indicate that observed vegetation increases, or “desert greening,” require direct measurements of vegetation cover to substantiate such claims [19]. Vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), provide quantitative insight into the spatial and temporal distribution of green biomass across arid and semi-arid regions. NDVI values, derived from satellite remote sensing, typically range from -1 to 1 , with higher values indicating denser and healthier vegetation [38]. These indices serve as critical tools for validating greening trends and linking climatic drivers, such as precipitation and soil moisture, with vegetation response in desert ecosystems.

The impacts of this change on human environment and well-being are multifaceted with positive and negative impacts. On the positive side, increased vegetation can lead to improved air quality, reduced dust storms, and enhanced biodiversity, which can have positive effects on human health and well-being [14]. The greening of the Sahara can also lead to increased agricultural productivity, improved food security, and enhanced economic opportunities for local communities [39]. Additionally, the increased vegetation can provide habitat for wildlife, supporting ecotourism and sustainable livelihoods [40]. The negative impacts on the other hand show that changes in precipitation patterns and increased vegetation can also lead to increased risk of water-borne diseases, such as malaria and water scarcity [41]. The shift in vegetation can alter traditional land-use patterns, leading to conflicts over resources and displacement of local communities [42]. Furthermore, the increased vegetation can also lead to changes in soil quality, potentially affecting agricultural productivity and ecosystem functioning [39]. Increased rainfall and altered precipitation patterns can also lead to increased risk of flooding, which can have devastating impacts on local communities, infrastructure, water quality and ecosystems [43]. Flooding can lead to loss of life, property damage and displacement of people.

This study aims to contribute to the understanding of the complex relationships between climate change, precipitation patterns, and ecosystem responses in the Sahara Desert. By analyzing precipitation data from NASA’s Giovanni dataset and considering the impacts of Earth’s orbital shift and rotation, the hypothesis that changes in precipitation patterns are driving the observed increase in vegetation in certain parts of the desert was investigated. Also, the Normalized Difference Vegetation Index (NDVI) data supplied in this study show the new greening areas. Hence, this research provides new insights into the dynamics of the Sahara’s climate and ecosystems, with implications for regional and global climate dynamics, human well-being, and sustainable development. The Sahara Desert lies between approximately 17°N and 35°N latitude and 18°W and 37°E longitude, however the coordinates used to define the spatial extent (accessible bounding box) in this study was 16.2378°N and 34.1675°N latitude and 17.9297°W and 35.5078°E longitude.

2. Methodology

2.1. Study Area

The Sahara Desert is the largest hot desert on Earth, spanning across North Africa, covering approximately 3.5 million square miles of sand dunes, mountains and waterways. The enormous desert transverses 10 countries (Algeria, Tunisia, Libya, Egypt, Sudan, Chad, Niger, Mali, Mauritania and Morocco (the territory of Western Sahara)). This desert region has a vast array of development opportunities and challenges. It is one of the lowest populations in the world, with only about 2.5 million people inhabiting the vast desert region, primarily near lakes and rivers. The sea to the North of the Sahara Desert after the landmass is the Mediterranean Sea. The climate of this study area is extreme heat, with daily temperatures often exceeding 40°C (104°F) and limited rainfall [5]. The map of the Sahara Desert is presented in Figure 1.

2.2. Data Collection

The global precipitation data [12] was accessed with subset for specific location using NASA’s Giovanni dataset [44]. This study accessed the precipitation (rain, snow, sleet, and hail) data of the Sahara Desert for two decades from the Giovanni [44]. Giovanni is an online (Web) environment for the display and analysis of geophysical parameters (Earth science data) for easy access of the data lineage (provenance). NASA’s Giovanni application is operated by the Goddard Earth Sciences Data and Information Services Center (GES DISC). The twenty years (November 2004 to October 2024) data accessed was pictorially downloaded in PNG [45]. On the Giovanni, the Sahara Desert region was not specifically specified as it is a transverse of ten countries and not completely spanning across all the individual country.

“Google chrome” was used as the modern web browser. To have unlimited access to the precipitation data, there was a need to register for a profile at NASA EarthData [46]. After the registration, the precipitation data was accessed through NASA’s Giovanni [44]. At the upper left of the page, under “Select Plot”, “Time Averaged Map” was selected as the appropriate analysis.



Figure 1. The Sahara Desert [47].

At the centre of the page (main interface), the keyword (selection of data field) “IMERG Final” was selected and searched. IMERG (Integrated Multi-satellite Retrievals for GPM) is a “Precipitation Data Set”, a type of satellite-derived product. Under IMERG Final, “Merged satellite-gauge precipitation estimate—Final Run (GPM_3IMERGM v07)’ was ticked. The features of the ticked that were displaced are: mm/hr (Unit); GPM (Source); Monthly (Temp.Res.); 0.1° (Spat. Res.); 1998-01-01 (Begin Date); 2024-10-31 (End Date).

The time range of interest was indicated at the upper middle of the page by selecting start and end dates using the calendar tool. At the upper right of the page, the geographic bound (area of interest or focus—Sahara Desert) was selected using the map interface. Hence, the coordinates used to define the spatial extent (bounding box) was 17.9297°W, 16.2378°N, 35.5078°E, 34.1675°N (i.e. -17.9297, 16.2378, 35.5078, 34.1675).

Figure 2 is used as an example to show the data processing and analysis. At the end “Plot Data” was clicked at the right down end of the page. The data generated was downloaded as an image (pictorial) data in PNG (Figure 3).

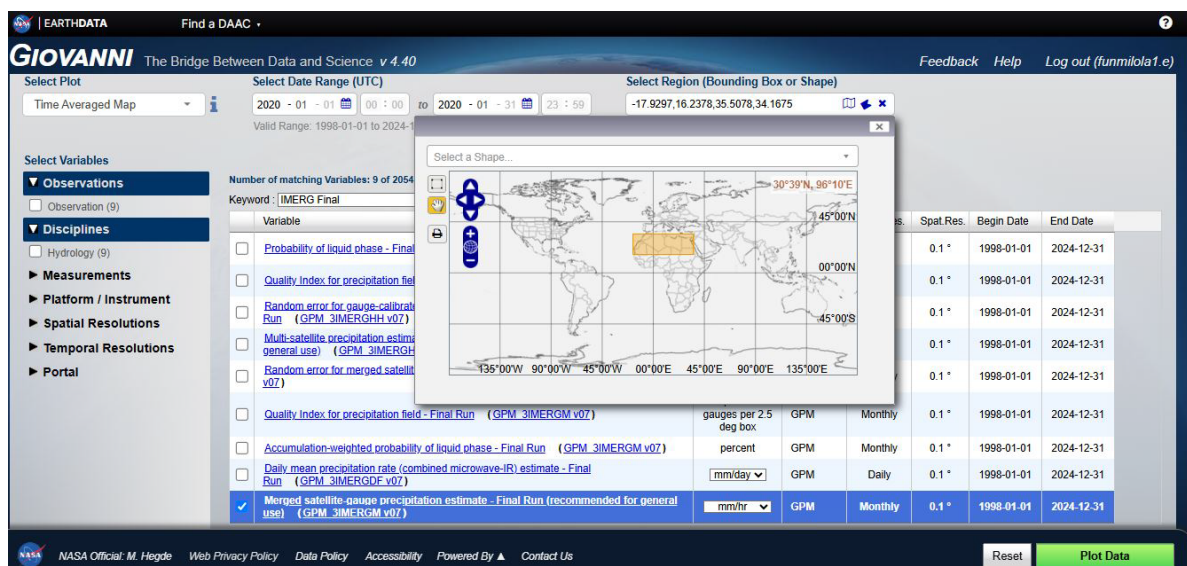


Figure 2. The accessed Giovanni page showing the analysis type, dataset selection, time range selection and geographic bounding.

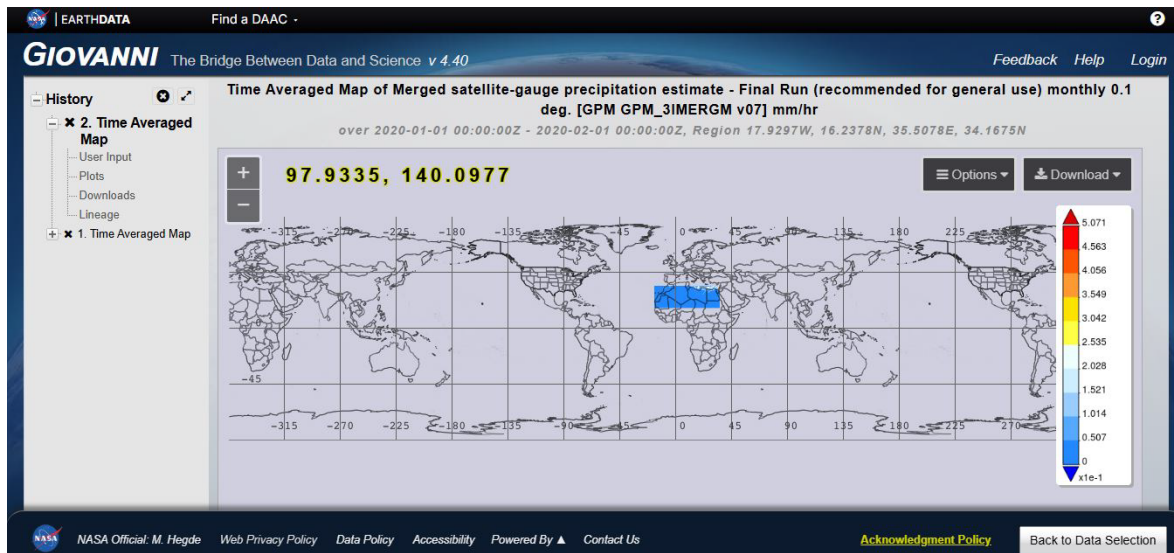


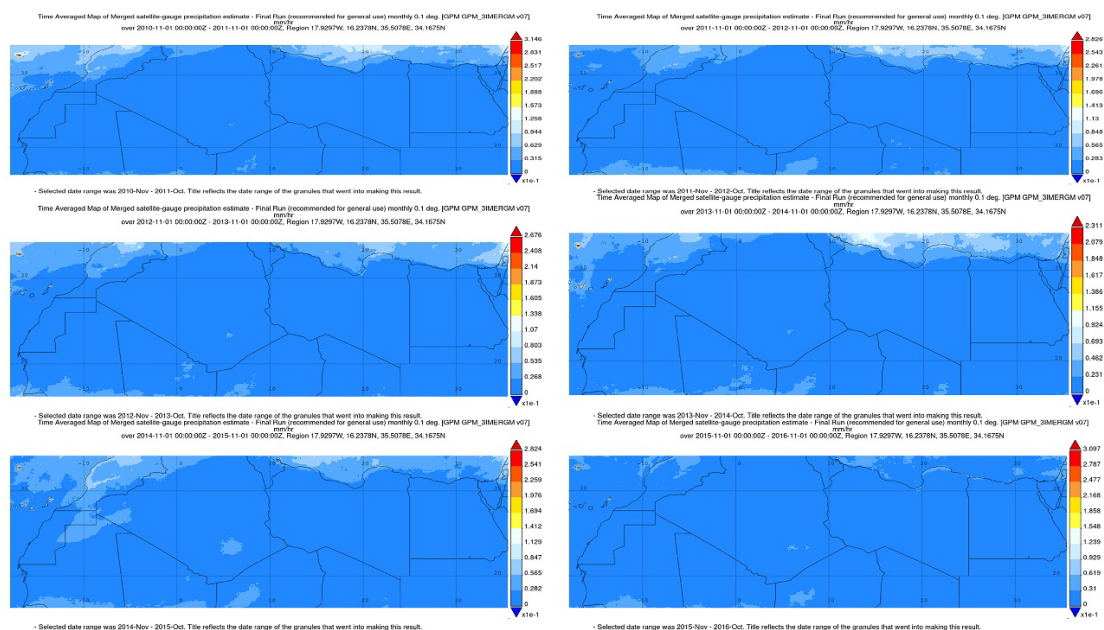
Figure 3. The accessed Giovanni page showing the plotted data.

3. Result and Discussions

3.1. Results

The pictorial data (PNG) downloaded from Giovanni [44] spans a range of colors from deep blue to deep red. Deep blue represents a no or low precipitation while a deep red represents high or maximum precipitation. An important point of note at the upper part of the pictures is that there is the Mediterranean Sea at the North of the Sahara Desert after the landmasses.

The 20 years precipitation data for Sahara Desert was first downloaded sequentially in 5 years series. The pictorially downloaded data in the 5 years series did not visibly show cogent differences. Hence, the 20 years precipitation data was further downloaded yearly for a better clarification (Figure 4a–d). It was observed from the yearly data that the cogent differences in the precipitation shift over the two decades, was only prevalent at the twentieth year (November 2023 to October 2024). This observation was attributed as the probable cause of the vegetation greenness seen over the satellite. There was a further download of the precipitation data monthly for the twentieth year (November 2023 to October 2024) (Figure 5a,b). The precipitation increase is from May 2024 to September 2024, with the peak in September 2024; however, a drastic reduction was observed in October 2024. There was also a download for each country found at the Sahara Desert and Nigeria (a sub-Sahara country) for the twentieth year (November 2023 to October 2024) (Figure 6). This was done because of the greening observed from the satellite image [20] which was attributed to the significant shift in precipitation in the twentieth year.



(A) (November 2004 to October 2010)

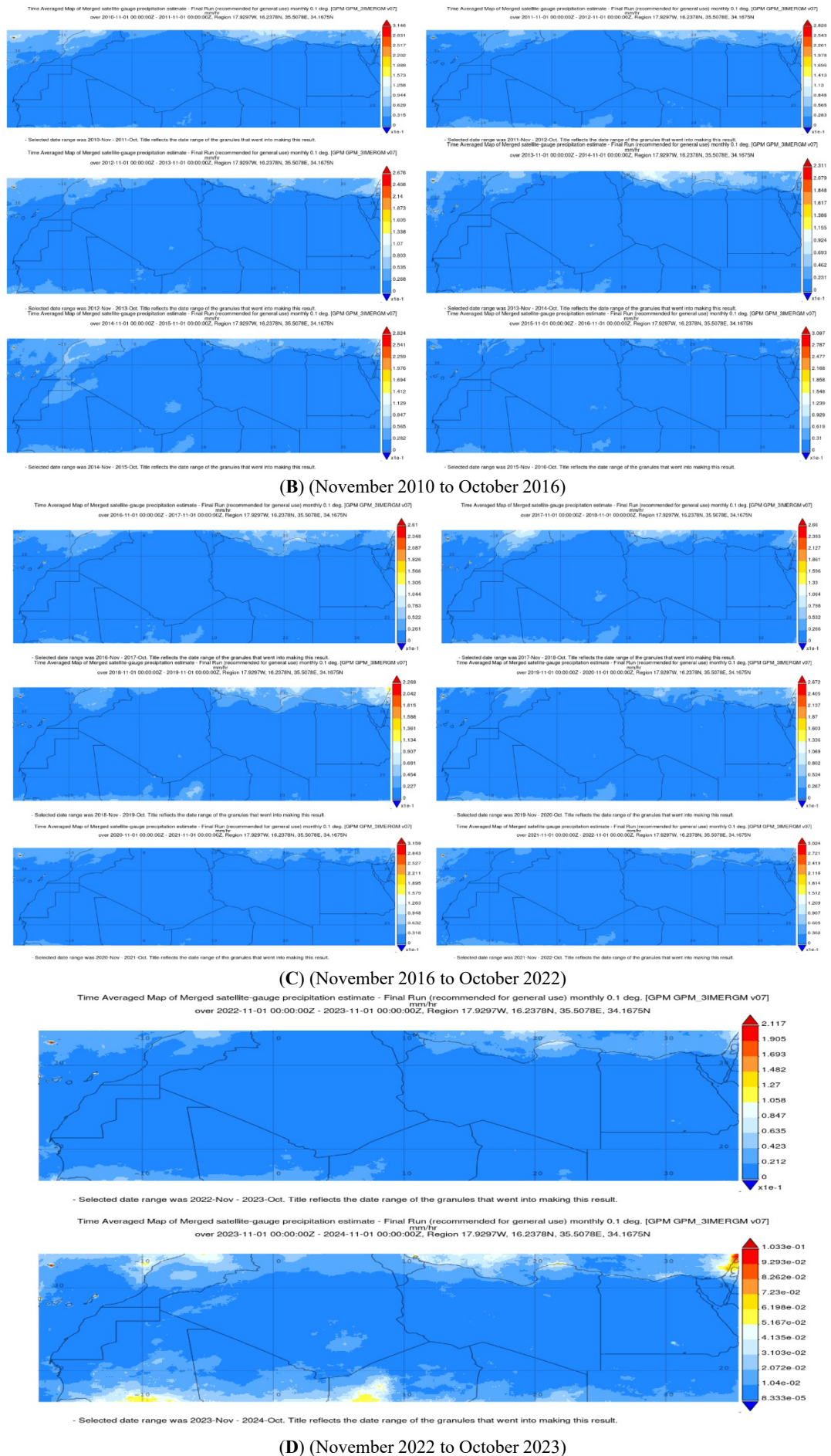


Figure 4. Yearly series of the precipitation data of the Sahara Desert.

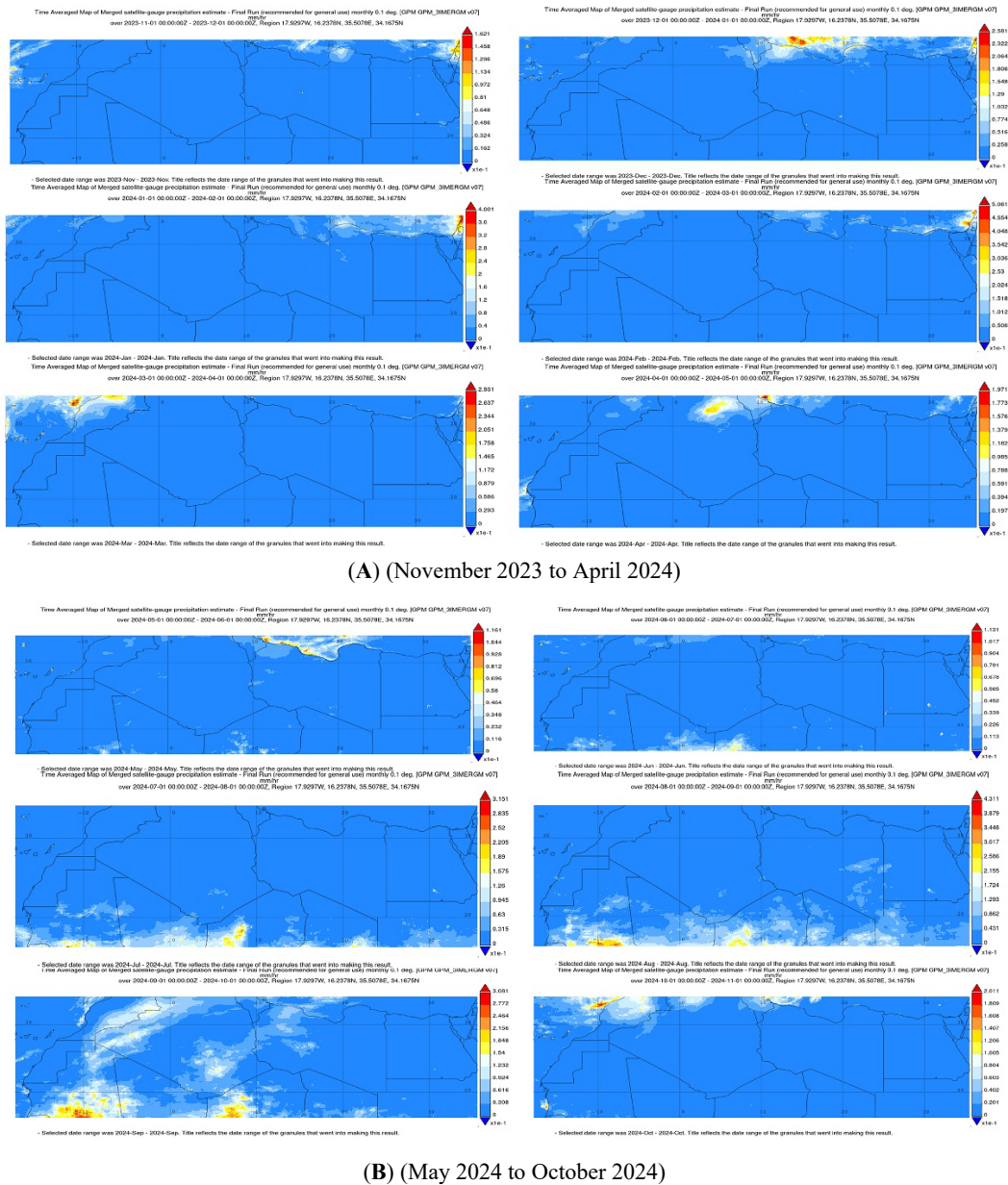


Figure 5. Monthly series of the precipitation data of the Sahara Desert.

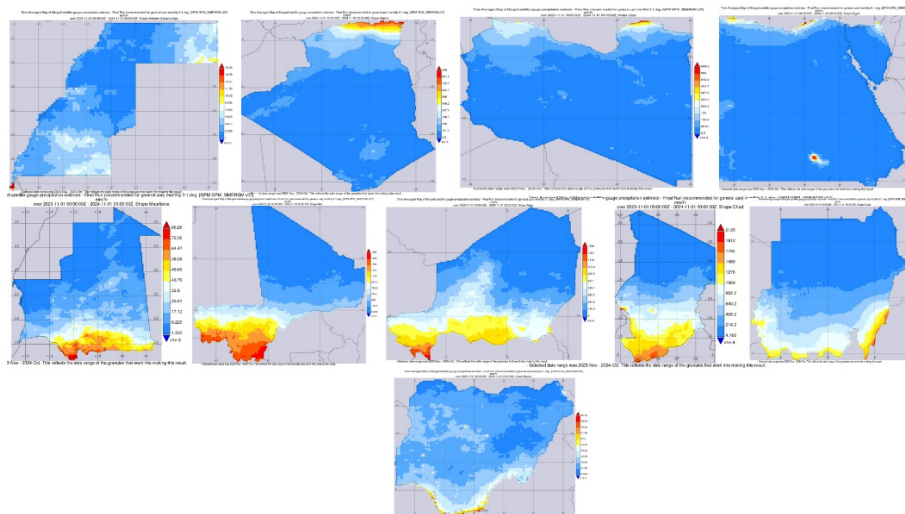


Figure 6. A twentieth year (November 2022 to October 2024) precipitation data of the Sahara Desert for the countries the Sahara Desert transverse through; and also, the Sub-Sahara Country, Nigeria.

3.2. Discussion

From historical context, the Sahara has periodically turned green in the past, most notably during the African Humid Period (11,000–5000 years ago), when it was covered in lakes and savannas. This was driven by Earth's orbital precession, which intensified monsoons. However, the current greening is distinct because it's tied to anthropogenic climate change rather than natural orbital cycles. Climate Change has been pointed out as part of the causes of the current precipitation shift in the region. Warmer temperatures increase moisture retention in the atmosphere, leading to heavier rainfall in typically arid regions. Also contributing to drastic precipitation shift is the extratropical cyclones that is, unusual weather systems, like a September 2024 cyclone, pulled moisture from equatorial Africa into the Sahara, causing sudden deluges and filling normally dry lakes [48,49]. This increase in precipitation can be observed from Figure 6. The precipitation in some of the countries within the Sahara Desert is higher than what was observed in Nigeria, a sub-Saharan nation.

The Shift in the Intertropical Convergence Zone (ITCZ) has been identified as the leading cause of this phenomenon. The ITCZ in the tropical rain belt, has moved farther north than usual due to warmer global temperatures, bringing storms into the southern Sahara. This shift is linked to both climate change and the transition from El Niño to La Niña [50].

While precipitation is a key driver of ecosystem dynamics in the Sahara Desert, recent studies indicate that observed vegetation increases, or “desert greening,” require direct measurements of vegetation cover to substantiate claims [19]. Vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), provides insight into the spatial and temporal distribution of green biomass across arid and semi-arid regions. Comparing Figure 7a,b; a clear greening trend across the Sahara region is evident in the later years of the study period. Figure 7a is derived from MODIS (Moderate Resolution Imaging Spectroradiometer), 250 m resolution 16-day composites, presents NDVI from 2002 to 2026, capturing fine-scale vegetation dynamics [51]. In contrast, Figure 7b, based on NOAA CDR data, offers a longer-term perspective but at coarser resolution [52]. Despite these differences in spatial and temporal characteristics, both datasets consistently show increased vegetation productivity in the latter part of the record, with the Sahara exhibiting pronounced greening. This inter-dataset agreement strengthens the inference that the observed trend reflects actual environmental change in the region.

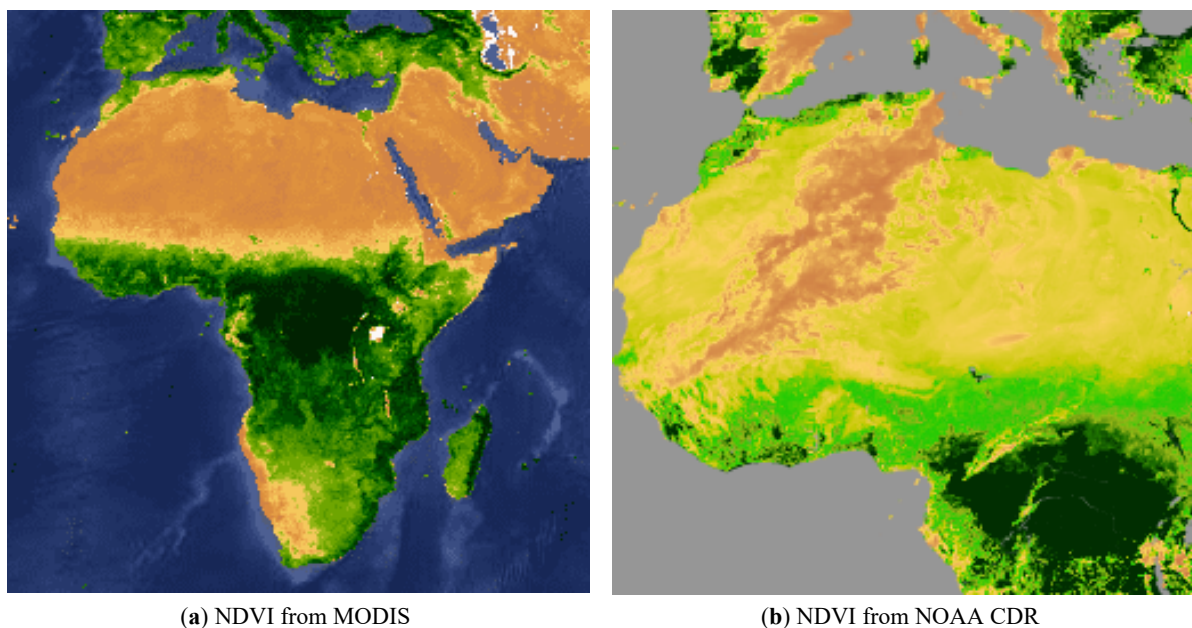


Figure 7. The Normalized Difference Vegetation Index (NDVI) data of the Sahara Desert from 2022 to 2026.

As the greening is ecologically fascinating, it has both beneficial and detrimental impacts. On the beneficial notes, the growth of shrubs and trees in the region could reduce dust emissions and alter regional climate patterns, potentially affecting global weather systems like the North Atlantic Oscillation. This increased plant growth can support animal populations, particularly rodents, by providing food and breeding opportunities for them. The areas under study typically receive just a few inches of rain annually but in recent times have experienced up to 400–500% of their usual rainfall since mid-2024. This increased rainfall can help replenish groundwater aquifers and refill dammed reservoirs, which are vital for desert communities.

The current precipitation shifts in the Sahara Desert are often perceived as positive environmental transformation; the increased rainfall and vegetation could combat desertification and may provide support for human livelihoods. However, this sudden ecological-transition comes simultaneously with some notable negative-impacts. Firstly, this present phenomenon may lead to sudden disruption of the regional climate. While increased vegetation might reduce overall dust emissions from stabilized areas, it is possible that the greening may alter the entire atmospheric circulation patterns. And consequently, shift dust emission hotspots or change dust transport pathways, impacting regions dependent on Saharan dust nutrients (like the Amazon) or suffering from poor air-quality downwind [53]. More so, there is a possibility of alteration to the monsoon pattern of the region which poses a significant potential climate risk for this region which heavily reliant on monsoon rainfall.

Also, there is a propensity of the region to suffer from severe soil erosion. While vegetation cover generally protects soil, the initial stages of greening often involve sparse vegetation on loose soils. Heavy rainfall events can cause severe sheet and gully erosion, stripping away valuable topsoil that took centuries to form. This degradation can leave the land more vulnerable than before when the next dry phase inevitably returns. Nutrient leaching is also another potential negative impact to watch out for. As noted by [54], Intense rainfall events on historically dry, nutrient-poor soils can lead to the washing away of vital nutrients like nitrogen deeper into the soil profile or into groundwater, beyond the reach of plant roots.

Another potential challenge that may stem from this development is socio-economic destabilization. While greening might appear to increase resources, its patchy and often ephemeral nature can intensify competition. Lush areas will attract more herders and their livestock, which in turn may lead to localized overgrazing, land degradation, and heightened conflicts over water points and pasture access between different pastoral groups or between pastoralists and farmers [55]. This greening-induced concentration can be a source of social tension and violence. In fact, increased moisture and vegetation create ideal breeding grounds for disease vectors like ticks and mosquitoes. This leads to higher incidences of livestock diseases (e.g., East Coast Fever, Rift Valley Fever, Trypanosomiasis), causing significant mortality and economic losses for pastoralist communities who depend entirely on their herds [56]. The very resource that sustains their animals also harbors greater threats to their health. These areas experiencing heavy rainfall after long dry periods or on degraded soil are highly susceptible to rapid runoff and flash flooding. The greening signal itself might mask underlying soil degradation that could worsen flood impacts in the region.

4. Conclusions

The current precipitation variation in the Sahara Desert region which is responsible for the greening of its environment is a complex phenomenon with significant positive and negative repercussions. It is imperative to go beyond embracing simplistic narrative of this phenomenon as environmental improvement because along with the fascinating positive impacts come also some counterbalancing impacts. While this shift offers localized opportunities, it also harbours the tendency to disrupt the fragile ecosystems of the desert and its bordering regions. This sudden development can facilitate the spread of invasive species and diseases, increase conflict potential over resources, pose new desertification risks through soil erosion and nutrient leaching. There is also a potential threat to regional food security via locust plagues and flash flooding which may perturb regional climate patterns. Managing this greening effectively requires moving beyond viewing it solely as good news. Instead, strategies must be put in place to focus on mitigating their downsides.

Therefore, the Sahara Desert region should unify in maximizing the greening and focus on managing the ecological transition for resilience, sustainability, and equity. There should be strategic and aggressive investment in building climate-resilient infrastructure such as roads, bridges, water storage, health facilities to withstand increased flood intensity and support adaptation in greening zones. This will also foster robust socio-economic activities across the region. There should be regional scientific and intergovernmental cooperation for early detection and rapid environmentally sensitive control of locust outbreaks triggered by greening conditions. There should be designation for interdisciplinary research combining remote sensing, ecology, climatology, hydrology, and social sciences to better understand long-term sustainability of greening trends and the complex interactions between vegetation and the regional climate. There should be development and deployment of localized, actionable early warning systems for both extreme rainfall/flooding and the return of drought. There should also be active awareness campaign to ensure warnings, reaching remote communities and linking to pre-planned response protocols such as evacuation routes, livestock movement plans, prepositioned aid etc.

Author Contributions

B.G.A.: conceptualization, project administration, resources, supervision, writing—review and editing; F.A.O.: data curation, formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing; S.O.O.: formal analysis, investigation, methodology, writing—original draft, writing—review and editing; B.C.A.: data curation, investigation, methodology, writing—original draft, writing—review and editing; K.B.D.: data curation, investigation, methodology, writing—original draft; O.S.T.: data curation, investigation, methodology, writing—original draft. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All the precipitation data used during this study are openly available from the NASA global precipitation data accessed with subset for specific location using NASA's Giovanni dataset precipitation measurement EarthData at <https://giovanni.gsfc.nasa.gov/giovanni/> as cited in NASA, 2025 [44].

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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