World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Understanding heat retention and release through outgoing longwave radiation dynamics in the upper Gangetic alluvial plain

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World Journal of Advanced Research and Reviews, 2025, 27(01), 1660-1672

Publication history: Received on 07 June 2025; revised on 15 July 2025; accepted on 17 July 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.27.1.2691

Abstract

Outgoing Longwave Radiation (OLR) is a fundamental component of Earth's energy budget, representing the planet's primary mechanism for heat loss to space. The physical principles governing OLR emission, including blackbody radiation and the role of atmospheric absorption by greenhouse gases and clouds, are crucial for understanding this energy flux. This study investigates the month-wise trends in daytime and night-time outgoing longwave radiation (OLR) over the period 2013 to 2025, aiming to assess seasonal variability and the relationship between day and night radiative fluxes. Using OLR values (in W/m^2), the analysis reveals distinct seasonal patterns daytime OLR peaks during the pre-monsoon months (April-May), indicating intense solar heating and clear-sky conditions, while significant drops during monsoon months (July-September) reflect increased cloud cover and atmospheric moisture. Night-time OLR follows a similar seasonal rhythm but is more influenced by nocturnal cloud cover and radiative cooling efficiency.

A scatter plot between daytime and night-time OLR shows a strong positive correlation (r = 0.86), suggesting that surface heating during the day is closely linked to heat retention and emission at night. The high correlation also indicates the consistency of radiative processes over the diurnal cycle, with deviations hinting at atmospheric disturbances such as cloud formation or humidity changes. This relationship is critical for understanding regional energy balance and climate behaviour. The study concludes that OLR trends can serve as valuable indicators for monitoring climatic variability, supporting heatwave forecasting, enhancing agricultural resilience, and informing local adaptation strategies in climate-sensitive regions like north western India.

Keywords: Outgoing Longwave Radiation; Day and night-time OLR; Karl Pearson; Muzaffarnagar; Monthly Analysis

1. Introduction

Energy is exchanged between the surface and the air radiatively at visible and infrared wavelengths through conduction, convection, or latently (Skhula & Dirmeyer, 1994). The Earth's climate system is governed by a delicate energy balance known as the radiation budget, which determines global temperature and climate. Solar radiation, mostly shortwave energy, enters the atmosphere, where some is reflected by clouds, aerosols, and Earth's surface (albedo), while the rest is absorbed, warming the planet. To maintain thermal equilibrium, Earth emits longwave radiation (OLR) back to space its only cooling mechanism. This balance between absorbed solar energy and emitted OLR powers the climate system and atmospheric dynamics. When energy imbalance occurs, Earth self-adjusts: excess absorption leads to warming, increasing OLR and restoring balance. OLR acts as the planet's thermostat, influencing weather and climate patterns. Latitude, season, cloud, precipitation, ground-effective radiation, underlying surface, and atmospheric temperature are some of the factors that affect the distribution and changes of OLR (You & Dong, 2019). Of these, latitude and seasonal

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influence determine the basic trend that OLR, cloud, precipitation, underlying surface, and atmospheric temperature, etc., will deviate from (Liu, Zhang, Chen, Wu, & Wang, 2021).

1.1. Definition and Fundamental Importance of Outgoing Longwave Radiation (OLR)

Outgoing Longwave Radiation (OLR) refers to the thermal radiation emitted from the top of Earth's atmosphere into space, primarily within wavelengths of 4 to 100 micrometres. It plays a central role in Earth's energy budget by balancing the incoming solar shortwave radiation. At the same time, the research on influencing factors of OLR is also beneficial to understand the influence of abnormal weather on the changes in the whole sea area (Fajary, Hadi, & Yoden, 2019). When absorbed solar energy exceeds OLR, a positive energy imbalance occurs, contributing to global warming. OLR is not just a measure of energy loss—it also serves as a proxy for atmospheric conditions. In the tropics, low OLR values indicate high, cold cloud tops linked to deep convection, while high values suggest clear skies or low, warm clouds. This makes OLR essential for monitoring phenomena like the Madden-Julian Oscillation (MJO) and El Niño-Southern Oscillation (ENSO). Moreover, the spectral characteristics of OLR reveal detailed atmospheric information, including cloud structure, humidity levels, and greenhouse gas concentrations. Specific gases leave identifiable signatures in the OLR spectrum, such as carbon dioxide's dip near 15 µm. Thus, OLR functions as a powerful diagnostic tool, providing critical insights into radiative processes, atmospheric dynamics, climate variability, and long-term climate change.

1.2. Significance and Applications of OLR Analysis

1.2.1. Role in Climate Modelling and Climate Change Detection

Outgoing Longwave Radiation (OLR) plays a vital role in climate modelling, which involves the mathematical simulation of Earth's climate components such as the atmosphere, land surface, oceans, and ice and their interactions. Accurate representation of OLR is crucial for maintaining Earth's energy balance, which directly affects the reliability of long-term climate predictions. Climate models use OLR data for both diagnostic analysis of past climate conditions and predictive modelling of future scenarios, helping researchers understand the sensitivity of the climate system to various factors like greenhouse gas emissions and cloud cover changes. OLR data is also a key component in validating the accuracy of climate models. These models are assessed based on their ability to accurately replicate historical climate patterns, including the observed warming trends of the 20th century.

A model's credibility in projecting future climate change depends largely on how well it reproduces observed OLR values. High-quality datasets such as CERES-EBAF and HIRS Climate Data Records (CDRs) are used as benchmarks in this process. Disparities between modelled and observed OLR can highlight deficiencies in model physics, particularly in how clouds and radiative processes are represented, necessitating further refinement. Beyond model development, OLR analysis serves as a critical tool in detecting signs of climate change. As greenhouse gas concentrations rise, the amount of longwave radiation escaping to space is reduced, causing a net positive energy imbalance. This means more energy is retained in the Earth system than emitted, which contributes directly to global warming. Thus, OLR is not just a by-product of climate models, but a core metric that influences model accuracy, climate diagnosis, and confidence in future projections. It is instrumental in identifying and understanding changes in the planet's radiative energy budget and is central to assessing the ongoing impact of anthropogenic activities on the Earth's climate system.

1.2.2. Applications in Weather Forecasting and Climate Dynamics

An essential diagnostic variable for weather forecasting and the investigation of large-scale climatic systems is outgoing longwave radiation (OLR). It helps validate numerical weather prediction models and detect variations in tropical cloud activity and rainfall key drivers of global atmospheric circulation. In tropical and subtropical regions, OLR acts as a reliable indicator of deep convection. Lower OLR values typically signal colder, higher cloud tops and intense convective activity, often associated with phenomena like El Niño. In contrast, higher OLR values suggest limited convection and reduced cloud cover, commonly observed during La Niña episodes. In the tropics, the Madden-Julian Oscillation (MJO) is a primary cause of intra-seasonal fluctuation, and its monitoring and analysis depend heavily on OLR. Standard diagnostics from CLIVAR heavily rely on OLR to trace the MJO's propagation, and to evaluate how well climate models capture its behaviour.

This highlights OLR's role not just in observation but also in improving model performance for short- to medium-range tropical forecasts. Beyond atmospheric processes, OLR data is a critical input for ocean circulation models, emphasizing its role in linking atmospheric and oceanic dynamics. Large-scale atmospheric systems like the Walker and Hadley circulations are thermally driven and influenced by regional convection patterns, which are reflected in OLR distributions. El Niño-Southern Oscillation (ENSO) events, by shifting heating patterns, directly alter these circulation cells. Since OLR captures latent heat release from convection, it serves as a direct observational footprint of these circulations. Thus, OLR not only represents energy loss to space but also reveals the inner workings of the climate system, making it a powerful tool for understanding and predicting complex phenomena such as ENSO and MJO.

1.2.3. Environmental Monitoring and Disaster Prediction

Outgoing Longwave Radiation (OLR) data has emerged as a valuable asset for monitoring and, in some cases, predicting a range of environmental phenomena and natural disasters. In drought monitoring, OLR anomalies when analysed alongside satellite-derived precipitation estimates and vegetation indices can effectively capture both the spatial extent and temporal evolution of severe droughts. This is particularly useful in areas lacking extensive ground-based rain gauge infrastructure. While GRACE satellite data provides insights into total water storage, OLR adds an atmospheric dimension, capturing patterns related to cloud cover and convection, thus enhancing the accuracy of drought assessments.

Tracking and predicting the intensity of tropical cyclones is another important function of OLR. Techniques like the Dvorak technique and its contemporary equivalents rely heavily on infrared satellite imaging, which provides OLR data. These approaches rely on interpreting cloud patterns to infer storm strength. With advancements in machine learning, new models are now incorporating OLR and other environmental data to provide more precise cyclone intensity predictions. Beyond meteorological applications, OLR has been explored for marine phenomena such as El Niño, and even in the study of volcanic and seismic activities. However, using OLR anomalies for earthquake prediction remains uncertain. Such anomalies are often sporadic and lack consistent spatial alignment with seismic zones, indicating that OLR alone cannot reliably predict earthquakes. Overall, while OLR offers critical atmospheric insights, its greatest value lies in integration with other datasets. In the context of environmental monitoring, OLR is most effective when used within a multi-variable framework, contributing to a comprehensive environmental intelligence system.

1.3. Scope of this paper

This paper aims to provide a comprehensive analysis of Outgoing Longwave Radiation (OLR), exploring its fundamental physical principles, the complex factors influencing its variability. Emphasis is placed on understanding OLR's critical role in Earth's energy budget and its utility as a diagnostic tool for atmospheric processes, cloud dynamics, and climate variability. In addition to theoretical insights, the paper presents an empirical analysis of both daytime and night-time OLR over the Muzaffarnagar region for the period 2013-2025. This regional assessment highlights temporal trends and potential climatic implications, contributing to localized climate monitoring and broader global change studies.

2. Physical Principles of Outgoing Longwave Radiation

2.1. Electromagnetic Spectrum and Thermal Emission

Radiation is the transfer of energy via electromagnetic waves, emitted by all objects above absolute zero. The Earth, being cooler, emits thermal radiation mainly in the infrared range known as longwave radiation. In contrast, the Sun, due to its high temperature, radiates energy primarily in the visible spectrum with shorter wavelengths. A 4 μm wavelength cut-off typically separates shortwave (solar) and longwave (terrestrial) radiation. The atmosphere is largely transparent to solar radiation but absorbs longwave radiation, forming the basis of the greenhouse effect. This wavelength-dependent behaviour also guides remote sensing technologies, which use specific spectral bands to study Earth's atmosphere and surface.

2.2. Blackbody Radiation, Stefan-Boltzmann Law, and Wien's Displacement Law

To understand thermal emission, the concept of a "blackbody" is essential. A blackbody is an idealized object that perfectly absorbs and emits electromagnetic radiation at all wavelengths. Although Earth is not a perfect blackbody, blackbody principles help model its radiative behaviour. The Stefan-Boltzmann Law states that the total energy radiated by a blackbody (E) is proportional to the fourth power of its absolute temperature (T), expressed as $E = \sigma T^4$, where σ σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K^4). This means small temperature increases can cause large increases in radiation emitted. Wien's Displacement Law relates an object's temperature to the wavelength of its peak emission. It states that the peak wavelength (λmax) is inversely proportional to temperature, given by $\lambda max = w \ / \ T$, where w = (2897 $\mu m \ K$). Thus, the hot Sun emits shortwave radiation, while the cooler Earth emits longwave infrared radiation. These laws explain Earth's self-regulating temperature system. As temperatures rise, more energy is radiated to space, acting as a negative feedback. Understanding these non-linear radiative processes is crucial for climate modelling, as they determine how the planet responds to radiative forcing like greenhouse gas increases.

2.3. Atmospheric Absorption, Emission and the Greenhouse Effect

While the Earth's surface emits longwave radiation continuously, much of this energy does not directly escape to space due to the atmosphere's relative opacity to infrared wavelengths. In contrast to its transparency to incoming solar radiation, the atmosphere strongly absorbs longwave radiation, primarily because of greenhouse gases (GHGs) such as water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and ozone (O_3). These gases absorb infrared radiation at specific wavelengths, with CO_2 and H_2O showing pronounced absorption features in the OLR spectrum. Once absorbed, this energy is re-emitted by GHGs in all directions, including back toward Earth's surface and outward into space. However, this re-emission occurs at higher, colder altitudes. According to the Stefan-Boltzmann Law, colder objects emit less radiation, so the upper atmosphere emits less energy than the surface. This key aspect of the greenhouse effect means that even though energy is re-emitted, the lower intensity due to colder temperatures causes less radiation to leave the Earth system. As GHG concentrations increase, the effective altitude of emission rises to even colder layers, reducing outgoing longwave radiation (OLR) further and enhancing warming. This shift in emission height and its thermal implications are central to understanding climate sensitivity. The greenhouse effect is thus defined by the reduction of OLR to space compared to what the surface emits. The "atmospheric window" between 8 and 11 μm, where absorption is low, allows some radiation to escape. However, this window is narrow, and increasing GHGs gradually close even this escape route, intensifying warming.

2.4. Materials and Methods

2.4.1. Study Area and Period

The study focuses on Muzaffarnagar region in northwest India, a region that is sensitive to changes in the climate and has a specific seasonal cycle. The temporal coverage includes 13 years of monthly OLR data for both daylight and nighttime observations, from January 2013 to April 2025.

2.4.2. Data Sources

The NASA AIRS (Atmospheric Infrared Sounder) instrument, more especially the AIRS3STM Version 7.0 dataset, provided the OLR data. The item that was used is called "Time Series, Area-Averaged of Outgoing Longwave Radiation (Daytime/Ascending, AIRS-only) monthly 1° resolution." With distinct records for daytime (ascending orbit) and nighttime (descending orbit) observations, this dataset offers area-averaged, satellite-derived OLR values in Watts per square meter (W/m2) at a spatial resolution of 1° × 1°.

2.4.3. Data Processing

Using Python modules like xarray, pandas, and numpy, data that had been downloaded in NetCDF format were transformed into tabular time-series. On the basis of matching monthly timestamps, the OLR data for daytime and nighttime were retrieved, verified, and combined. We looked at any missing or unusual data and, if needed, interpolated them.

2.4.4. Analytical Methods

Using Python's statsmodels module, the seasonal, trend, and residual components of OLR were assessed using time series decomposition. The monthly variability of daytime and nighttime OLR was visualized using line graphs. To determine the link between daytime and nighttime OLR, scatter plots were made. To evaluate the linear relationship between day and night OLR values, the Pearson correlation coefficient (r) was calculated.

3. Factors Affecting OLR

3.1. Surface Temperature and Emissivity

The Earth's surface temperature directly influences the amount of outgoing longwave radiation (OLR), as described by the Stefan-Boltzmann law higher temperatures result in greater thermal emission. This creates a natural negative feedback: warming increases energy loss, helping stabilize the climate. However, surface emissivity also affects OLR. Emissivity measures how efficiently a surface emits radiation relative to a blackbody (value of 1.0) and varies across landscapes. In the 8-13 μm range, emissivity typically ranges from 0.65 to 0.99, with deserts showing the lowest values. The global average is about 0.95. Regions with lower emissivity emit less OLR, affecting local energy budgets and contributing to spatial climate variability.

3.2. Atmospheric Temperature and Water Vapor Profiles

The vertical profiles of atmospheric temperature and water vapor are key regulators of outgoing longwave radiation (OLR). Since higher altitudes are colder, radiation emitted from there has lower intensity. Water vapor, the most effective natural greenhouse gas, has broad infrared absorption bands and strongly influences how much OLR escapes to space. As the climate warms, atmospheric water vapor increases, amplifying warming through a positive feedback loop. In humid regions, water vapor's greenhouse effect can be 75-100 times stronger than CO_2. In contrast, dry areas like deserts and polar zones are more sensitive to CO_2 increases, affecting regional climate responses and OLR patterns.

3.3. Cloud Cover: Type, Altitude, and Optical Depth

Clouds play a complex role in regulating Earth's energy balance and outgoing longwave radiation (OLR). They absorb and scatter longwave radiation, limiting how much escapes to space. Because of their high albedo, clouds have the ability to both cool and warm the earth by reflecting incoming solar energy and absorbing and re-emitting longwave radiation, such as greenhouse gases. The net effect depends on cloud properties type, altitude, thickness, and optical depth. Low clouds (e.g., stratocumulus) usually cool the planet by reflecting sunlight. In contrast, high, thin clouds (e.g., cirrus) often warm the atmosphere by trapping heat and re-emitting radiation from cold altitudes. Cloud feedback how clouds respond to and influence climate change is a major uncertainty in climate projections. Whether cloud changes amplify or dampen warming is still unresolved. This uncertainty in cloud feedback contributes significantly to the wide range of predictions in climate models regarding future warming and OLR trends. OLR also serves as a useful proxy in tropical regions for monitoring convection and cloud cover, with negative OLR anomalies signalling increased cloudiness and deep convection. Improving OLR measurements and cloud representation is critical for refining future climate projections and understanding radiative processes.

3.4. Role of Aerosols and Dust

Reck, R. A. (1974, 75) investigated the effects of surface albedo and aerosol layer height fluctuations on the equilibrium of atmospheric radiation in the 1970s. Aerosols, including dust and fine particulate matter suspended in the atmosphere, significantly influence Earth's outgoing longwave radiation (OLR). While they are well known for reflecting solar radiation and producing a cooling effect, some aerosols especially larger or absorbing types can also absorb solar energy, warming the atmosphere locally. This absorbed heat is then re-emitted as longwave infrared radiation, some of which escapes to space. Aerosols thus affect both shortwave and longwave components of the energy budget. Unlike greenhouse gases or clouds, aerosols alter OLR by warming the atmosphere rather than blocking surface emission, making their impact complex and crucial to monitor for accurate climate assessments.

Table 1 Major Greenhouse Gases and Their Infrared Absorption Characteristics

Greenhouse Gas	Chemical Formula	Primary Absorption Wavelengths/Bands (μm)	Key Role in OLR/Greenhouse Effect
Water Vapor	H_2O	Numerous broad peaks (0.8-10 μm)	Most potent natural GHG, strong positive feedback
Carbon Dioxide	CO_2	2.6, 4, >13 μm (strong absorption)	Significant reduction in OLR, central to anthropogenic warming
Methane	CH_4	3.5, 8 μm	Potent GHG, contributes to warming
Nitrous Oxide	N_2O	5, 8 μm	Potent GHG, contributes to warming
Ozone	O_3	9.6-9.8 μm (in atmospheric window), UV	Absorbs in atmospheric window, shields UV

4. Result and Discussion

Figure 1 Month wise Day Time Outgoing Longwave Radiations During 2013-2025 from Muzaffarnagar Region

The provided plot illustrates the month-wise average daytime outgoing longwave radiation (OLR) from 2013 to 2025 in units of W/m^2. OLR represents the energy radiated from the Earth's surface and atmosphere back into space during the day. It is closely linked with surface temperature, cloud cover, and atmospheric composition. Higher OLR values generally indicate warmer, clearer conditions, while lower values correspond to cooler or cloudier skies.

A clear seasonal pattern emerges from the analysis. April to June consistently show high OLR values, reflecting the intense pre-monsoon heating in the region. For example, May month shows some of the highest values across all months, peaking in years like 2013 and 2025, suggesting years with intense heat and possibly reduced cloud cover. This aligns with India's climatology, where these months often experience rising surface temperatures before the onset of the monsoon. Conversely, the monsoon months July through September display significantly lower OLR values, with troughs around 2018 and 2019. This is due to the extensive cloud cover and rainfall that suppresses outgoing radiation during active monsoon phases. August and July, in particular, reach some of the lowest OLR readings in the entire dataset. Post-2020, there is a slight recovery in OLR during these months, possibly indicating weaker or more intermittent monsoon activity.

The winter months (December to February) maintain moderate OLR values, with subtle year-to-year variability. January and December tend to remain within a narrow band, though slight peaks in 2017 and 2025 suggest clearer winter skies and possible warming events. Meanwhile, October and November, which mark the transition from monsoon to winter, show significant inter-annual fluctuations, indicating variability in monsoon withdrawal timing and post-monsoon cloud cover. Overall, the dataset reveals increasing inter-annual variability, particularly after 2018, possibly tied to climatic changes or larger-scale drivers like El Niño events, aerosol interactions, or land-use changes. The sharp contrast in OLR between pre-monsoon and monsoon months also emphasizes the seasonally driven energy balance shifts in the region. This analysis could be further enriched by linking it with precipitation, temperature, or vegetation indices to understand the broader climate dynamics.

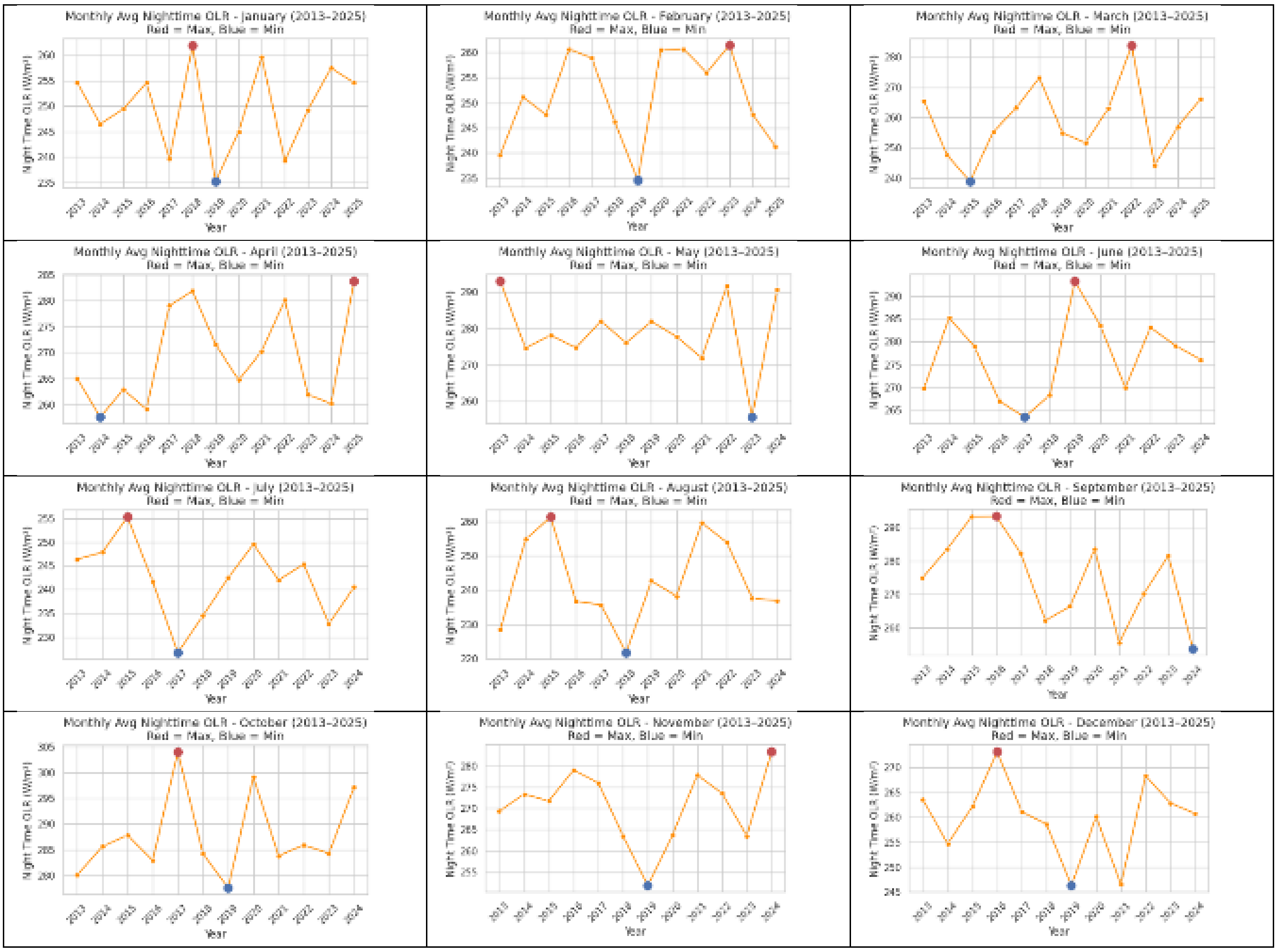

Figure 2 Month wise Night Time Outgoing Longwave Radiations During 2013-2025 from Muzaffarnagar Region

It highlights maximum values (in red) and minimum values (in blue) for each month across the years. Night-time OLR is influenced primarily by surface cooling and atmospheric conditions such as cloud cover, humidity, and greenhouse gas concentrations. High night-time OLR suggests clearer skies and warmer ground temperatures at night, whereas lower values are typically associated with cloudier or cooler nights. During the pre-monsoon months (April-June), the highest OLR readings are observed, particularly in April and May. For instance, April 2016 and May 2013 record the highest night-time OLR values in their respective months, indicating extremely clear skies and strong night-time radiation losses possibly due to dry conditions and heatwave events. Conversely, April 2020 and May 2020 show minimum values, reflecting increased night-time cloudiness or humidity, likely related to climatic anomalies during that period, such as post-lockdown atmospheric changes in 2020.

In the monsoon period (July–September), there is a notable decline in night-time OLR. August 2018 and September 2024 exhibit the lowest OLR values of the dataset, implying strong cloud cover and moisture retention during night-time. July 2020, on the other hand, shows a high OLR peak possibly indicating a dry spell or break in the monsoon. The significant inter-annual variability in these months reflects the influence of monsoon dynamics, cloud fluctuations, and atmospheric moisture. The winter months (December–February) show more moderate values, with occasional spikes and dips. December 2019 and February 2020 stand out for their higher OLR values, indicating warmer or clearer winter nights. On the other hand, February 2021 and December 2017 mark minimums, likely due to colder conditions or nocturnal cloud presence. January 2021, with its minimum value, could correspond to a cold wave event or enhanced radiation cooling due to clearer skies.

Overall, the plot underscores the strong seasonal and inter-annual variability in night-time OLR, driven by shifts in atmospheric clarity, moisture, and surface temperatures. Peaks in pre-monsoon months and troughs during monsoon highlight the seasonal energy cycle, while anomalies in specific years such as 2020 and 2021 may point to broader climatic disturbances. Comparing this plot with daytime OLR patterns could help isolate surface vs. atmospheric contributions to the region's radiation budget and refine our understanding of local climate dynamics.

5. Karl Pearson Correlation Analysis

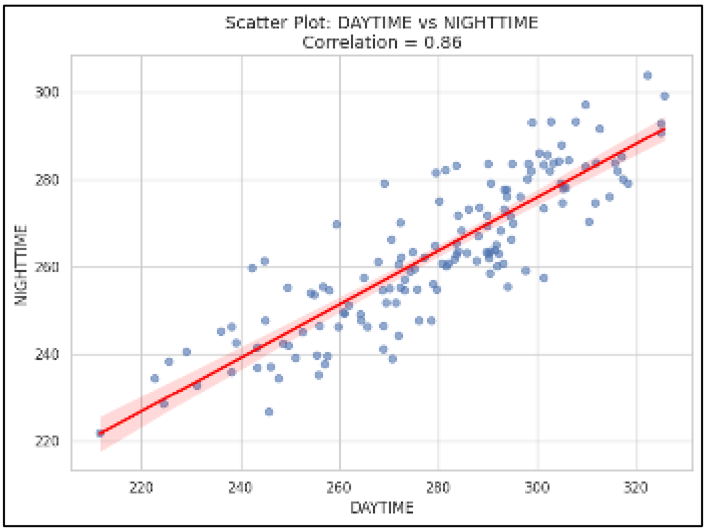

Figure 3 Karl Pearson Correlation Between Day Time and Night Time OLR

By using Karl Pearson formula, Liu et al. (2023)

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \cdot \sum(y_i - \bar{y})^2}}$$

Where,

r = Pearson correlation coefficient (ranges from **–1 to +1**), x_i= individual value of 1st variable, y_i= individual value of 2nd variable, $\bar{x}$= mean value of 1st variable, $\bar{y}$= mean value of 2nd variable, $\sum$= summation across all data points.

The scatter plot illustrates the relationship between daytime and night-time outgoing longwave radiation (OLR) values across multiple observations, likely representing monthly or seasonal averages. A strong positive linear correlation is visually evident and is statistically supported by the Pearson correlation coefficient of 0.86, which suggests a high degree of association between the two variables. The regression line, shaded in red, closely follows the data points with a narrow confidence band, further confirming this consistency. This high correlation implies that periods with elevated daytime OLR (typically associated with higher surface temperatures and clear skies) tend to coincide with higher night-time OLR. This is logical in a climatic context: when the Earth's surface absorbs more solar radiation during the day, it retains heat and continues to emit longwave radiation during the night. Thus, clear-sky and warm-surface conditions during the day often extend their influence into night-time, especially in semi-arid or tropical regions with limited diurnal cloud development.

However, the plot also displays some scatter and variability around the regression line, indicating that while the relationship is strong, it is not perfectly linear. This deviation may be attributed to factors such as cloud cover, atmospheric water vapor, or aerosol concentration, which can differentially affect daytime and night-time OLR. For example, high humidity or cloud formation in the evening can trap heat, elevating night-time OLR without necessarily having a proportionate daytime counterpart. Similarly, daytime OLR can be influenced by solar input and surface albedo, while night-time values are more dependent on atmospheric emissivity and radiative cooling.

From a climatological perspective, this relationship between daytime and night-time OLR can serve as an indicator of energy balance stability, urban heat retention, or even the extent of cloud-free conditions. A region consistently showing high correlation between day and night OLR may be experiencing enhanced radiative feedback loops possibly from ongoing warming, deforestation, or reduction in cloud and vegetation cover. Monitoring this correlation over time could help track regional climate shifts or the effectiveness of land-surface management interventions.

The correlation plot reinforces the physical linkage between daytime surface heating and night-time radiative cooling. The strong statistical relationship suggests that both components of the diurnal radiation cycle are interconnected and influenced by similar atmospheric and surface processes. This insight can be critical for climate modelling, regional heatwave prediction, and energy balance studies, especially in agriculturally sensitive zones like Muzaffarnagar or similar areas under climatic stress.

5.1. Month wise Correlation Interpretation

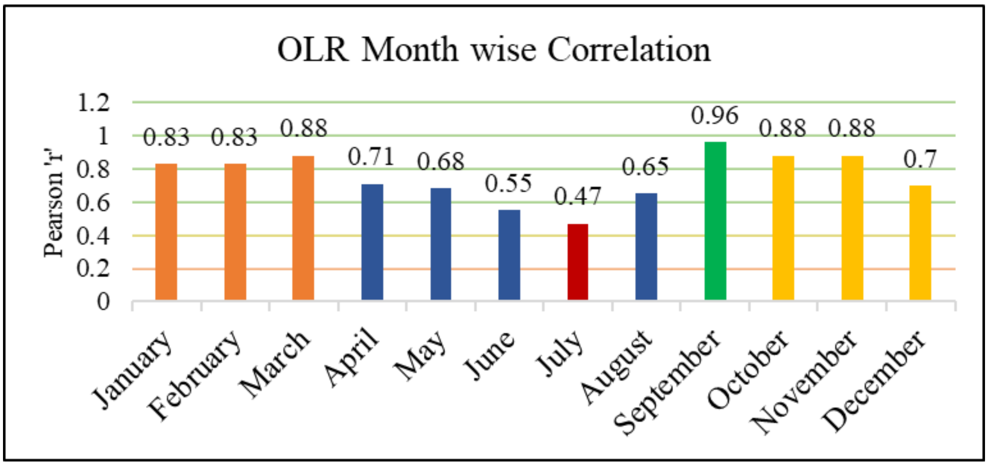

Figure 4 Month wise from (2013-2025) Karl Pearson Correlation for Day and Night Time OLR for Muzaffarnagar Region

The table shows the month-by-month Pearson correlation coefficients between the outgoing longwave radiation (OLR) readings at night and during the day. These correlations offer insight into how strongly daytime OLR patterns are mirrored by night-time emissions, effectively reflecting the diurnal consistency of radiative processes and atmospheric stability across seasons. The values range from 0.47 in July to 0.96 in September, indicating varying degrees of linkage throughout the year. During the winter (January - March) and post-monsoon (October - November) months, correlations are consistently high (0.83-0.88), suggesting a strong radiative coherence between day and night. This likely reflects clear-sky conditions and relatively stable atmospheric profiles, where the surface absorbs heat during the day and releases it efficiently at night. In these months, less atmospheric moisture or cloud cover may disrupt this balance, hence the strong correlations.

In contrast, the summer and monsoon months (May August) show a notable drop in correlation, particularly in July (0.47) and June (0.55). These months are characterized by heavy cloud cover, convective activity, and high atmospheric moisture, which can decouple daytime heating from night-time cooling. Cloud cover during the night can trap heat, increasing night-time OLR independently of daytime trends, leading to reduced correlation.

Interestingly, September (0.96) shows the highest correlation, which may indicate a transition phase during the retreat of the monsoon, where the atmosphere begins to stabilize and clearer conditions emerge. This spike suggests the reestablishment of radiative symmetry. Similarly, April (0.71) and December (0.70) reflect transitional behaviours with moderate correlation, likely due to partial cloud interference or variability in heat retention. Overall, this analysis indicates that radiative symmetry is seasonally dependent, with stronger day-night coupling in dry and clear months and weakened coupling during the humid and cloudy monsoon season. These insights are valuable for refining climate models, understanding regional energy dynamics, and predicting extreme weather patterns tied to radiative flux anomalies.

6. Conclusion

The analysis of outgoing longwave radiation (OLR) patterns both daytime and night-time-from 2013 to 2025 reveals strong seasonal and inter-annual variability linked to surface temperature, cloud cover, and monsoonal activity.

Daytime OLR tends to peak in the pre-monsoon months (April-May), reflecting intense solar heating and dry conditions, whereas night-time OLR dips during peak monsoon months (July-August) due to dense cloud cover and atmospheric moisture. These variations align with known climatological processes and indicate both natural seasonal rhythms and potential emerging anomalies due to climate variability.

The observed strong positive correlation (r = 0.86) between daytime and night-time OLR underscores a stable radiative coupling between day and night energy exchanges. Warmer days with high OLR are often followed by warmer nights, which points to less atmospheric insulation (e.g., fewer clouds or lower humidity) and higher surface heat retention. While this relationship is generally consistent, small deviations suggest the role of transient weather events, changes in atmospheric composition, or land-use dynamics. Together, the findings highlight the importance of continuous monitoring of surface energy fluxes as indicators of regional climate shifts and surface-atmosphere interactions.

Suggestions

- Enhance Ground-Level Monitoring: Establish automated weather stations (AWS) to monitor surface radiation, temperature, humidity, and cloud cover. This would help validate satellite-based OLR estimates and improve climate models.
- Integrate OLR with Agricultural Planning: Use OLR trends, especially pre-monsoon values, as indicators of soil moisture stress and evapotranspiration. This can assist farmers in scheduling irrigation and managing crop heat stress.
- Develop Early Warning Systems for Heatwaves: High daytime and night-time OLR values may serve as early signals for upcoming heatwave events. These metrics can be incorporated into regional climate risk dashboards.
- Investigate Land Use and Surface Change Impacts: Conduct localized studies to assess whether changes in vegetation cover, urban expansion, or irrigation practices are altering the surface energy balance reflected in OLR variations.
- Climate Adaptation Policy Integration: Policymakers should consider OLR trends in climate vulnerability assessments, particularly in regions like Muzaffarnagar where agriculture and water resources are climate-sensitive.

Compliance with ethical standards

All ethical guidelines were followed when conducting this study. There were no human or animal participants, and all information used came from approved and publicly accessible sources.

Acknowledgments

The authors gratefully acknowledge the support of relevant government data sources and agricultural databases that made this analysis possible. Special thanks to academic mentors and peers for their valuable feedback throughout the research process. The insights gained from this study are a result of collaborative learning and ongoing discussions on regional agricultural development.

Disclosure of conflict of interest

Authors declare no conflict of interest.

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