Remote Sensing - Based Estimation of Evapotranspiration Using the Triangle Method: Insights from Tropical Forests of Northeast India

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(Received on 08 April 2026; In final form on 17 July 2026)

DOI: *https://doi.org/10.58825/jog.2026.20.2.323*

Abstract: Understanding the interactions between LST, vegetation dynamics, and ET is critical in the context of climate change and its impacts on terrestrial ecosystems and the hydrological cycle. This study investigates the seasonal variability of ET and its relationship with LST and NDVI over forested regions of Lakhimpur, Dhemaji, and Dibrugarh districts in Assam. The analysis is specifically restricted to forest areas using a Dynamic World land use/land cover mask to ensure ecological consistency and minimize land cover heterogeneity. Evapotranspiration was estimated using the NDVI–LST triangle method, which derives evaporative fraction (EF) from the LST–NDVI feature space through the identification of dry and wet edges. Landsat 8 data were used to generate high-resolution NDVI and LST, while net radiation (Rn) was obtained from ERA5-Land and resampled to match Landsat spatial resolution. The results were further compared with widely used datasets, including MOD16A2, GLDAS, and FLDAS, to assess consistency and variability. The findings reveal clear seasonal patterns, with ET peaking during the monsoon (up to ~3.17 mm/day) and decreasing during pre- and post-monsoon periods. Forested areas exhibit relatively stable NDVI and lower LST, contributing to consistent and spatially coherent ET patterns. MOD16A2 significantly overestimates ET, while GLDAS and FLDAS provide more stable and physically realistic estimates. The approach demonstrates strong potential for monitoring seasonal ET dynamics in data-scarce regions. Future work should focus on integrating in-situ observations, improving methodological frameworks, and adopting multi-source data fusion techniques to enhance the accuracy and reliability of ET estimation for climate and water resource applications.

Keywords: NDVI, LST, Evapotranspiration, Water stress

1. Introduction

As our planet undergoes unprecedented changes due to climate change, driven by natural variability and human activities, it becomes increasingly crucial to comprehend the intricate relationship between various environmental factors. As the Earth's climate shifts, it affects numerous aspects of our environment, including land surfaces and the delicate balance of ecosystems, these changes have far-reaching effects on various aspects of our planet, including its surface and vegetation (Stern & Kaufmann, 2014). In this study, we embark on an exploration of the interconnection between Land surface temperature (LST), vegetation dynamics, and evapotranspiration. LST is a vital parameter reflecting the thermal characteristics of the Earth's surface, which is influenced by a combination of natural factors and human-induced modifications to the Earth's surface (Fu & Weng, 2016). By analysing LST variations, we can gain valuable insights into the impacts of climate change and anthropogenic activities on the Earth's surface dynamics. Meanwhile, the Earth's vegetation emerges as another crucial character, intricately connected to LST. The health and distribution of vegetation serve as a barometer of environmental change (Fu & Weng, 2016). Remote sensing techniques have emerged as the most promising means for estimating actual evapotranspiration (ETa) over extensive areas, owing to their capacity to provide synchronized and comprehensive observations of large land surfaces across different temporal scales(Zhang et al., 2016). The integration of Normalized Difference Vegetation Index (NDVI) and LST has advanced our understanding of their impact on evapotranspiration (ET). Studies have shown that the slope of LST/NDVI relates to ET rates and can be used to estimate air temperature. It is also associated with leaf stomatal resistance and ET in different surface types (Han et al., 2006; Prihodko & Goward, 1997). A parameterization for regional ET can be achieved by utilizing satellite-derived surface parameters, specifically employing the surface temperature-vegetation index (Ts-VI) triangle method developed by Jiang & Islam, 1999, further refined in subsequent studies(Jiang & Islam, 2003). Proper selection of the dry and wet edges within the Ts-VI triangle space is crucial for the method's success. Previous studies have identified the wet edge using various approaches such as the lowest observed clear pixel surface temperature, air temperature, or average temperature of inland water bodies. This comprehensive case study holds paramount importance as it addresses critical aspects of Earth's surface dynamics, specifically focusing on LST and NDVI, as well as estimating ET using the Triangle Method. By investigating the temporal patterns and correlations between LST and NDVI, the study contributes to our understanding of land-climate interactions and ecosystem dynamics over time. Identifying significant long-term trends in LST and NDVI offers valuable insights into potential climate change impacts and land-use changes, essential for informed decision-making in areas

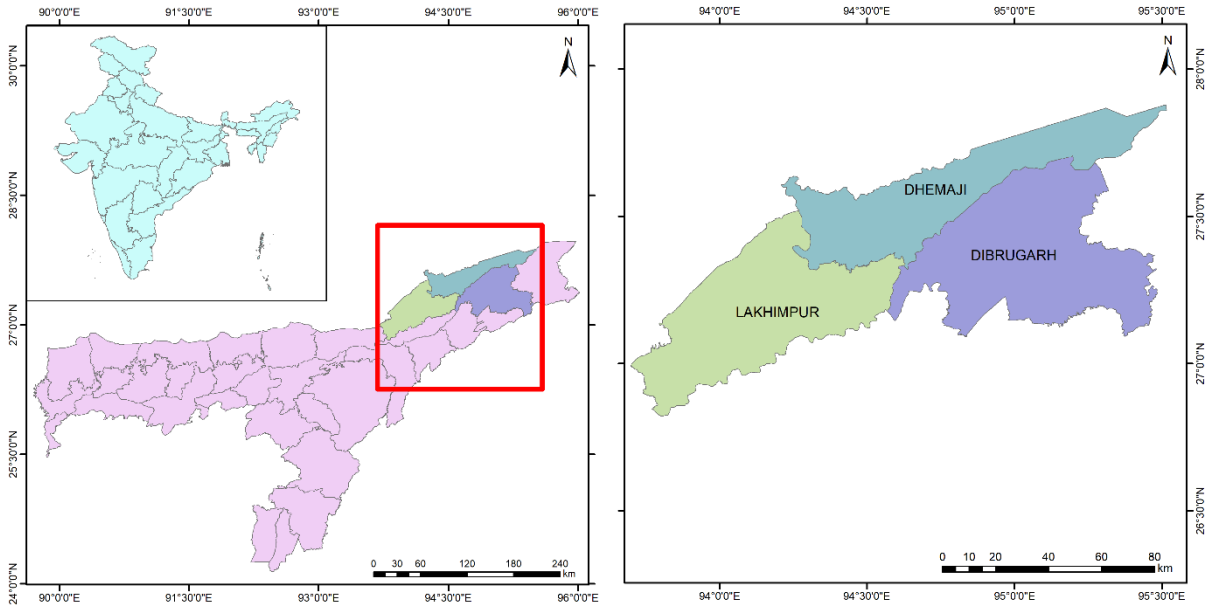


Figure 1: Location Map

such as agriculture, urban planning, and environmental conservation. ET is the second largest component of the terrestrial water cycle, accounting for approximately 60% of annual terrestrial precipitation that returns to the atmosphere (Ersi et al., 2022). As a critical process in the global climate system, ET impacts the exchange of water, carbon, and energy, as well as the regional distribution of energy, water, surface temperature, and atmospheric humidity. Consequently, ET is closely linked to climate change dynamics(Cui et al., 2020; Ersi et al., 2022; Saha et al., 2022). Moreover, the utilization of the Triangle Method for ET estimation enhances our ability to monitor water availability, assess drought risks, and manage water resources sustainably. As such, this study provides vital scientific knowledge and analytical tools to tackle complex challenges related to land-surface processes, climate variability, and water management.

While numerous research studies (Zhang et al., 2016; Olivera-Guerra et al., 2017; Han et al., 2006; Prihodko & Goward, 1997) worldwide have employed various algorithms, there remains a notable gap in research focusing on the diverse environmental factors influencing ET in the region. The primary objective of this study is to investigate the seasonal dynamics of evapotranspiration (ET) and its relationship with land surface temperature (LST) and vegetation dynamics (NDVI) over forested regions of Northeast India (Lakhimpur, Dhemaji & Dibrugarh, Assam) using remote sensing techniques.. It further focuses on estimating actual ET using the NDVI–LST triangle method and evaluating its capability to capture spatial and temporal patterns in tropical forest ecosystems. This study makes a significant scientific contribution by advancing the application of the NDVI–LST triangle method in complex tropical forest ecosystems, where high humidity, dense canopy cover, and persistent cloud conditions pose challenges for conventional evapotranspiration estimation techniques. The focus on Northeast India is particularly justified due to its ecological sensitivity, rich biodiversity, and critical role in regional and global carbon and water cycles, yet it remains underrepresented in remote sensing–based ET studies.. A key objective is to compare the triangle method–derived ET with established datasets such as MOD16A2, GLDAS, and FLDAS in order to assess consistency, variability, and potential biases.

2. Study Area

The study is conducted in the upper Brahmaputra floodplain region of Northeast India, specifically focusing on three contiguous districts—Lakhimpur, Dhemaji, and Dibrugarh—located in the state of Assam (Figure 1). Geographically, the region lies along the northern bank of the Brahmaputra River and is bounded by the foothills of Arunachal Pradesh to the north.

Climatically, the region is characterized by a humid subtropical regime with strong monsoonal influence, receiving high annual precipitation primarily during the southwest monsoon (June–September). The area frequently experiences extreme hydrological events, including seasonal flooding, channel migration, and sediment deposition, which significantly shape land surface processes and ecosystem dynamics.

For the purpose of this study, the analysis is explicitly restricted to forested landscapes to ensure ecological consistency in evapotranspiration (ET) estimation. Forest cover was delineated using the Dynamic World Land Use/Land Cover (LULC) dataset derived from Sentinel-2 imagery. Pixels classified under the “tree cover” category were extracted to generate a forest mask, thereby excluding other land-use classes such as croplands, built-up areas, water bodies, and barren surfaces. This approach enables the isolation of ET dynamics associated specifically with forest ecosystems, minimizing the influence of heterogeneous land surface conditions.

The selection of this region is scientifically justified by its ecological significance and relative underrepresentation in remote sensing–based ET studies. The upper Brahmaputra floodplain forms part of a biodiversity-rich and

environmentally sensitive zone that plays a critical role in regional carbon cycling, hydrological regulation, and climate feedback mechanisms. However, the region is increasingly subjected to anthropogenic pressures, including deforestation, agricultural expansion, and floodplain modifications, which can alter vegetation structure and surface energy balance. Furthermore, the complex interplay of monsoonal climate, flood-driven geomorphic processes, and heterogeneous vegetation cover provides a robust framework for evaluating the applicability of the NDVI–LST triangle method under challenging environmental conditions. By focusing exclusively on forest pixels within well-defined administrative boundaries, this study ensures that the derived ET estimates are representative of intrinsic ecosystem processes, thereby enhancing the reliability and regional relevance of the results.

3. Dataset and methodology

3.1 Data Sources and Preprocessing

To capture the seasonal variability in land surface processes, the study period was divided into three distinct seasons based on the regional monsoonal climate of Northeast India: pre-monsoon (March–May 2024), monsoon (June–September 2024), and post-monsoon (October–November 2024). Evapotranspiration (ET) was estimated using satellite-derived Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) as primary inputs, along with net radiation (Rn) from ERA5-Land. Landsat 8 Surface Reflectance and thermal bands were preprocessed using radiometric scaling to obtain surface reflectance and LST in degrees Celsius. Cloudy pixels (>20% cloud cover) were filtered out, and all images were clipped to the study area. A forest mask derived from Dynamic World land-cover data was applied to ensure that ET estimation was limited to forested areas, avoiding contamination from cropland, settlements, or water bodies. To ensure consistency in spatial resolution, the ERA5 data were resampled to match the resolution of the Landsat imagery.

3.2 NDVI–LST Triangle Method and Edge Detection

The NDVI–LST scatterplot was used to define dry and wet edges, following the Triangle Method. NDVI values were binned (50 bins between 0–1), and for each bin, the 95th percentile of LST was selected as the dry edge (T_dry), representing water-stressed surfaces, and the 5th percentile as the wet edge (T_wet), representing surfaces with maximal evapotranspiration. Here, the 95th percentile refers to the LST value below which 95% of the observations within a given NDVI bin fall, effectively capturing the highest temperature extremes while minimizing the influence of outliers or noise. Similarly, the 5th percentile represents the LST value below which only 5% of the observations occur, capturing the coolest and most moisture-sufficient conditions within that NDVI range. Linear regressions were fitted to the dry and wet edges as a function of NDVI:

$$T_{\text{dry}}(NDVI) = a_d + b_d \cdot NDVI, T_{\text{wet}}(NDVI) = a_w + b_w \cdot NDVI$$

This step ensures that the edges are physically consistent and account for vegetation heterogeneity.

3.3 Evaporative Fraction (EF) Calculation

Using the dry and wet edge temperatures, Evaporative Fraction (EF) was calculated for each pixel inside the forest mask according to Liu et al., 2018:

$$EF = \frac{T_{\text{dry}} - T_{\text{obs}}}{T_{\text{dry}} - T_{\text{wet}}}$$

Here, T_{obs} is the observed LST at each pixel. EF represents the fraction of available energy used for evapotranspiration and is bounded between 0 and 1, where EF = 1 indicates a fully wet surface, and EF = 0 indicates water stress. This approach explicitly separates energy-limited and water-limited conditions and avoids the misapplication of TVDI or other indices.

3.4 Ground Heat Flux (G) and Net Radiation (Rn)

Ground heat flux (G) was estimated from NDVI and net radiation using the relationship:

$$G = R_n \cdot (0.05 + 0.18 \cdot e^{-5.21 \cdot NDVI})$$

This formula accounts for the decrease in soil heat flux under dense vegetation canopies, ensuring that energy partitioning between soil and atmosphere is physically realistic. Net radiation (Rn) was calculated as the sum of net solar and net thermal radiation from ERA5-Land data, averaged over each season (pre-monsoon, monsoon, post-monsoon) and clipped to the forest mask.

The actual evapotranspiration in energy units (MJ/m²/day) was computed using:

$$ET_{\text{energy}} = EF \cdot (R_n - G)$$

To convert to water flux (mm/day), the latent heat of vaporization ($\lambda = 2.45$ MJ/kg) was applied:

$$ET_{\text{mm/day}} = \frac{ET_{\text{energy}}}{\lambda}$$

This ensures that ET estimates are in realistic, physically meaningful units, with typical forest ET values ranging between 1–6 mm/day depending on season and water availability.

4. Result and Discussion

4.1 Fluctuation of NDVI and LST

Analysis of NDVI and LST within the forest mask reveals that forested areas maintain high vegetation greenness and relatively stable surface temperatures throughout the year (Figure 2). During the pre-monsoon season, NDVI ranges from approximately 0.35 to 0.84 (2nd–98th percentile) with a mean of 0.62, indicating that forests remain moderately green even under dry conditions, while lower NDVI values (<0.35) likely correspond to edge effects or small non-forest patches. NDVI increases during the monsoon (0.10–0.90, mean ≈ 0.71), reflecting peak canopy greenness driven by rainfall, and slightly decreases post-monsoon (0.51–0.89, mean ≈ 0.78), showing that the forest canopy continues to maintain healthy vegetation cover. Similarly, LST within forested areas is consistently cooler than surrounding non-forest land, with pre-monsoon temperatures ranging from ~26.5 to 38.9 °C (mean ≈ 32.9 °C). During the monsoon, LST generally decreases (~25–41 °C) due to increased cloud cover and rainfall,

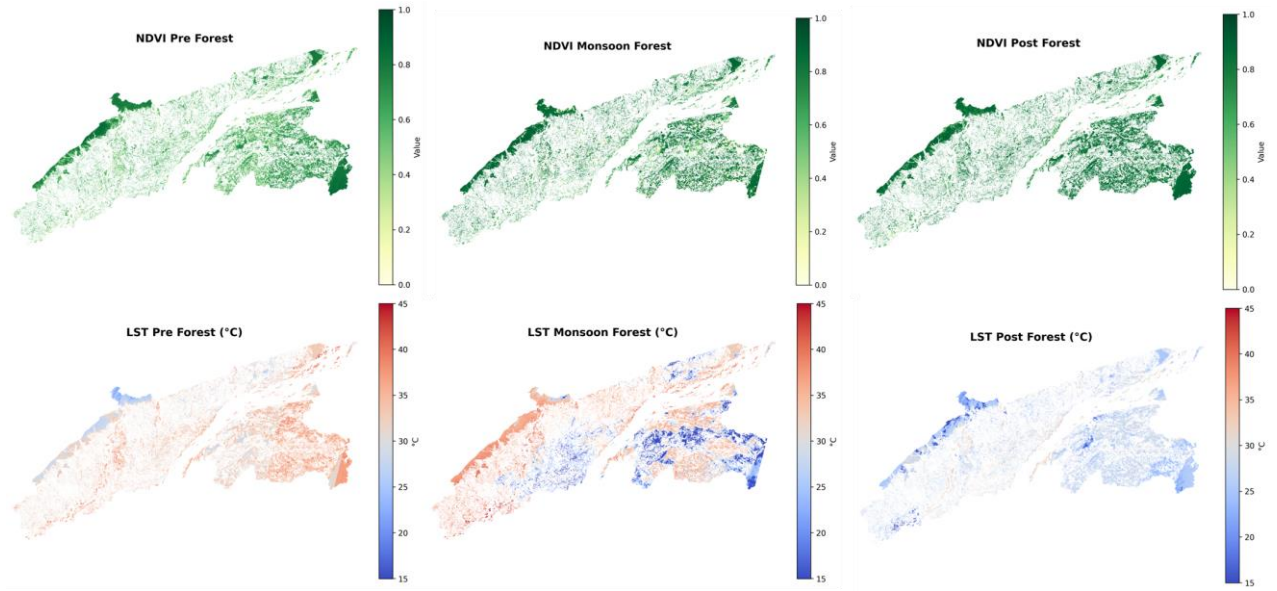


Figure 2: NDVI & LST of the study area during the Pre, During and Post Monsoon, 2024

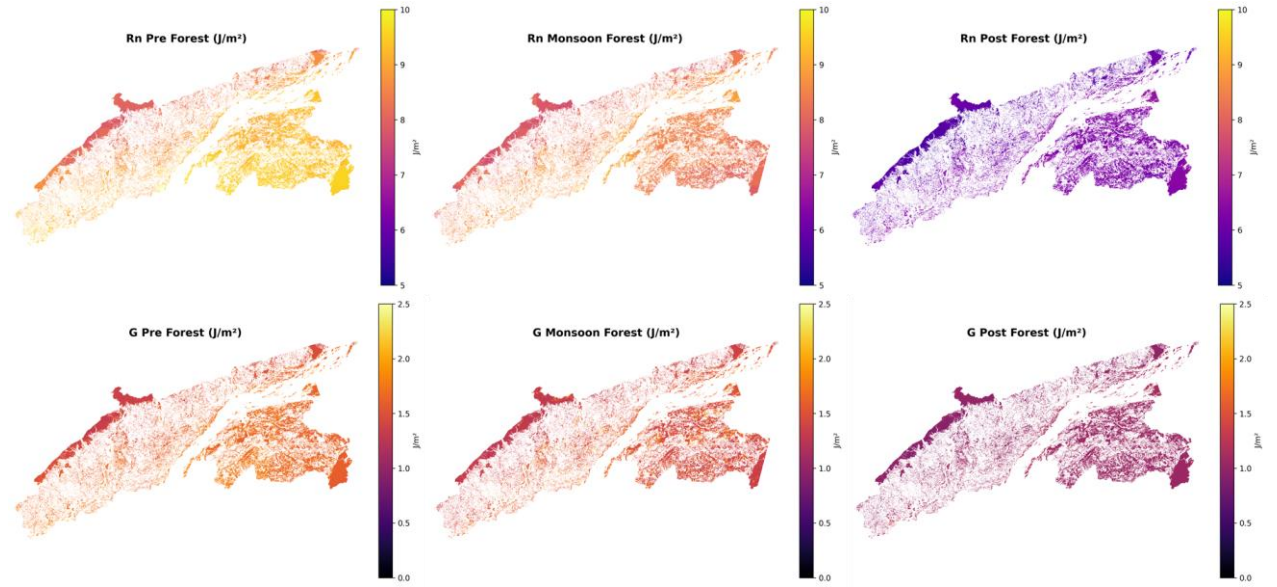


Figure 3: Net Radiation (Rn) and Soil heat flux (G) (Pre, During and Post Monsoon)

while post-monsoon temperatures rise slightly (~16.6–31.8 °C), yet forests remain cooler than exposed lands. The standard deviation of LST in forests (~3–4 °C) is substantially lower than that of the full landscape, highlighting reduced thermal variability within canopy-covered areas. Restricting the analysis to forest pixels eliminates extreme negative or unrealistic NDVI and LST values, ensuring that only physically meaningful vegetation and canopy temperatures are considered. These results validate the use of the forest mask for subsequent calculations of evapotranspiration and evaporative fraction, and clearly demonstrate that seasonal patterns—NDVI peaking and LST dropping during the monsoon—are strongly modulated by forest canopy cover.

4.2 Estimation and Fluctuation of Rn & ET

Seasonal analysis of net radiation (Rn) within the forest mask shows relatively stable energy availability throughout the year. During the pre-monsoon season, Rn ranges from approximately 7.87 to 9.85 MJ/m²/day (2nd–98th percentile: 7.88–9.58 MJ/m²/day) with a mean of 8.98 MJ/m²/day, indicating high incoming radiation despite dry conditions (Figure 3). In the monsoon, Rn decreases slightly to a range of 7.72–9.21 MJ/m²/day (mean ≈ 8.38 MJ/m²/day) due to increased cloud cover and precipitation, while post-monsoon values are lower (5.63–6.64 MJ/m²/day, mean ≈ 6.17 MJ/m²/day) as the seasonal solar input declines. The standard deviation of Rn within forested pixels remains low across all seasons (0.23–0.50 MJ/m²/day), and the coefficient of variation is less than 6%, highlighting minimal spatial variability in net radiation under dense canopy cover. These findings confirm that forests experience relatively homogeneous radiation conditions, which is important for accurately estimating evapotranspiration and energy fluxes within the canopy.

Seasonal estimates of evaporative fraction (EF) and evapotranspiration (ET) within the forest mask reveal clear patterns consistent with canopy structure and climatic conditions (Figure 4). During the pre-monsoon season, EF

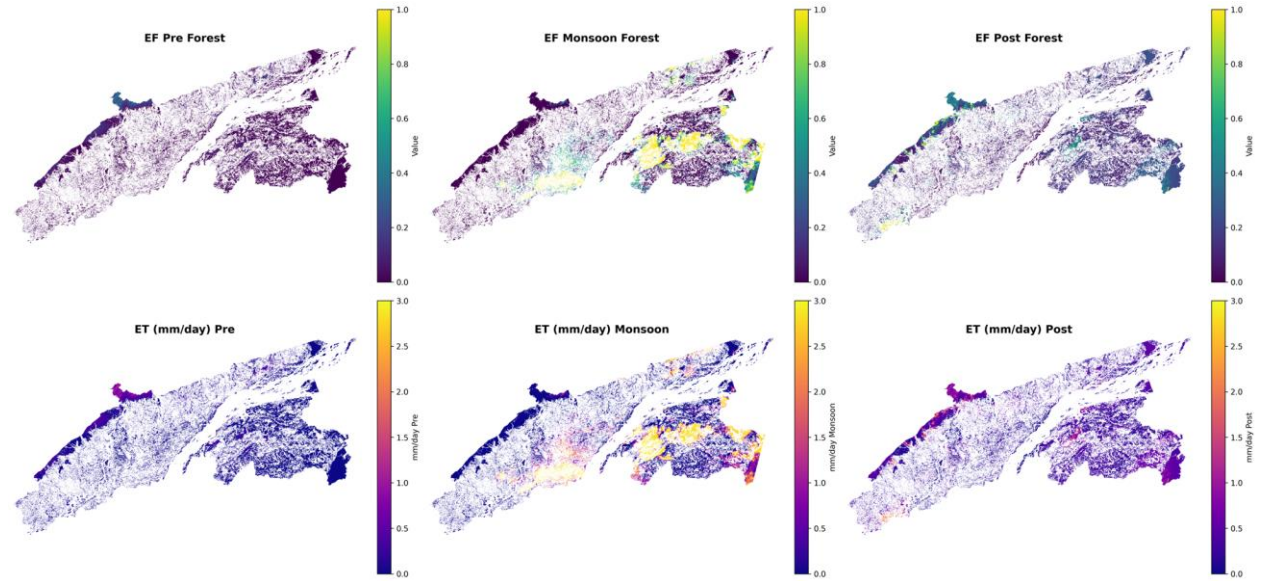


Figure 4: Evaporative factor (EF) and Evapotranspiration (ET) (Pre, During and Post Monsoon)

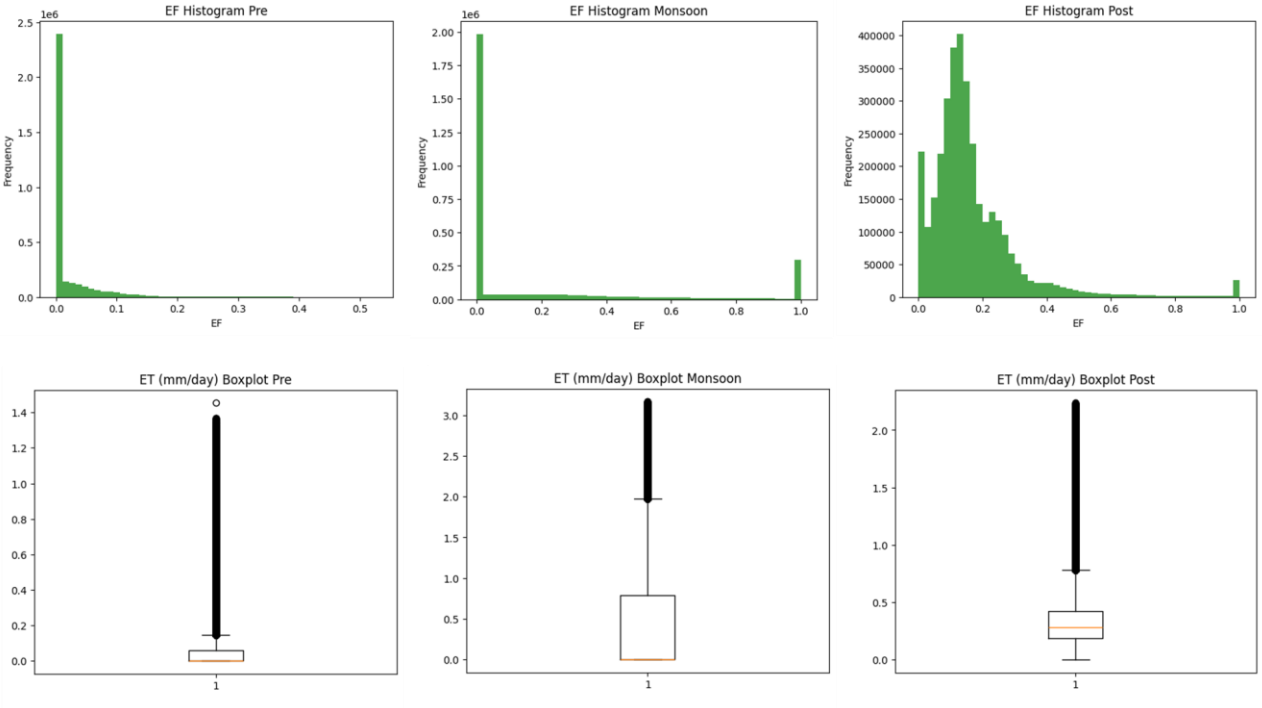


Figure 5: Histogram & Boxplot of ET (Pre, During and Post Monsoon)

ranges from 0.00 to 0.53, and ET varies from 0.00 to 3.56 MJ/m²/day (equivalent to 0.00–1.45 mm/day), reflecting moderate water stress and limited canopy transpiration under dry conditions.

In the monsoon season, EF increases substantially, reaching the maximum value of 1.00, while ET rises to 7.76 MJ/m²/day (≈3.17 mm/day), indicating peak transpiration supported by abundant rainfall and high soil moisture. Post-monsoon, EF remains high (up to 1.00), with ET decreasing moderately to 5.48 MJ/m²/day (≈2.24 mm/day), reflecting a gradual reduction in water fluxes as the wet season ends. Across all seasons, forested areas exhibit spatially coherent EF and ET patterns, with few extreme low or negative values, demonstrating that dense canopy cover stabilizes evaporative processes and mitigates large fluctuations observed in open or mixed land-cover areas (Figure 5). These results validate the forest mask approach for accurate quantification of seasonal water and energy fluxes in tropical forest ecosystems.

4.3 Comparison with Existing

The seasonal comparison of evapotranspiration (ET) derived from MOD16A2, GLDAS, and FLDAS with the triangle-based ET reveals substantial differences in magnitude, variability, and distribution across pre-monsoon, monsoon, and post-monsoon periods (Figure 6,7,8).

The MOD16A2 product consistently exhibits the highest ET values across all seasons, with mean ET ranging from approximately 2.15 mm/day (pre-monsoon) to 3.58 mm/day (monsoon), followed by a decline to 2.62 mm/day (post-monsoon). These values are accompanied by

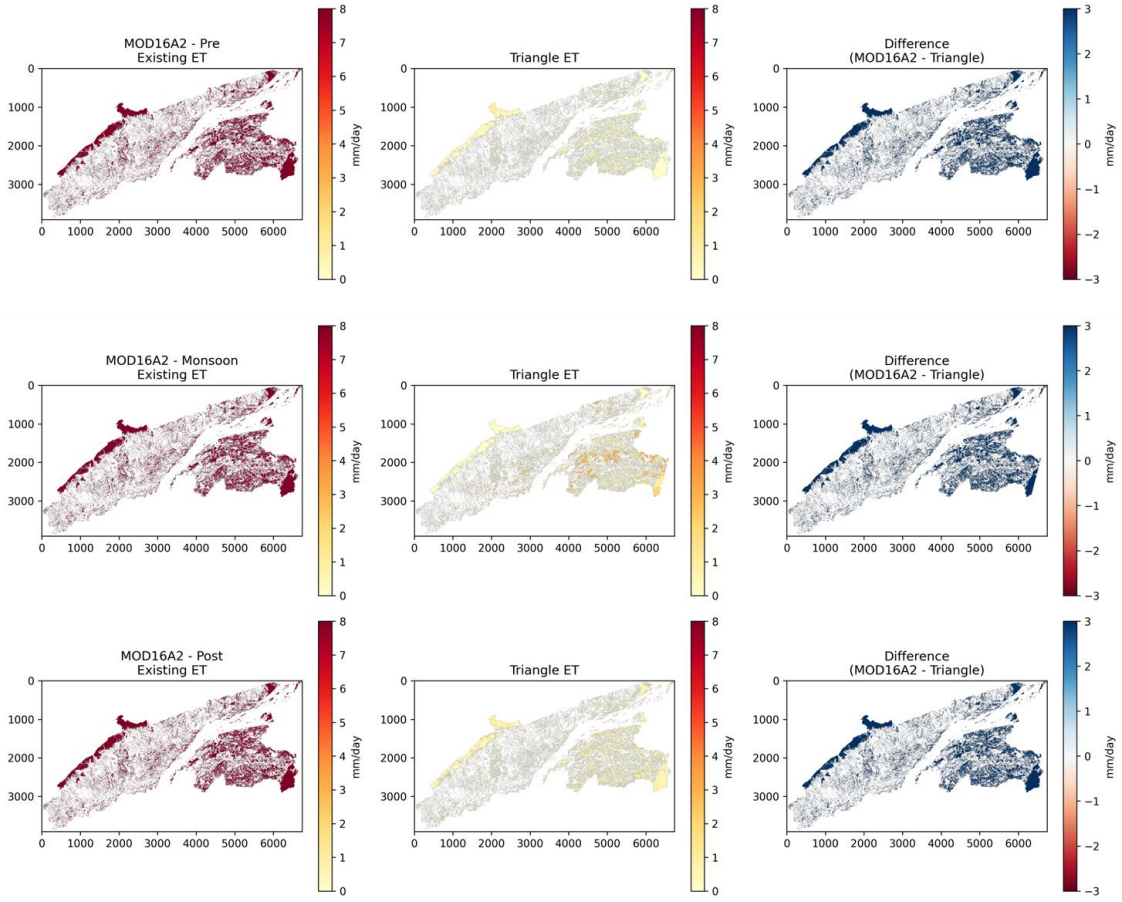


Figure 6: Difference Between MOD16A2 ET Product and Estimated ET (Pre, During and Post Monsoon)

relatively high variability (standard deviation: ~0.68–0.8 mm/day) and a wide range of maximum values exceeding 5.5–6.4 mm/day. The coefficient of variation (CV: 0.21–0.37) further suggests moderate dispersion, particularly higher during the pre-monsoon season.

In contrast, GLDAS-derived ET values are significantly lower and more stable, with mean values ranging from 1.95 to 2.89 mm/day across seasons. The variability is minimal (standard deviation ~0.22–0.29 mm/day; CV ~0.09–0.11), indicating a smoother and more conservative representation of surface fluxes. Similarly, FLDAS shows slightly higher ET estimates than GLDAS, with seasonal means between 2.86 and 4.57 mm/day, and moderate variability (CV ~0.08–0.16), reflecting its enhanced sensitivity to land surface and meteorological forcing compared to GLDAS.

The triangle method, on the other hand, produces substantially lower ET estimates across all datasets and seasons, with mean values ranging from 0.06 mm/day (pre-monsoon) to 0.56 mm/day (monsoon). While the seasonal trend (lowest in pre-monsoon, highest during monsoon) is consistent with other datasets, the magnitude is significantly underestimated. The maximum ET values from the triangle approach remain below ~3.17 mm/day, suggesting a constrained estimation likely due to limitations in capturing the full energy balance or edge detection in the LST–NDVI space.

Error analysis further highlights these discrepancies. The mean bias between MOD16A2 and the triangle method is extremely high (ranging from ~21.5 to 35.3 mm/day), with correspondingly large RMSE and MAE values, confirming a substantial overestimation by MOD16A2 relative to the triangle-based estimates. In comparison, GLDAS and FLDAS show much lower biases (typically ~1.6 to 4.0 mm/day), indicating closer agreement with the triangle method, although still consistently higher. The mean absolute error follows a similar pattern, reinforcing that physically based land surface models (GLDAS/FLDAS) are more aligned with the triangle-derived ET than satellite-based MODIS estimates.

While all datasets capture the expected seasonal dynamics with peak ET during the monsoon, the large differences in magnitude suggest that the triangle method may underestimate ET, whereas MOD16A2 may overestimate it under certain conditions. GLDAS and FLDAS provide comparatively realistic intermediate estimates with lower variability, making them more consistent with physically plausible ET ranges.

5. Conclusion

This study explores the seasonal dynamics of ET and its relationship with land surface LST) and NDVI in a tropical forest-dominated landscape under changing climatic conditions. The study evaluates ET using the NDVI–LST triangle method and compares it with widely used datasets such as MOD16A2, GLDAS, and FLDAS, highlighting differences arising from varying model assumptions and data sources. The methodology is based on the NDVI–LST triangle approach, where dry and wet edges are derived from the NDVI–LST feature space to compute.

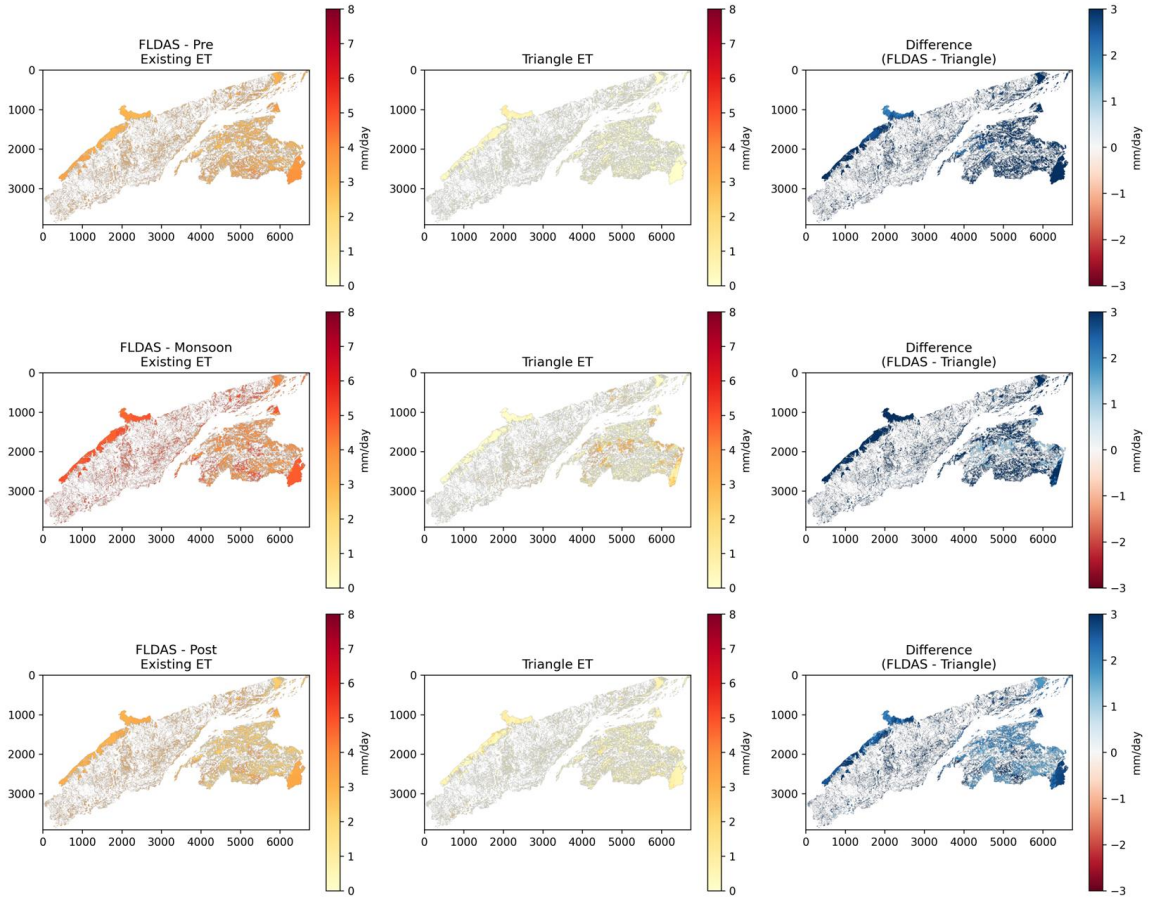


Figure 7: Difference Between FLDAS ET Product and Estimated ET (Pre, During and Post Monsoon)

evaporative fraction (EF). The results indicate strong seasonal variability in ET, with maximum values during the monsoon and lower values during pre- and post-monsoon periods. Forested regions exhibit stable NDVI and relatively lower LST, resulting in consistent ET patterns. The triangle method successfully captures seasonal trends but underestimates ET magnitude, likely due to simplifications in the energy balance representation and dependence on edge detection in the NDVI–LST space. Despite these differences, all datasets consistently reflect the dominance of monsoon-driven moisture availability in controlling ET dynamics.

The study is subject to several limitations that must be carefully considered. A major limitation arises from the resampling of coarse-resolution ERA5-Land net radiation (Rn) to Landsat resolution. This mismatch can affect evapotranspiration (ET) estimation by introducing biases in energy balance components, particularly net radiation and surface fluxes. As a result, localized ET variations driven by land surface heterogeneity may not be accurately represented, leading to underestimation or overestimation of ET at finer scales. Additionally, the absence of ground-based validation data (e.g., eddy covariance flux towers or lysimeter measurements) restricts the ability to assess the absolute accuracy of ET estimates. The triangle method itself has inherent limitations, including sensitivity to dry and wet edge selection, NDVI binning, and outliers in LST, and it does not explicitly account for key atmospheric variables such as wind speed, vapor pressure deficit, and aerodynamic resistance. Moreover, simplifying assumptions in estimating ground heat flux (G) and the use of generalized empirical relationships may not fully capture local heterogeneity in soil and canopy conditions.

Future work should focus on improving the robustness and accuracy of ET estimation by integrating ground-based validation data to quantify uncertainties and calibrate model outputs. The use of higher-resolution meteorological datasets or downscaling techniques could reduce errors associated with resampling coarse data such as ERA5-Land. Enhancing the triangle method by incorporating additional atmospheric constraints or hybrid approaches combining physical models and machine learning could improve ET estimation accuracy. Furthermore, multi-sensor data fusion approaches that better harmonize spatial and temporal scales would help overcome current limitations. Such improvements are essential for advancing our understanding of land–atmosphere interactions and for developing reliable tools for climate change assessment and sustainable water resource management.

Declaration

During the revisions of this work the author(s) used services of Paperpal by Editage in order to correct the language and grammar. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

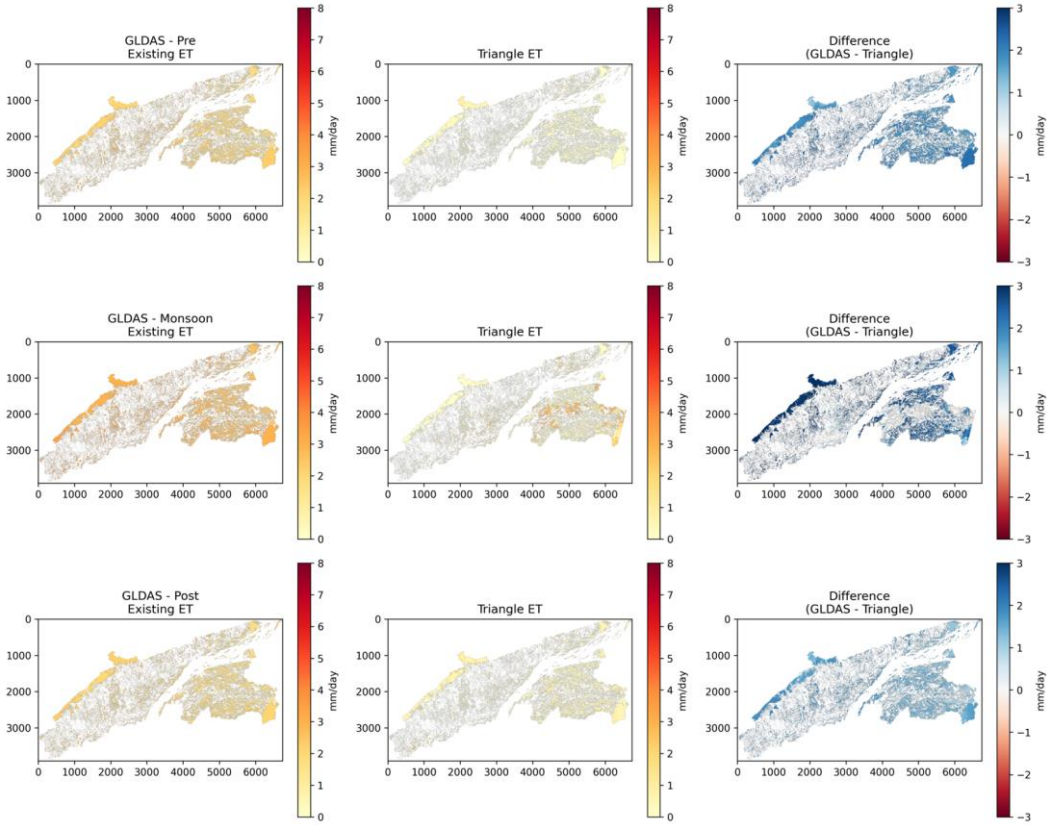


Figure 8: Difference Between GLDAS ET Product and Estimated ET (Pre, During and Post Monsoon)

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