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Evaluation of All-sky Solar Irradiance and Near-surface Air Temperature (T2M) Variability Across East African Countries Using NASA POWER Reanalysis Data (2021-2024)

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Abstract

Understanding the variability of solar radiation and surface temperature is crucial for energy planning, agriculture, and climate research. East Africa is one of the most climatically diverse regions in the world. In regions such as East Africa, where climate-dependent sectors dominate livelihoods, understanding the behavior of these variables is especially critical. This study investigates the seasonal and inter-annual variability of All-sky Solar Irradiance and Near-surface Air Temperature (T2m) across five key East African countries: Ethiopia, Kenya, Sudan, Tanzania, and Uganda, using NASA POWER reanalysis data spanning the period 2021-2024. Results from the monthly and annual mean data reveal distinct regional patterns. Sudan consistently exhibits the highest annual mean irradiance and temperature. Ethiopia and Kenya exhibit bimodal irradiance structures, with marked reductions during the mid-year rainy seasons. In contrast, Tanzania and Uganda maintain the lowest annual mean irradiance and temperature. Critically, all five countries share a pronounced irradiance trough in July, corresponding to peak cloud cover during the Northern Hemisphere summer monsoon season. Inter-annual variations in both irradiance and temperature are minimal across all countries, indicating stable climatic forcing and reliable long-term solar resource availability across the region. These findings contribute to understanding the radiative energy balance and potential for renewable energy utilization in East Africa.

Key words: Solar radiation; Surface temperature; NASA POWER; East Africa;

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1 Introduction

Solar irradiance and near-surface air temperature (T2M) are fundamental variables governing the surface energy balance, atmospheric circulation, and ecological productivity. Solar irradiance is the primary driver of the Earth's surface energy balance and directly influences near-surface air temperature through radiative heating processes (Liou 2002; Wild 2016). East Africa has one of the highest solar energy potentials globally, making accurate characterization of irradiance variability crucial for energy planning (Hailu and Fung 2019). The region is a climatically diverse region characterized by complex interactions between the Inter-tropical Convergence Zone (ITCZ), monsoon systems, topography, and regional circulation patterns. In East Africa, irradiance varies spatially and temporally due to latitude, altitude, cloud cover, and seasonal weather patterns (Manirambona et al. 2022) . The region's climate is strongly modulated by the seasonal migration of the Inter tropical Convergence Zone (ITCZ), producing two major rainy seasons and significant cloud- radiation interactions (Camberlin and Philippon 2002; Nicholson 2017).

Temperature, closely linked with irradiance, plays a key role in energy demand, crop productivity, and atmospheric studies. Seasonal temperature patterns in East Africa are also influenced by monsoon systems, elevation, and proximity to large water bodies (Nicholson 2017). Studies show that areas near the equator experience less seasonal variation, while higher altitude regions exhibit cooler temperatures and larger diurnal ranges (Omuto et al. 2019). The relationship between solar irradiance and surface air temperature is complex and region-dependent. High irradiance generally correlates with higher surface temperatures, but cloud cover, albedo, and atmospheric aerosols can modulate this effect (Li et al. 2018). In East Africa, some studies report a positive correlation between monthly mean irradiance and temperature, particularly during dry seasons, which is critical for solar energy system efficiency (Gathaara et al. 2015).

Understanding irradiance and temperature variability is essential for solar energy planning, agricultural productivity, and climate change adaptation. Several models integrate monthly or daily irradiance and temperature to optimize photovoltaic system deployment (Ndeto et al. 2024). Furthermore, long-term trends of irradiance and temperature inform climate models, drought assessment, and water resource management (Nicholson 2017; Omuto et al. 2019).

In regions such as East Africa, where climate-dependent sectors dominate livelihoods, understanding the behavior of these variables is especially critical. While there are some studies on East African climate, gaps remain in long-term multi-country datasets. Most studies focused on single countries. Comparative, country-by-country assessments across the country are limited. Seasonal monthly correlations between irradiance and temperature have not been fully characterized across different climatic zones.

This study addresses these gaps by integrating all-sky solar irradiance and T2M datasets for East African countries, analyzing their spatial patterns, temporal variability, and interrelationships.

This study utilizes NASA POWER reanalysis data, a critical resource for regions lacking dense ground meteorological station networks, to provide a comprehensive evaluation of the spatial and temporal variability of these two parameters across Sudan, Ethiopia, Kenya, Uganda, and Tanzania over the recent four-year period (2021–2024). The results will enhance understanding of climate-energy dynamics in the region and provide a foundation for solar resource assessment, energy planning, and climate impact studies.

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2 Materials and Methods

2.1 Study Area

The study focuses on major East African countries, including Ethiopia, Kenya, Uganda, Tanzania, and Sudan. The region lies roughly between latitudes 10°S -15°N and longitudes 25°-50°E, encompassing both equatorial and subtropical climatic conditions.

2.2 Data Used

Data were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) reanalysis platform (https://power.larc.nasa.gov/). The dataset provides globally consistent, satellite-derived and model-assimilated meteorological variables optimized for solar energy and agricultural applications. For this analysis, two key parameters were downloaded for the period January 2021 to December 2024:

1. All-sky surface shortwave downward irradiance (kWh/m²/day)
2. Near-Surface Air Temperature at 2 meters (T2M) (°C)

Data were extracted for five East African countries: Ethiopia, Kenya, Uganda, Tanzania, and Sudan. Representative coordinate points within each country were selected based on spatial relevance to the regional climate zones and the availability of continuous data in the NASA POWER archive. All datasets were processed using Python (pandas, NumPy, and matplotlib). Monthly and annual means were computed and plotted for both Irradiance and T2M for each country across the four years and statistically analyzed to identify seasonal cycles, long-term trends, and correlations between the two parameters.

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3 Results and Discussion

3.1 All-Sky Solar Irradiance Variability (2021–2024)

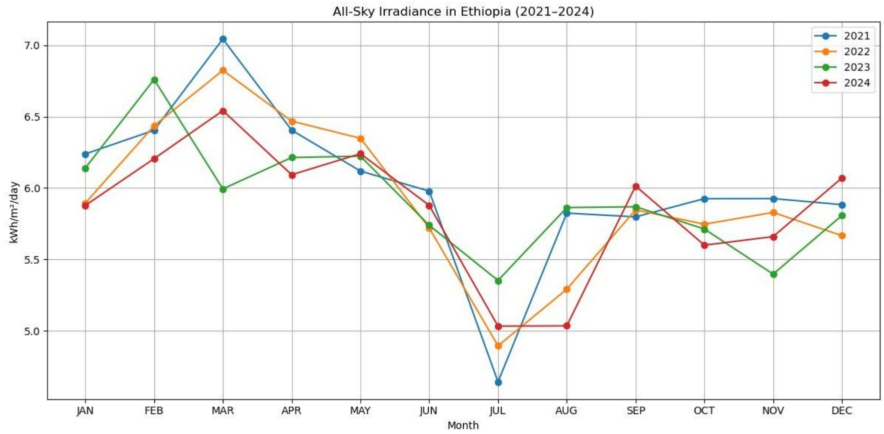
The temporal evolution of monthly all-sky solar irradiance over Ethiopia, Kenya, Sudan, Tanzania and Uganda from 2021 to 2024 demonstrates clear seasonal signatures that are strongly modulated by the regional climate regimes and the annual migration of the Intertropical Convergence Zone (ITCZ). Although the magnitude and timing of peak irradiance differ among the five countries, all exhibit consistent interannual persistence, indicating stable solar resource availability during the four-year period.

The irradiance pattern over Ethiopia displays a distinct bimodal distribution, with pronounced maxima occurring during February - March each year. During this period, irradiance values commonly exceed 6.5 - 7 kWh/m²/day, reflecting the clear-sky conditions that dominate the early dry season. A secondary enhancement is observed during September - November, although the magnitude remains lower than the first peak. The lowest irradiance values occur during July, with minima around 4.5–5.0 kWh/m²/day, corresponding to the peak of the Kiremt rainy season, when extensive cloud cover substantially suppresses incoming shortwave radiation. 2021 registered an extreme low, dropping below 4.75 kWh/m²/day. This indicates an exceptionally heavy and prolonged cloud cover event in 2021. 2023 shows the highest values during this period (about 5.75 kWh/m²/day), suggesting a less severe or shorter rainy season. The interannual variations among the four years are relatively small, suggesting that Ethiopia's seasonal solar irradiance is robust against year-to-year climatic fluctuations.

Kenya exhibits a seasonal cycle comparable to Ethiopia, with a bimodal distribution. The highest irradiance values occur in January, February and March and again in September, reaching 6.4 - 6.7 kWh/m²/day. These peaks align with the country's dry seasons when cloud cover is minimal. 2023 recorded the highest values in the first quarter (Feb - Mar, about 6.9 kWh/m²/day). All four years show a relatively consistent trough in July, with irradiance values dropping to approximately 4.6 - 5.0 kWh/m²/day. This period coincides with the aftermath of the long rains (March - May) and the mid-year cloudy season, which significantly diminish solar radiation. The four years follow nearly identical seasonal trajectories, indicating a high degree of interannual stability in Kenya's solar resource.

Sudan experiences its highest irradiance during April - May, consistently exceeding 7.0kWh/m²/day, the highest values among the five study regions. This peak reflects the combined effect of intense solar exposure and the predominantly clear-sky conditions characteristic of Sudan's arid and semi-arid climate zones. Following this peak, irradiance declines sharply toward August, which marks the annual minimum of approximately 5.50 - 5.7 kWh/m²/day. This reduction is linked to Sudan's short rainy season, during which moisture influx and cloud cover increase. A moderate recovery occurs in September–October, although irradiance gradually decreases toward December.

Tanzania in 2024 shows a stark anomaly, recording the lowest value of the period in January (approximately 4.5 kWh/m²/day). This suggests a highly unusual cloud cover or heavy rainfall event at the start of that year. Outside of this anomaly, the peak season (September - October) shows good clustering around 6.0 - 6.5 kWh/m²/day. A significant anomaly is observed in Uganda in July 2024, which dropped to the absolute lowest value for Uganda (approximately 4.45 kWh/m²/day).


All-Sky Irradiance in Ethiopia (2021–2024)
2021
2022
2023
2024
kWh/m²/day
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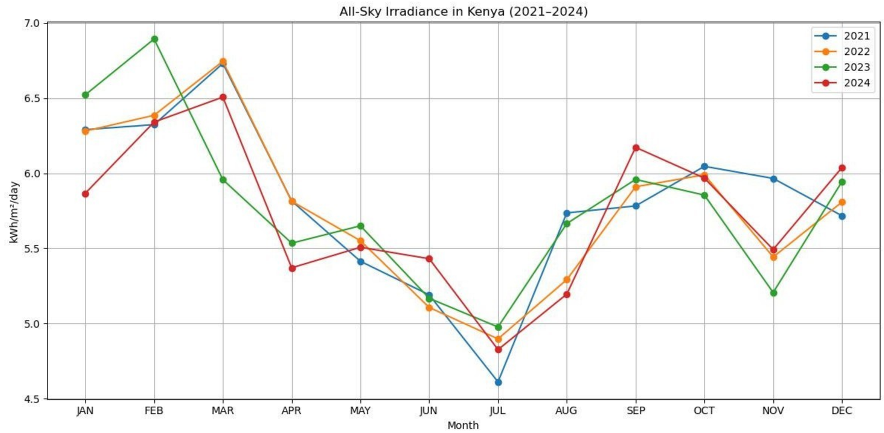
All-Sky Irradiance in Kenya (2021–2024)
2021
2022
2023
2024
kWh/m²/day
Month
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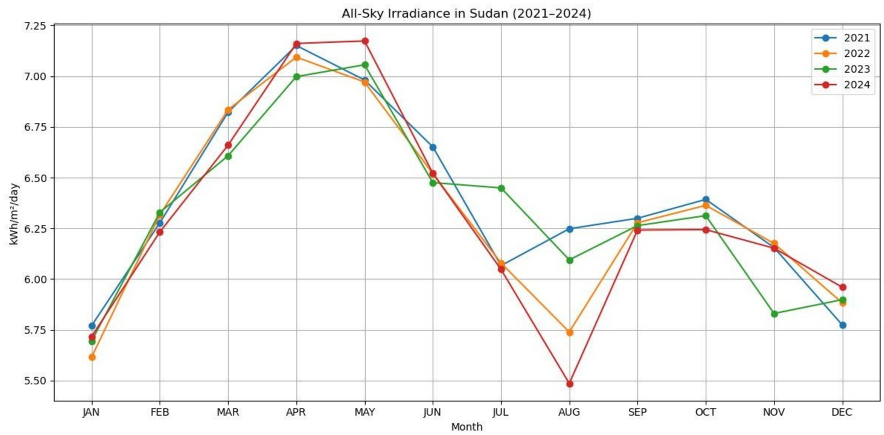
All-Sky Irradiance in Sudan (2021–2024)
2021
2022
2023
2024
kWh/m²/day
Month
JAN
FEB
MAR
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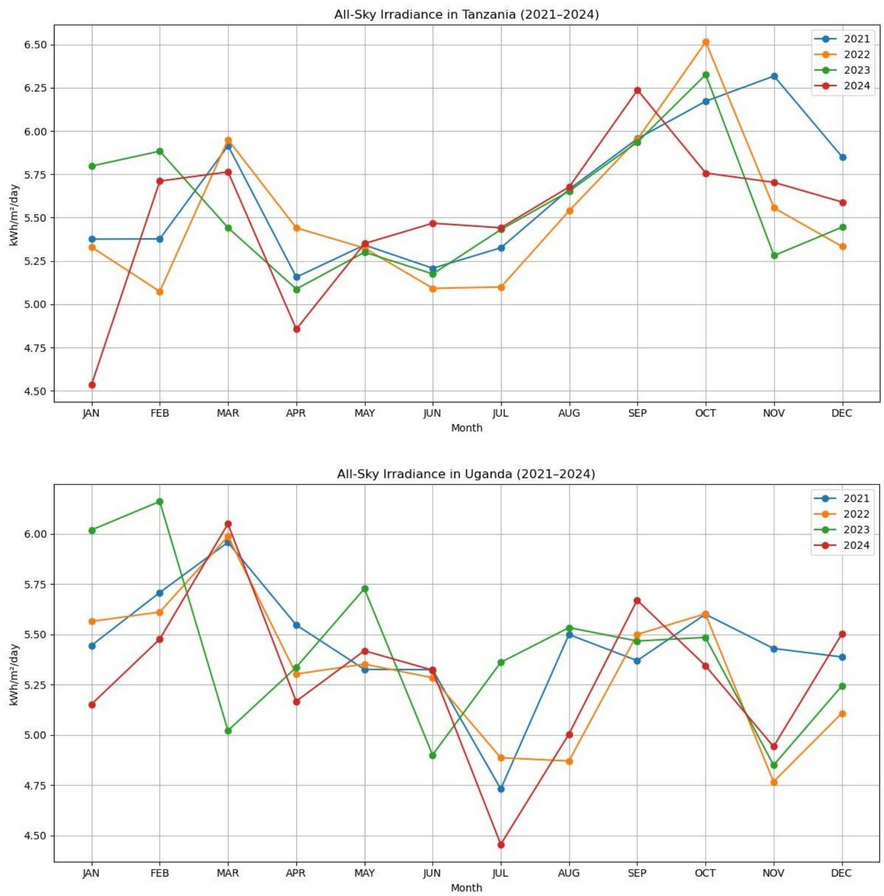

Figure 1: Monthly All-sky Solar Irradiance Variability in East African Countries (2021–2024)

A comparative assessment across the five countries indicates that Sudan consistently exhibits the highest irradiance, reflecting its desert-dominated landscape and prolonged periods of cloud-free conditions. Ethiopia and Kenya share similar seasonal characteristics, with mid-year depressions driven by cloud cover and rainfall associated with the Kiremt (Ethiopia) and long rains (Kenya).

Tanzania and Uganda show lower-intensity profiles. Despite these regional contrasts, interannual variability from 2021 to 2024 remains modest across all countries. The inter-annual analysis confirms the strong reliability of the seasonal timing and magnitude of the resource (i.e., peaks occur in the same months, and annual means are stable). This consistency underscores the reliability of solar irradiance as a renewable energy resource in East Africa and highlights the potential for sustained solar energy deployment across the region. The observed July irradiance minimum across all countries corresponds to enhanced cloud cover associated with the seasonal northward displacement of the ITCZ, which increases atmospheric convection and reduces incoming shortwave radiation.

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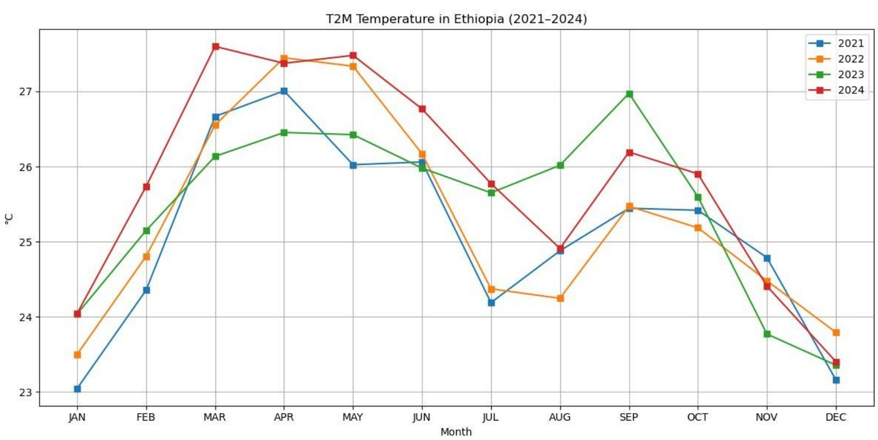
3.2 Near-Surface Air Temperature (T2M) Variability (2021–2024)

Temperature Profiles also show seasonal variability. Ethiopia's temperature profile with T2M values generally exhibit two transition periods: warming during January - March and cooling during June - August. Year 2024 experienced the hottest value, with March, April and May temperatures peaking near 27.5°C. The lowest temperatures occur during the June - August season, which coincides with the Kiremt rainy season (around 24.0°C to 25.0°C). Increased cloud cover and precipitation during these months limit solar heating and induce a cooling effect. Interannual variations across the four years remain minor, although slight warming can be observed during the dry seasons, consistent with broader warming trends reported in East Africa.

Kenya's T2M plot a clear warming phase during January–March, with temperatures reaching 24–28°C in most areas. The hottest month (March) shows a large spread: 2024 and 2022 recorded the highest values (near 27.5°C), while 20223 and 2021 were significantly cooler (near 26.5°C). A secondary warming is often observed in October–November, corresponding to the short dry season. 2021 was noticeably warmer than 2023 in the final quarter. The coolest period occurs during June–July, when T2M declines to around 23°C - 24°C. Similar to Ethiopia, interannual differences remain small, indicating stable year-to-year temperature behavior.

Sudan demonstrates the most pronounced annual temperature cycle among the five countries due to its predominantly arid environment and low cloud cover outside the rainy season. Temperatures reach their maximum values during April–June, often exceeding 30–34°C, reflecting intense solar heating and minimal moisture-induced moderation. A noticeable temperature decline occurs in July–August, when T2M drops to approximately 26–29°C. This cooling corresponds to Sudan's short rainy season, during which cloud cover, increased humidity, and precipitation contribute to moderating daytime temperatures. After August, temperatures gradually rise and then stabilize during the post-rainy season. No major interannual anomalies are observed, indicating that Sudan's temperature regime remained relatively stable from 2021 to 2024.

Across both Tanzania and Uganda, monthly T2M temperature patterns exhibit a consistent annual cycle. In Tanzania, temperatures generally range from 20 °C (July) to 25 - 25.5 °C (October - November), with 2023 and 2024 showing slightly elevated warm-season temperatures relative to 2021 - 2022. Uganda displays a similar pattern but with higher overall temperatures, fluctuating between 22–23 °C (June - July) and 25.5 - 26.2 °C (February - March).



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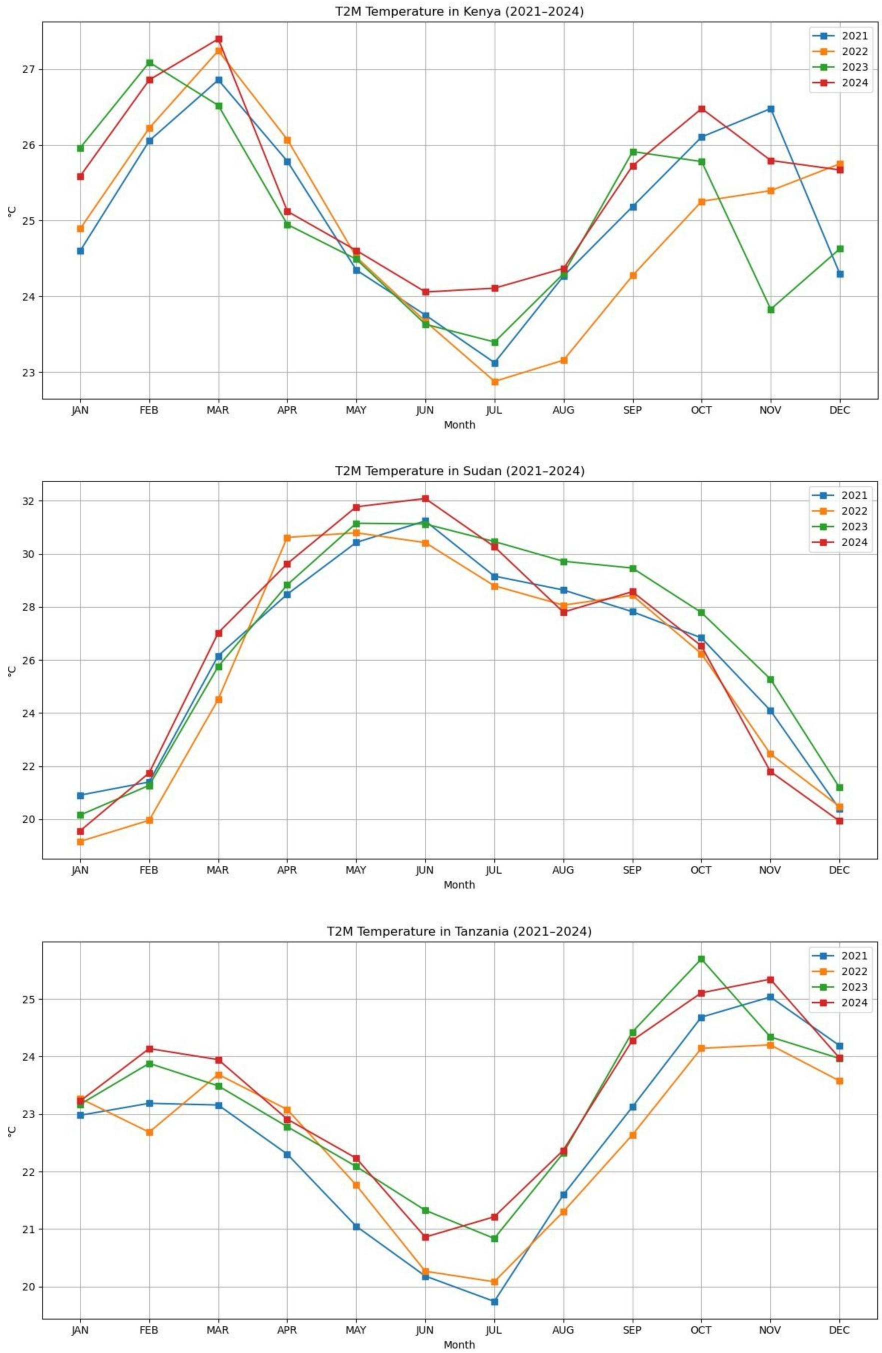

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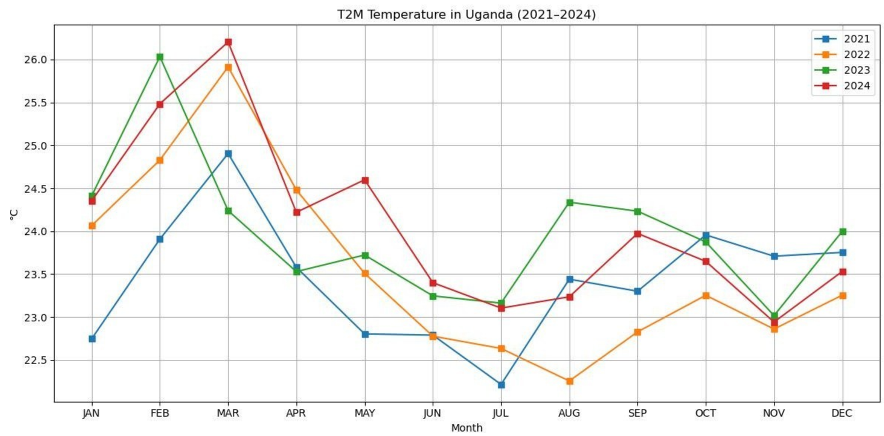

Figure 2: Monthly Mean Near-Surface Air Temperature (T2M) Variability (2021–2024)

Temperature also shows minimal inter-annual variability. Across the 2021–2024 period, all five countries show limited interannual variability, emphasizing the stability of regional climate forcing and the reliability of T2M data from NASA POWER for climatological assessments.

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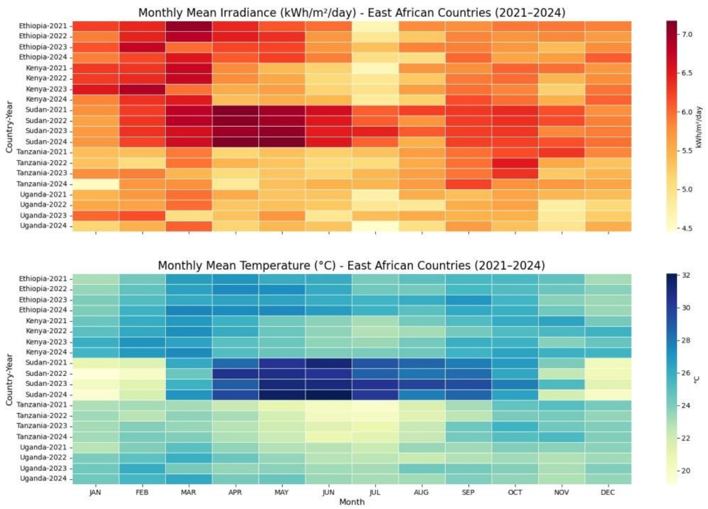

Figure 3: Monthly mean irradiance and Temperature of East African countries

3.3 Comparative Analysis of East African Climate Variability (2021–2024)

The data shows significant variation in mean monthly irradiance across the five countries. Sudan consistently exhibits the highest irradiance levels for most of the year, while Uganda and Tanzania generally record the lowest. All countries show their highest irradiance values during the period leading up to their respective summer or dry seasons, likely due to reduced cloud cover. Sudan's irradiance peaks sharply in April/May, exceeding 7.0 kWh/m²/day. Ethiopia and Kenya also peak around March/April/May, with values approaching 6.5 kWh/m²/day. Irradiance levels show a strong seasonal dependence, largely driven by the movement of the Inter-Tropical Convergence Zone (ITCZ). Lowest Irradiance occurs during the respective rainy seasons, typically around June-August, when high cloud coverage attenuates solar radiation. For instance, all countries' irradiance levels drop considerably in July. The high average annual irradiance levels, generally ranging from 5.0 to 7.0 kWh/m²/day across the region, indicate a strong potential for solar energy generation in East Africa. The data provides crucial insights for planning solar energy projects by highlighting periods of peak and minimum resource availability.

The five East African countries exhibit a broadly similar seasonal cycle in solar irradiance, characterized by higher values during the boreal spring (February–April) and lower values during June–July, which coincides with regional cloudiness and rainfall peaks. Sudan consistently records the highest irradiance throughout the year, reaching over 7.0 kWh/m²/day in April, reflecting its arid climate and extensive clear-sky conditions. Ethiopia and Kenya show comparable patterns, with irradiance maxima around 6.4–6.6 kWh/m²/day in February–March and annual minima near 4.9–5.0 kWh/m²/day in July. Tanzania and Uganda exhibit the lowest irradiance levels, generally between 5.0 and 5.7 kWh/m²/day, with modest seasonal peaks in March and September–October.

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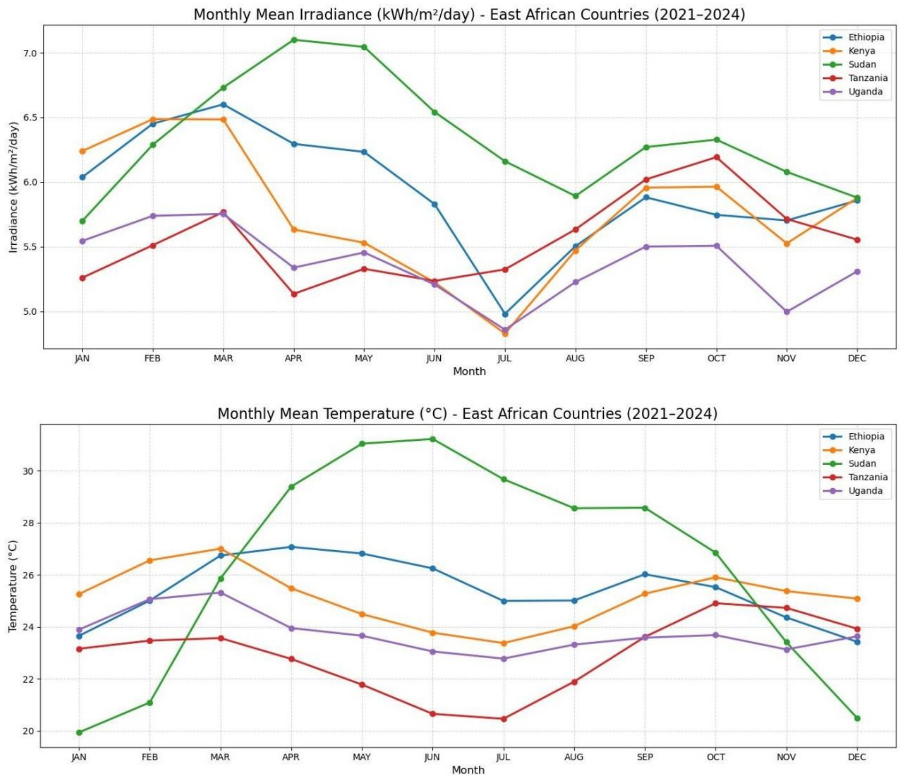

Figure 4: Comparative Analysis of Irradiance and Temperature Trends (2021-2024)

Sudan (green line) consistently records the highest mean monthly temperatures across the monitored period (2021-2024), peaking at around 31°C between May and July. It also shows the greatest seasonal variability, with temperatures dropping significantly by December. Kenya and Ethiopia (orange and blue lines) show moderate temperatures compared to Sudan, generally ranging between 23°C and 27°C. Their temperature lines track relatively closely, suggesting similar influencing factors, possibly related to their proximity to the equator and high-altitude regions. Kenya shows a slightly warmer profile than Ethiopia in the first half of the year. Uganda and Tanzania (purple and red lines) generally exhibit the lowest temperatures. Tanzania, in particular, maintains the coolest profile for most of the first half of the year, with a minimum temperature of approximately 20.5°C in July. All countries demonstrate distinct seasonal patterns, with a general warming trend leading into the middle of the year and cooling towards December. This is largely influenced by the migration of the Inter-Tropical Convergence Zone (ITCZ). The data indicates significant month-to-month variability, especially evident in the sharp incline for Sudan from March to May and its decline from October to December.

The irradiance and temperature time-series across all countries show that Strong seasonal oscillations with two major peaks each year, reflecting the bi-annual solar maxima near the equator. Sudan exhibits the largest amplitude, while Uganda shows the smoothest curve with less variability.

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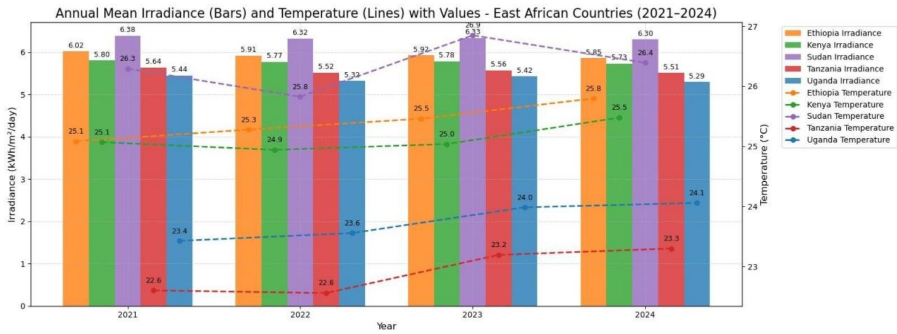

Figure 5: Annual mean irradiance and Temperature

For all five countries, the annual mean irradiance and temperature remained remarkably stable across the four years (2021-2024), showing minimal deviation. This suggests high reliability for long-term solar project planning. There is slight year-to-year variation in Irradiance and Temperature values. Irradiance values remain largely stable across the four-year period, showing minimal inter-annual variability compared to temperature. Sudan (green bars) consistently records the highest annual mean irradiance values throughout the four years, peaking at 6.38 kWh/m²/day in 2021 and maintaining values near 6.32, 6.28, and 6.30 in subsequent years. Kenya and Ethiopia (orange and blue bars) show strong, stable irradiance levels, generally hovering between 5.7 to 6.0 kWh/m²/day. Tanzania (red bars) and Uganda (purple bars) show slightly lower but still significant irradiance, often slightly below 5.5 kWh/m²/day. .

Sudan (green line) registers the highest mean annual temperatures. Ethiopia and Kenya (orange and blue lines) maintain moderate average temperatures. Uganda and Tanzania (purple and red lines) exhibit the lowest annual mean temperatures. Tanzania remains particularly cool, with temperatures consistently around 22°C-23°C. The data highlights that Northern countries (Sudan, Ethiopia) tend to be hotter and receive more intense solar radiation. Southern and equatorial countries (Tanzania, Uganda) are cooler with slightly moderated irradiance, likely due to factors like higher altitude or proximity to water bodies and different rainfall patterns. This analysis underscores the varied climatic zones within East Africa, providing crucial baseline data for climate modeling and renewable energy infrastructure planning.

3.4 Possible Influence of Solar Variability and Global Climate Change

The analyzed time period (2021–2024) coincides with the rising phase of Solar Cycle 25, during which solar activity gradually increases. Variations in solar activity produce small fluctuations in total solar irradiance, typically on the order of approximately 0.1% across the solar cycle. Although these variations are relatively small compared to regional cloud-driven variability, solar cycle changes may still contribute to subtle variations in surface radiation and temperature patterns.

While the present study focuses primarily on regional climatic drivers such as cloud cover and seasonal circulation systems, solar variability represents an additional factor that may influence long-term radiative forcing. Quantifying the direct contribution of solar cycle variability would require longer observational records spanning multiple solar cycles, which is beyond the scope of the present analysis.

In addition to natural variability associated with solar activity, global climate change may also influence regional temperature patterns. Over recent decades, global mean surface temperatures have shown a persistent increasing trend, largely attributed to rising atmospheric greenhouse gas concentrations, particularly carbon dioxide (CO_2). Although the four-year dataset used in this study is insufficient to detect long-term climate trends, the observed temperature behavior may reflect the combined influence of regional atmospheric dynamics and broader global warming signals.

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3.5 Relationship Between All-Sky Solar Irradiance and Near-Surface Air Temperature (T2M)

Generally, the data suggests a strong inverse correlation between rainfall/cloud cover and irradiance, and a direct correlation between irradiance and temperature. Periods of high solar irradiance often precede or coincide with peak temperatures, while periods of low irradiance (due to cloud cover) correlate with cooler months. Both temperature and irradiance peak around March, indicating that maximum solar input drives peak warmth. Both variables hit their lowest point around July when cloud cover is highest. These findings highlight how seasonal cloud patterns, likely influenced by the Inter-Tropical Convergence Zone, are the primary drivers for the variability in both temperature and the availability of solar resources in East Africa.

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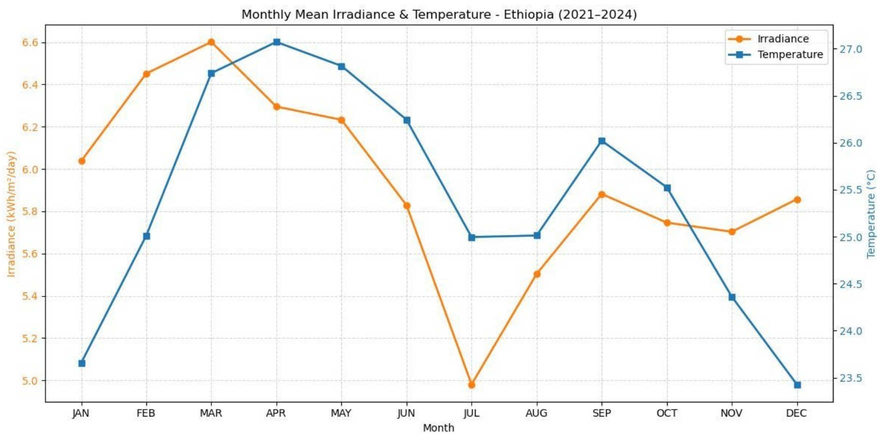

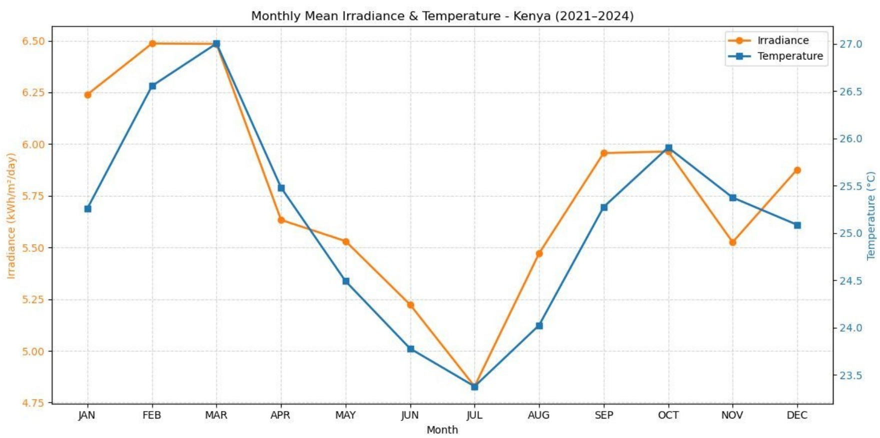

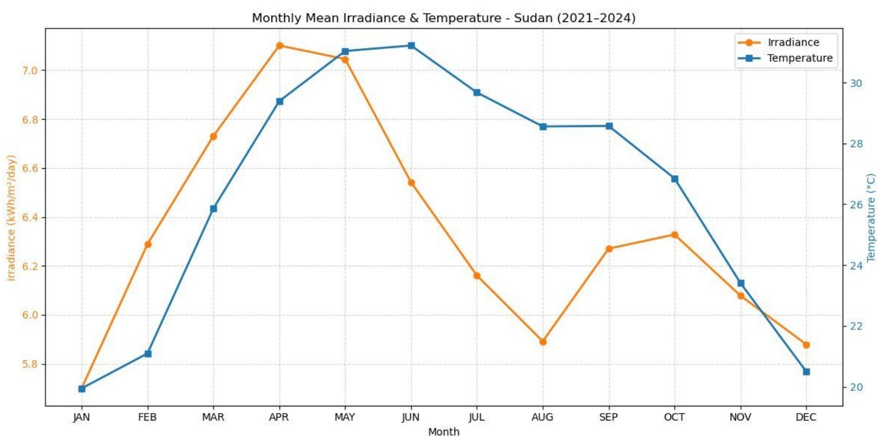

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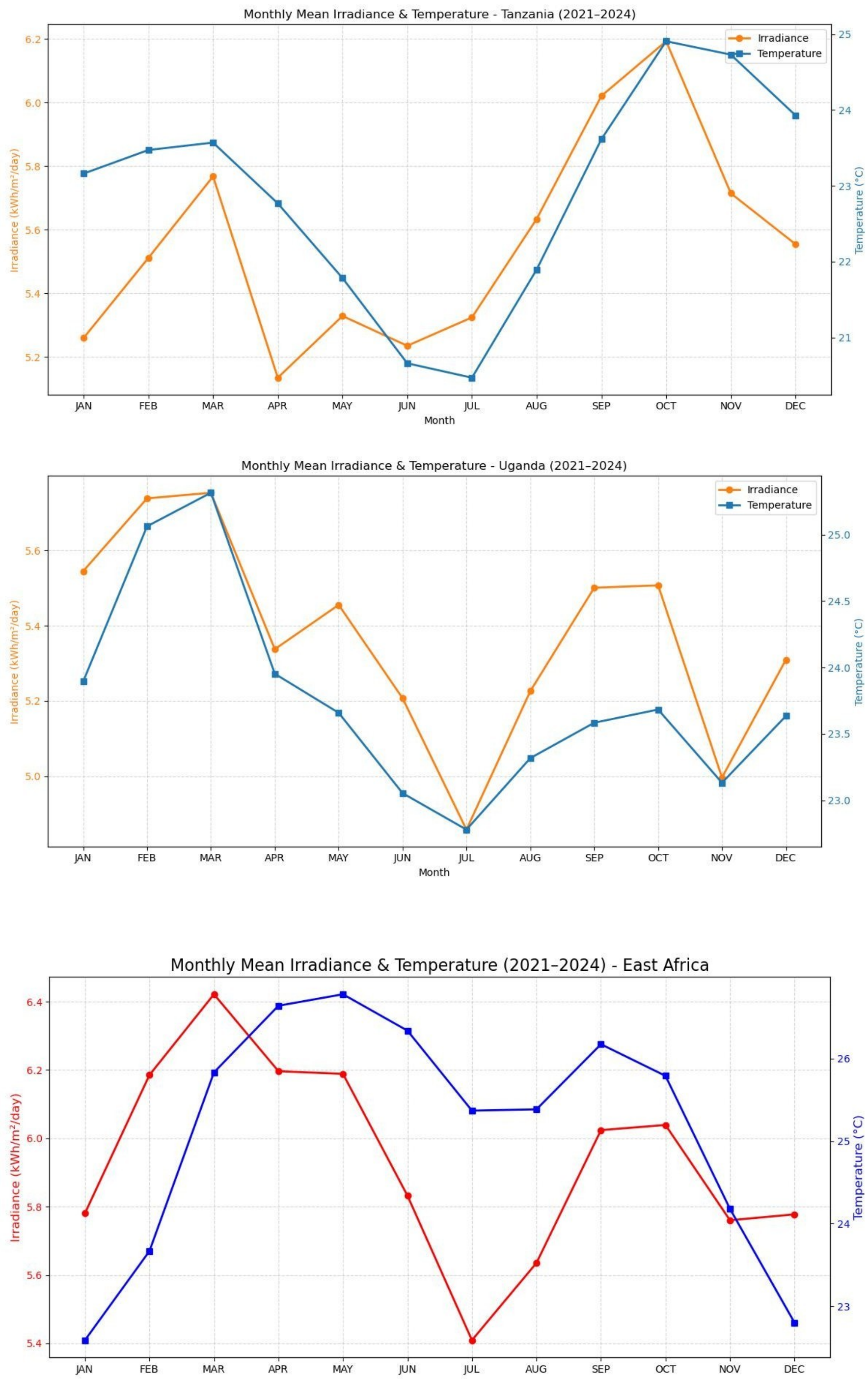

286 Figure 6: Relationship Between All-sky Solar Irradiance and Near-Surface Air Temperature

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Conclusion

This study provided a detailed climatological assessment of all- sky solar irradiance and near- surface air temperature across East African countries. The study examined the seasonal and interannual variability of all-sky solar irradiance and near-surface air temperature (T2M) across Ethiopia, Kenya, Sudan, Tanzania and Uganda from 2021 to 2024 using NASA POWER reanalysis data. The analysis reveals that East Africa exhibits a characteristic bimodal pattern of solar irradiance, with prominent peaks occurring during February–March and again in October. Near-surface air temperature closely follows the seasonal behavior of irradiance. Among the examined countries, Sudan consistently records the highest levels of solar irradiance, whereas Uganda exhibits the lowest. Inter-annual variability during the 2021–2024 period remains relatively modest, with no major anomalies detected in either irradiance or temperature fields. Both variables demonstrate a strong positive correlation at monthly and annual timescales, indicating coherent seasonal energy-cycle dynamics across the region. Furthermore, the regional climate patterns appear synchronized among the countries, largely governed by the seasonal migration of the Intertropical Convergence Zone (ITCZ). Overall, the findings indicate that the East African region possesses considerable potential for solar energy utilization, supported by stable irradiance profiles and predictable seasonal behavior. The results also emphasize the suitability of NASA POWER reanalysis data for regional climate analyses and renewable energy assessments. Furthermore, the minimal interannual variability observed from 2021 to 2024 underscores the reliability of solar energy as a long-term investment, reinforcing its suitability for national electrification agendas, rural energy access programs, and climate mitigation strategies. Integrating these climatological insights into regional energy policies can enhance sustainable development outcomes and support East Africa's transition toward a low-carbon energy system.

The study period (2021–2024) coincides with the rising phase of Solar Cycle 25, during which solar activity and solar irradiance gradually increase. Although variations in total solar irradiance are relatively small, they can still contribute to changes in surface radiation and atmospheric temperature. Therefore, part of the observed variations in shortwave downward irradiance and surface temperature over East Africa may also be influenced by solar cycle variability (figure 5). However, quantifying this influence requires longer time series data and dedicated solar–climate analysis, which is beyond the scope of the present study. Because the analysis is based on a relatively short observational window (2021–2024), the results primarily describe recent variability rather than long-term climatic trends.

Future research may extend this study by incorporating longer climatological windows, evaluating aerosol and cloud dynamics, or integrating ground-based observations to further refine the spatial and temporal characterization of East African solar and thermal environments. In addition to natural variability such as solar activity,global temperature trends are strongly influenced by anthropogenic factors, particularly increasing atmospheric CO_2 concentrations. According to recent global climate assessments, surface temperatures have shown a persistent increasing trend over the last decades. The temperature variations observed in this study may therefore reflect a combination of regional climatic variability, cloud cover differences, and broader global warming trends.

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Author Contributions

Meseret Amisaya Shibabaw: Conceptualization, data analysis, methodology, writing original draft preparation.

Mogese Wassaie Mersha: Supervision, review and editing, validation of results.

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Code and Data Availability

Data Availability

The datasets analyzed during the current study are publicly available from the NASA POWER Data Access Viewer (https://power.larc.nasa.gov/). The processed data and analysis scripts used in this study are available from the corresponding author upon reasonable request.

Code Availability

The Python codes (pandas, NumPy, matplotlib) used for data processing and visualization are available from the corresponding author upon reasonable request.

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