

# Variability and Trends in Evaporation and Water Balance over Tanzania

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## Abstract

Evaporation is a critical component of the hydrological cycle, shaping water resource availability in climate-sensitive regions such as Tanzania. This study examines the spatiotemporal variability and long-term trends of evaporation and the precipitation-evaporation balance (P-E) from 1995 to 2025 using high-resolution ERA5-Land reanalysis data. Monthly spatial patterns, seasonal correlations with temperature and precipitation, and decadal trends were analyzed to assess changes in water availability and evaporative demand. Results highlight strong seasonal and spatial heterogeneity, with evaporation peaks during the wet season (November-May) under energy-limited conditions, while it weakens in the dry season (June-October) under moisture-limited constraints. The P-E balance indicates seasonal surpluses in the rainy periods (March-May and November-December) and deficits in dry months, most pronounced in the semi-arid central plateau. Correlation analysis shows that evaporation is positively linked to temperature across most months, while its relationship with precipitation shifts: negative during dry periods and positive in wet months, reflecting energy-moisture interactions. Trend analysis reveals a significant decline in evaporation across most months, particularly June-October, with the strongest negative trend in November/(approximately  $-6.2$  mm). March, however, shows a consistent increase. These declining evaporative rates, combined with shifting precipitation patterns, suggest a tightening regional water balance with implications for agriculture, surface water availability, and drought resilience. By linking national-scale evaporation dynamics to both local soil-moisture processes and large-scale climate drivers, this study bridges basin-level findings with broader hydrological trends, offering a comprehensive framework for climate-sensitive water resource management in East Africa.

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## Keywords

Climatic Water Balance (P-E), Land-Atmosphere Interactions, Evaporation Trends, Hydroclimatic Variability, ERA5-Land Reanalysis, Tanzania

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## 1. Introduction

The global water cycle is a fundamental component of the Earth system, governing the continuous movement of water among the atmosphere, land surface, oceans, cryosphere, and biosphere. Through interconnected processes such as evaporation, condensation, precipitation, infiltration, and runoff, the water cycle regulates climate, sustains ecosystems, and supports human livelihoods (Yang et al., 2021). The balance between incoming precipitation and outgoing evaporation largely determines freshwater availability at regional and local scales, shaping hydrological regimes and influencing droughts, floods, and water security (Aldous et al., 2011; Shen & Chen, 2010).

At regional scales, the hydrological cycle is tightly coupled with land-atmosphere interactions. Solar radiation provides the primary energy source that drives evaporation from water bodies, soils, and vegetation, while atmospheric circulation redistributes moisture and energy across the globe (Huryna & Pokorný, 2016; Spiridonov et al., 2025). Evaporation acts as a key link between the surface and atmosphere by converting liquid water into water vapor, which subsequently influences cloud formation, precipitation, and atmospheric stability.

The partitioning of net radiation at the land surface into latent heat (evaporation) and sensible heat fluxes is strongly controlled by soil moisture availability, vegetation cover, and surface temperature (Bateni et al., 2013). In humid regions, evaporation is primarily energy-limited, whereas in semi-arid and arid regions it becomes water-limited, constrained by soil moisture deficits rather than available energy (Zhang et al., 2023). This distinction is critical for understanding how changes in precipitation and temperature translate into variations in evaporation and overall water balance.

Land-atmosphere feedback further complicates hydrological responses. For example, reduced soil moisture limits evaporation, increases sensible heat flux, and amplifies surface warming, which in turn enhances atmospheric demand for moisture (Zhou et al., 2021). Such feedback mechanisms can reinforce drought conditions and lead to persistent drying trends, particularly in vulnerable tropical and subtropical regions.

Evaporation, precipitation, and temperature constitute the primary climatic controls of terrestrial water balance (Williams et al., 2012). Precipitation represents the main input of water to land surfaces, while evaporation and transpiration collectively account for the dominant pathways of water loss to the atmosphere. Temperature modulates both processes by influencing atmospheric moisture demand, saturation vapor pressure, and surface energy availability (Allen et al., 1998; Gu et

al., 2006). Globally, evaporation has increased in response to rising temperatures, although its relationship with precipitation varies regionally. In some areas, enhanced evaporation offsets precipitation gains, leading to little or no improvement in water availability (Sala et al., 2015). In others, declining precipitation combined with increasing evaporation accelerates drying trends and intensifies hydrological droughts (Dai et al., 2018; Zaitchik et al., 2023). Consequently, assessments based solely on precipitation are increasingly recognized as insufficient for characterizing hydrological change, emphasizing the need to explicitly consider evaporation and climatic water balance (P-E).

Tropical and equatorial regions play a disproportionately large role in the global water cycle due to high solar radiation, warm temperatures, and intense convective rainfall (Sud et al., 2002). These regions exhibit some of the highest evaporation rates globally, driven by abundant energy and, in many areas, substantial moisture availability (Trenberth, 2022). However, the balance between precipitation and evaporation in the tropics is highly sensitive to climate variability and land-surface conditions. Despite generally high rainfall, many tropical regions experience seasonal or chronic water deficits because evaporation consumes a large fraction of precipitation (Worden et al., 2007). In semi-arid tropical zones, evaporation often exceeds precipitation for much of the year, resulting in negative water balances and strong dependence on groundwater and surface storage (Abdalla, 2008). Climate warming further intensifies these conditions by increasing atmospheric evaporative demand, potentially offsetting precipitation increases and reducing effective moisture availability. Equatorial Africa represents a complex hydroclimatic transition zone influenced by the Intertropical Convergence Zone (ITCZ), monsoon systems, and large-scale climate modes such as ENSO and the Indian Ocean Dipole. Variability in these drivers produces pronounced spatial and temporal contrasts in rainfall and evaporation, making the region particularly sensitive to climate-induced changes in water balance.

Tanzania occupies a climatically diverse region of East Africa, spanning equatorial, tropical, and semi-arid zones. The country experiences both bimodal and unimodal rainfall regimes, with the bimodal pattern dominating northern and coastal areas (March-May and October-December) and the unimodal pattern prevailing in the southern and western regions (November-April). Mean annual precipitation averages approximately 1000 - 1100 mm but exhibits strong spatial variability (Nicholson, 2017). Despite moderate to high rainfall in many regions, evaporation in Tanzania is exceptionally high due to intense solar radiation, warm temperatures, and seasonal moisture limitations. Previous studies suggest that evaporation can account for more than 70% - 80% of annual precipitation in several Tanzanian catchments, leaving limited water available for runoff, groundwater recharge, and ecosystem functioning (Makula et al., 2025). As a result, water scarcity persists even in years with above-normal rainfall, particularly in semi-arid and inland regions. Rising temperatures observed over recent decades have further intensified evaporation across Tanzania. Climate projections indicate contin-

ued warming throughout the 21st century, with potential increases in evaporation sufficient to offset projected rainfall gains in some regions (Cioffi et al., 2016). This dynamic raises concerns about the reliability of future water resources, agricultural productivity, and hydropower generation.

Tanzania's hydroclimatic characteristics vary markedly across its major regions. The coastal zone experiences relatively high humidity and moderate evaporation due to maritime influences, yet still exhibits seasonal water deficits during dry periods. The Lake Victoria Basin receives high rainfall but also sustains substantial evaporation from open water surfaces, influencing regional moisture recycling and lake level variability. The central plateau, characterized by semi-arid conditions, experiences low and highly variable rainfall combined with strong evaporative demand, resulting in persistent negative water balances. The northern and southern highlands benefit from orographic rainfall and comparatively lower temperatures, which reduce evaporation rates and support relatively more favorable water balances. However, even these regions are increasingly affected by increases in evaporation driven by warming. Understanding these regional contrasts is essential for effective water resource management, as national-scale averages often mask localized vulnerabilities and hotspots of hydroclimatic stress.

High evaporation rates have profound implications for Tanzania's water, agricultural, and energy sectors. Agriculture, which employs a large proportion of the population, is predominantly rain-fed and highly sensitive to moisture deficits. Elevated evaporation reduces soil moisture availability, shortens growing seasons, and increases crop water requirements. Similarly, evaporation losses from reservoirs diminish water storage capacity and hydropower reliability, while reduced groundwater recharge threatens domestic and industrial water supplies.

Ecosystems are also affected, as altered water balances influence wetland extent, river flows, and biodiversity. These impacts are expected to intensify under continued warming, underscoring the need for integrated assessments of evaporation and water balance.

Despite the recognized importance of evaporation in Tanzania's hydrology, comprehensive assessments of its variability, trends, and role in water balance remain limited. Many previous studies have focused primarily on precipitation variability, often neglecting evaporation due to data scarcity and methodological challenges. The lack of long-term, spatially consistent evaporation datasets has constrained understanding of how warming temperatures are reshaping Tanzania's hydrological regime. Recent advances in reanalysis products, such as ERA5-Land, provide an opportunity to address these gaps by offering high-resolution, physically consistent estimates of evaporation, precipitation, and temperature. Leveraging these datasets enables a more complete characterization of climatic water balance and its drivers across Tanzania.

Understanding evaporation dynamics and water balance is critical for hydrological planning and climate adaptation in Tanzania, a country highly dependent on rainfall-driven agriculture and water resources. By analyzing long-term rea-

analysis data, this study provides insights into how energy availability and moisture supply jointly regulate evaporation, and how seasonal reversals in water balance shape drought and flood risks. The findings offer a diagnostic framework for evaluating climate model performance, improving water resource management, and guiding agricultural decision-making under increasing climate variability.

This study aims to investigate the variability and trends of evaporation and water balance over Tanzania, focusing on seasonal cycles, long-term changes, and the coupling between evaporation, precipitation, and temperature.

## 2. Literature Review

Evaporation is a fundamental process within the hydrological cycle, representing the phase change of liquid water to vapor from open water bodies, soil surfaces, and wetted land surfaces. When combined with plant transpiration, this process is collectively referred to as evapotranspiration (ET), which constitutes the dominant pathway through which terrestrial water returns to the atmosphere (Katul et al., 2012). In hydrological and climatological studies, ET is commonly partitioned into potential evapotranspiration (PET) and actual evapotranspiration (AET). PET represents the atmospheric demand for moisture under conditions of unlimited water supply, while AET reflects the actual water loss constrained by soil moisture availability, vegetation characteristics, and land surface conditions (Rao et al., 2011; Pimentel et al., 2023). This distinction is particularly important in water-limited environments, where PET may substantially exceed AET, leading to persistent soil moisture deficits.

In tropical and subtropical climates, high solar radiation and elevated temperatures result in strong atmospheric evaporative demand. Consequently, PET frequently exceeds precipitation for large parts of the year, especially in semi-arid and seasonally dry regions, leading to negative climatic water balances and increased water stress (Onyutha et al., 2021). Numerous studies across Africa have demonstrated that ET accounts for a substantial proportion of annual precipitation, typically ranging from 60% to over 90%, depending on climate zone, land cover, and soil characteristics (Gong et al., 2006; McNally et al., 2017). In humid tropical regions, ET is often energy-limited, whereas in semi-arid regions it becomes water-limited, with evaporation tightly coupled to rainfall variability and soil moisture dynamics.

Accurate estimation of evaporation and ET remains a central challenge in hydrology, particularly in data-scarce regions. A wide range of empirical and physically based models has been developed to estimate ET at different spatial and temporal scales. These models form the basis of many operational hydrological and agricultural applications and are recommended by the Food and Agriculture Organization (FAO) as standard approaches for PET estimation (Jayathilake & Smith, 2021). However, their application requires detailed meteorological inputs, including radiation, humidity, wind speed, and temperature, which are often unavailable

or unreliable in many parts of Africa.

To address data limitations, simpler empirical approach formulations have been widely applied, particularly in arid and semi-arid environments (Yurtseven & Serengil, 2021). These models rely primarily on precipitation and temperature, making them attractive for regional-scale studies where observational networks are sparse. Comparative evaluations across Africa indicate that while Penman-based methods tend to provide accurate estimates of PET, empirical formulations such as Turco-Pike often perform better in estimating AET under conditions of strong soil moisture limitation (Han et al., 2024; Yurtseven & Serengil, 2021). This highlights the importance of selecting ET estimation methods that are consistent with the dominant hydrological regime.

Recent advances in remote sensing and land-surface reanalysis products have substantially improved the availability of spatially continuous evaporation datasets. Products such as ERA5-Land integrate physically based land-surface models with atmospheric reanalysis, providing long-term, high-resolution estimates of evaporation, precipitation, and temperature (Aboelnour et al., 2025; Muñoz-Sabater et al., 2021). These datasets have been increasingly used to investigate hydroclimatic variability and trends at continental and regional scales, particularly in regions with limited in situ observations. Studies comparing reanalysis-based ET estimates with flux tower and basin-scale water balance observations generally report reasonable performance, although uncertainties remain, especially in heterogeneous landscapes and complex terrain (Xiong et al., 2023).

In East Africa, evaporation has been identified as a key control on hydrological variability and drought dynamics. Several studies in Kenya, Ethiopia, and the Greater Horn of Africa demonstrate that rising temperatures have led to significant increases in PET over recent decades, in some cases offsetting observed increases in precipitation (Omondi et al., 2014; Teshome & Zhang, 2019). These findings suggest that warming-induced evaporation may reduce effective rainfall and exacerbate water scarcity, even in regions experiencing intensified rainfall events. The interaction between evaporation, temperature, and precipitation has also been linked to changes in land-atmosphere feedbacks, which can amplify drought persistence and heat extremes (Miralles et al., 2019; Seneviratne et al., 2010).

In Tanzania, however, explicit analyses of evaporation and climatic water balance remain relatively limited. Much of the existing literature has focused on rainfall variability, seasonal predictability, and extreme events, particularly in relation to the El Niño-Southern Oscillation and the Indian Ocean Dipole (Glantz et al., 1991; Hulme et al., 2001; Lyon & DeWitt, 2012; Nicholson, 2017). While these studies provide valuable insights into precipitation dynamics, they offer only a partial view of hydrological change, as they do not account for concurrent changes in evaporation driven by rising temperatures and land-surface processes. Basin-scale studies suggest that evaporation can account for more than 70 %- 80% of precipitation in several Tanzanian catchments, implying limited runoff genera-

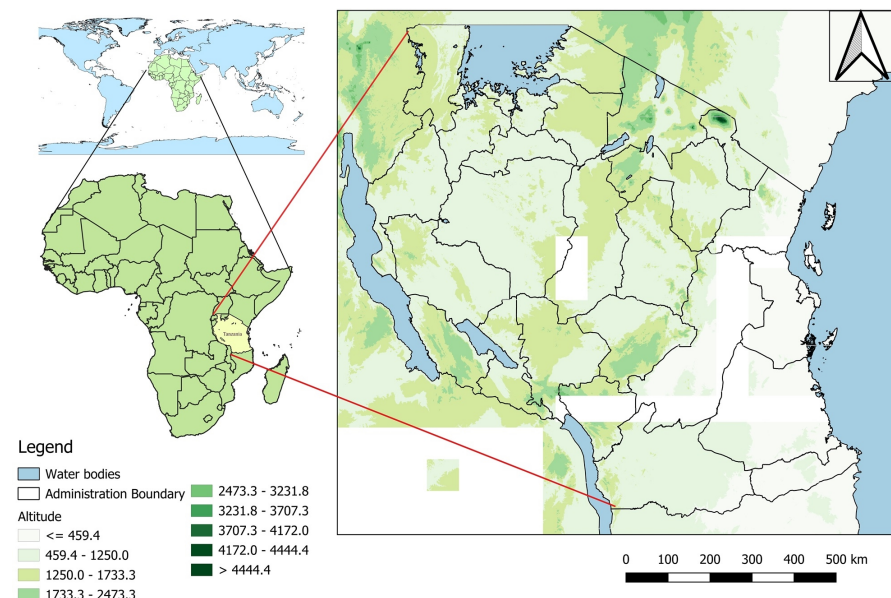
tion and groundwater recharge, but these findings are often localized and lack a national-scale assessment.

Climate change projections further underscore the importance of evaporation in shaping future water availability in Tanzania and East Africa more broadly. Coupled climate-hydrology model simulations indicate that while mean annual precipitation may increase in some regions, higher temperatures are likely to enhance evaporation losses, leading to uncertain or even negative net water balance outcomes (IPCC, 2023; Tierney et al., 2015). These studies suggest that evaporation may offset precipitation gains by tens to hundreds of millimeters annually, particularly in semi-arid and seasonally dry regions, increasing the risk of agricultural drought, water shortages, and ecosystem stress.

Despite growing recognition of evaporation's importance, significant knowledge gaps remain regarding its long-term variability, spatial heterogeneity, and relative contribution to water balance changes in Tanzania. There is limited understanding of how evaporation trends differ across climatic zones, how strongly they are driven by temperature versus precipitation, and how they influence regional water balance under ongoing climate change. Addressing these gaps requires the use of spatially consistent, long-term datasets capable of capturing land-atmosphere interactions at appropriate scales.

By using high-resolution reanalysis products such as ERA5-Land, this study seeks to advance understanding of evaporation dynamics and climatic water balance over Tanzania. In doing so, it contributes to a more comprehensive assessment of hydroclimatic change in Tanzania and provides critical information for water resource management, climate adaptation, and drought risk reduction in a warming climate.

### 3. Data and Methodology



**Figure 1.** Study area map of Tanzania showing the relief.

Tanzania is located between latitudes 1°S and 12°S and longitudes 29°E and 41°E, covering an area of approximately 945,000 km<sup>2</sup> as shown in **Figure 1**. Topography ranges from coastal plains to the Eastern Arc Mountains and the highlands surrounding Mount Kilimanjaro. Climate is influenced by altitude, proximity to the Indian Ocean, and large-scale circulation patterns.

### 3.1. Data Sources

This study utilized the ERA5-Land reanalysis dataset, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-Land provides hourly estimates of land-surface variables at a spatial resolution of 0.1° × 0.1°, making it particularly suitable for regional hydroclimatic analysis (Muñoz-Sabater et al., 2021). For Tanzania, monthly and annual averages of evaporation, precipitation, and near-surface air temperature were extracted for the period 1995-2025, ensuring consistency with the climatological baseline and capturing recent variability. Evaporation in ERA5-Land is expressed as a negative flux (mm/month), where more negative values indicate stronger water loss from the land surface to the atmosphere. Precipitation and temperature fields were also obtained from ERA5-Land to enable correlation analysis and water balance computations (P-E). The dataset was selected due to its high spatial resolution, physically consistent land-surface modeling, and widespread use in hydrological and climate studies across Africa.

### 3.2. Methodology

#### 3.2.1. Monthly and Annual Climatology

Monthly and annual climatology of evaporation was derived by averaging ERA5-Land data across the 30-year study period. For each month  $m$ , the climatological mean was computed as:

$$E_m = \frac{1}{N} \sum_{i=1}^N E_{i,m}$$

where  $E_{i,m}$  is the evaporation in month  $m$  for year  $i$ , and  $N$  is the total number of years (1995-2025). Annual averages were similarly computed by aggregating monthly values across each year.

#### 3.2.2. Trend Analysis

Long-term trends in evaporation were estimated using linear regression applied to monthly time series at each grid cell. The regression equation is expressed as:

$$E_t = \alpha + \beta t + \varepsilon$$

where  $E_t$  is evaporation at time  $t$ ,  $\alpha$  is the intercept,  $\beta$  is the slope (trend in mm/month), and  $\varepsilon$  is the residual error. Statistical significance was assessed using a two-tailed Student's T-test, with trends considered significant at ( $p < 0.05$ ). To account for potential serial correlation, a non-parametric Mann-Kendall test with pre-whitening was further applied, which confirmed the robustness of the detected trends (Khanmohammadi et al., 2018).

### 3.2.3. Correlation Analysis

To examine the coupling between evaporation and climatic drivers, Pearson correlation coefficients were computed between evaporation and precipitation, and between evaporation and temperature. The correlation coefficient  $r$  is defined as:

$$r_{XY} = \frac{\sum_{i=1}^N (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^N (X_i - \bar{X})^2} \cdot \sqrt{\sum_{i=1}^N (Y_i - \bar{Y})^2}}$$

where  $X$  and  $Y$  represent the paired variables (e.g., evaporation vs precipitation),  $\bar{X}$  and  $\bar{Y}$  are their means, and  $N$  is the number of observations. Values of  $r$  range from  $-1$  (perfect negative correlation) to  $+1$  (perfect positive correlation).

### 3.2.4. Water Balance

The monthly water balance was computed as the difference between precipitation and evaporation:

$$WB = P - E$$

where  $WB$  is the water balance (mm/month),  $P$  is precipitation (mm/month), and  $E$  is evaporation (mm/month). Positive values ( $WB > 0$ ) indicate surplus conditions (precipitation exceeds evaporation), while negative values ( $WB < 0$ ) denote deficit conditions (evaporation exceeds precipitation). Both mean and median values were calculated to capture central tendencies and spatial heterogeneity.

## 4. Results

### 4.1. Average Evaporation (E)

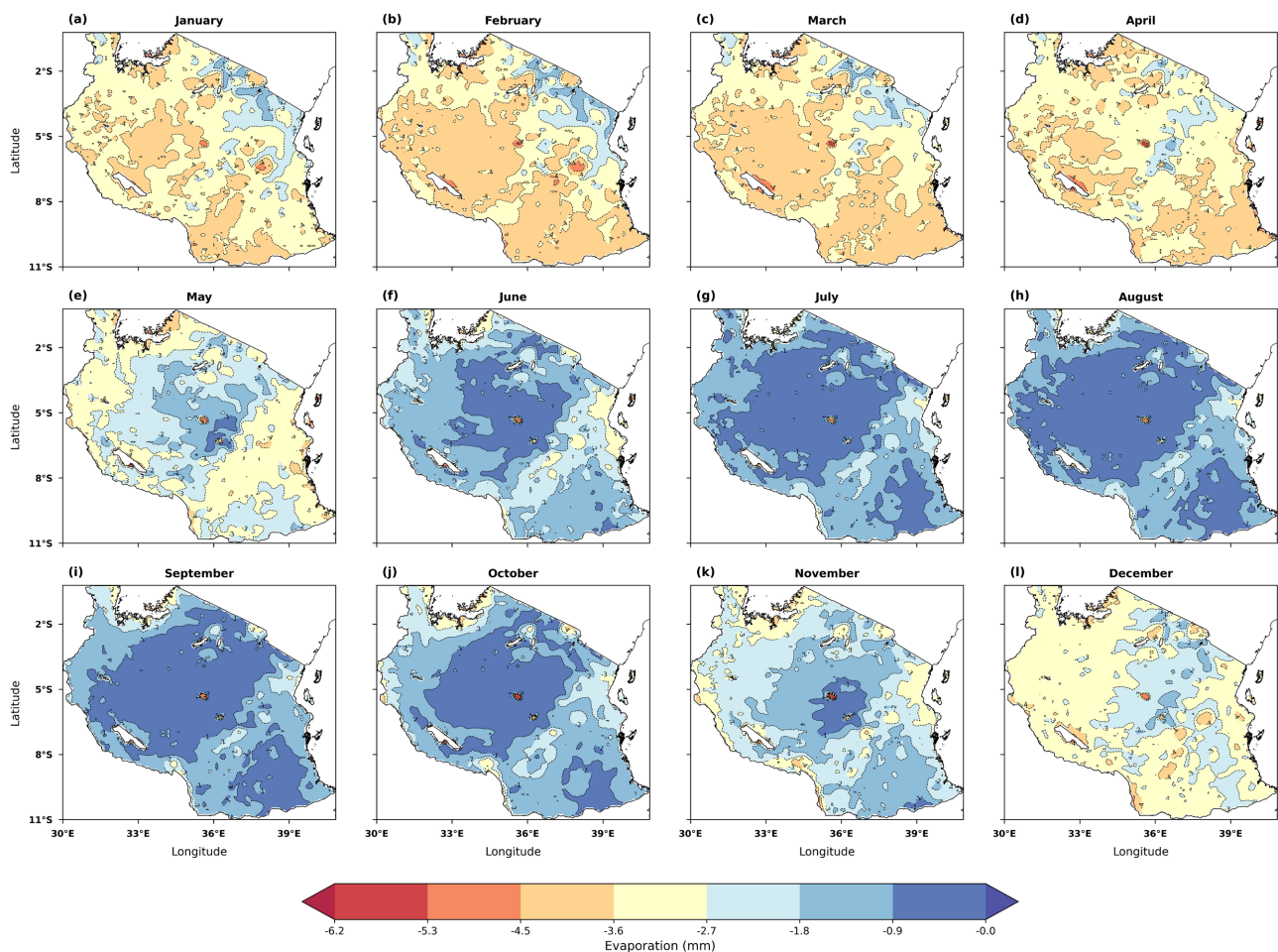
#### 4.1.1. Monthly Average Evaporation

The spatial distribution of monthly evaporation over Tanzania was examined using long-term (1995-2025) climatological means derived from ERA5-Land reanalysis data (Figure 2). Monthly evaporation fields were computed by averaging all years for each calendar month, thereby isolating the mean seasonal signal while minimizing short-term variability. In ERA5-Land, evaporation is expressed as a negative flux, where more negative values indicate stronger evaporative water loss from the land surface to the atmosphere.

The results reveal a clear and consistent seasonal cycle in evaporation across Tanzania. Strong evaporative losses (reaching approximately  $-6.2$  mm) dominate during the period from November to May under limited energy conditions, and the main rainy seasons (OND and MAM). During these months, elevated temperatures across the country, especially on 23<sup>rd</sup> March when the sun is overhead on the equator, and abundant surface moisture due to the rain seasons of bimodal and unimodal jointly enhance evaporation rates, particularly over lowland and interior regions. The availability of moisture during the rainy season allows atmospheric evaporative demand to be more fully realized, resulting in stronger evaporation despite increased precipitation. In contrast, evaporation weakens

substantially during the June to October period, as indicated by values closer to zero across much of the country, especially the central part. This period corresponds to the cooler and drier season, during which reduced temperatures and moisture constrain evaporation. The suppression of evaporation during these months reflects a shift toward a moisture-limited regime, where insufficient surface water availability restricts evaporative losses even under relatively clear-sky conditions.

Spatially, higher evaporation magnitudes during November-May are most pronounced over central Tanzania, the Lake Victoria basin, and other lowland regions, while comparatively weaker evaporation persists over the southern highlands, where cooler temperatures and elevation effects limit atmospheric demand. Coastal areas and areas around Lake Victoria exhibit moderate evaporation throughout the year, influenced by higher humidity and maritime air masses that reduce vapor pressure gradients.



**Figure 2.** Monthly evaporation averaged over Tanzania for 1995-2025.

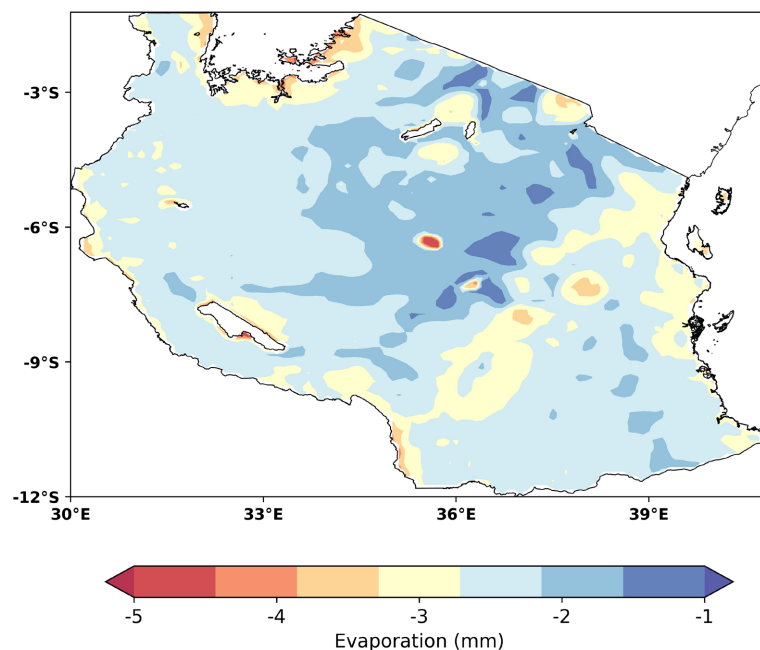
These results demonstrate that evaporation over Tanzania is strongest during the warm and wet months and weakest during the cool dry season, highlighting

the dominant role of temperature and moisture availability in regulating evaporative losses.

#### 4.1.2. Annual Average Evaporation

**Figure 3** presents the spatial distribution of annual mean evaporation over Tanzania for the period 1995-2025, derived from ERA5-Land reanalysis. Evaporation is expressed as a negative surface flux, with more negative values indicating stronger evaporative losses. The long-term mean reveals coherent regional patterns, with relatively stronger evaporation (approximately  $-4$  to  $-5$  mm) over the central plateau and western parts of the country, and weaker evaporation ( $-1$  to  $-2$  mm) over the coastal zone, northern highlands, and southern highland regions.

These spatial contrasts reflect persistent differences in surface energy availability, land-atmosphere coupling, and topographic influences. Low-lying interior regions are characterized by warmer conditions and enhanced net radiation, promoting stronger evaporative fluxes, whereas high-elevation and coastal areas experience reduced evaporation due to cooler temperatures, higher atmospheric humidity, and increased cloud cover. The spatial coherence of these patterns over the 30-year period indicates a stable climatological control on evaporation at the national scale.



**Figure 3.** Annual water balance (P-E) averaged over Tanzania for 1995-2025.

Although the annual mean provides a useful baseline for identifying regions of persistent evaporative loss, it integrates contrasting wet- and dry-season processes and therefore obscures the pronounced seasonal variability that governs evaporation dynamics in tropical climates. Consequently, interpretation of the annual evaporation climatology is complemented by monthly and seasonal analyses, which

more explicitly capture the influence of rainfall seasonality and temperature variability on Tanzania’s surface water balance.

## 4.2. Precipitation-Evaporation (Water Balance)

### 4.2.1. Monthly Average Precipitation-Evaporation (P-E)

Figure 4 illustrates the spatial distribution of monthly precipitation minus evaporation (P-E) over Tanzania, highlighting seasonal variations in surface water surplus and deficit. Positive values indicate precipitation exceeding evaporation, while negative values denote net water deficit conditions. The results reveal strong seasonal and regional contrasts in water balance, closely aligned with Tanzania’s bimodal and unimodal rainfall regimes, topography, and large-scale atmospheric circulation.

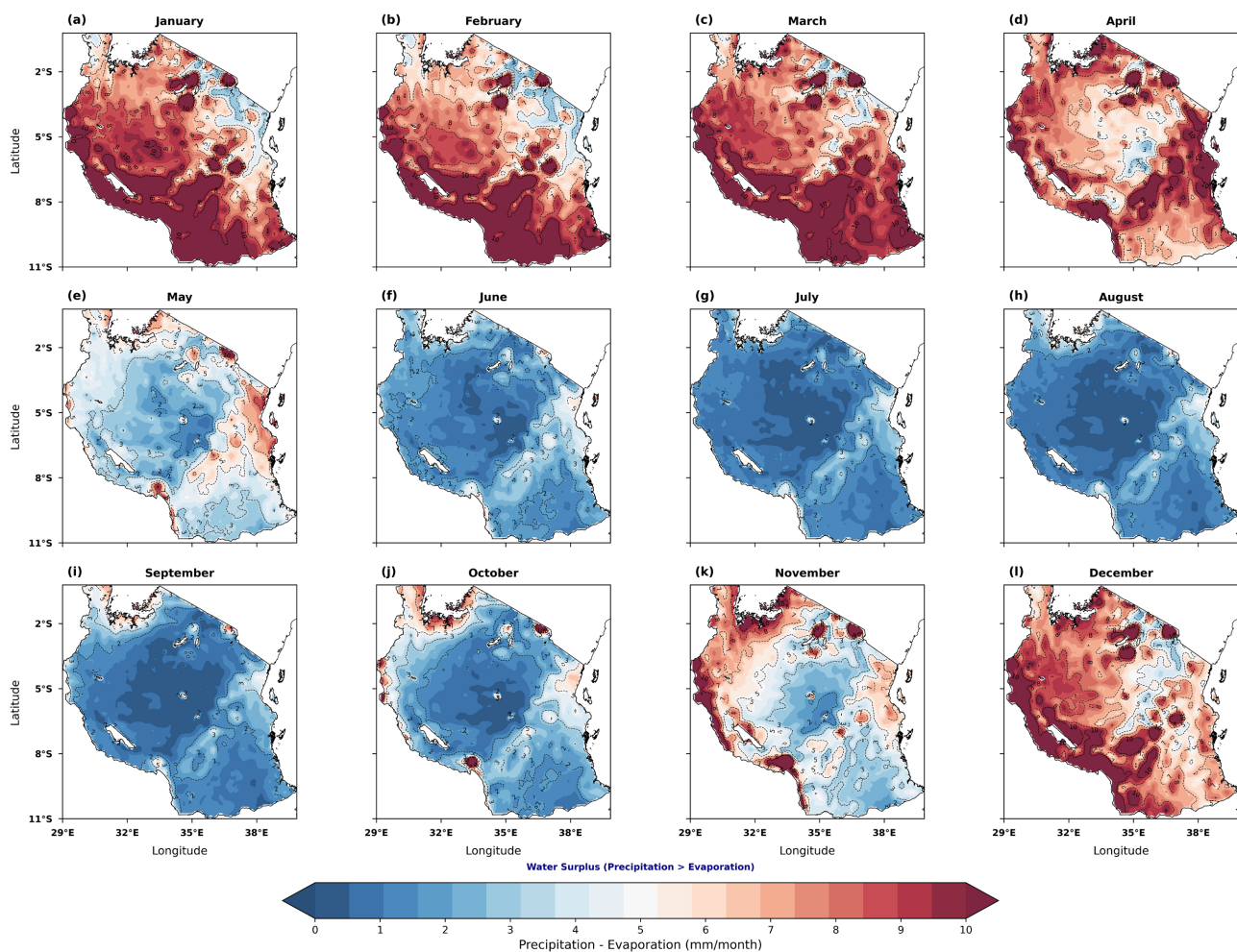


Figure 4. Monthly water balance (P-E) averaged over Tanzania for 1995-2025.

During the dry season (June-September), extensive areas of central Tanzania exhibit pronounced water deficits ( $P-E \leq 0$ ), reflecting suppressed precipitation combined with persistent evaporative demand. This deficit is most evident over the central plateau and western interior, where limited moisture availability and

clear-sky conditions dominate. In contrast, regions surrounding Lake Victoria and Mount Kilimanjaro maintain positive water balances during this period, indicating the buffering influence of large water bodies and orographic lifting, which enhance localized precipitation and reduce effective moisture stress.

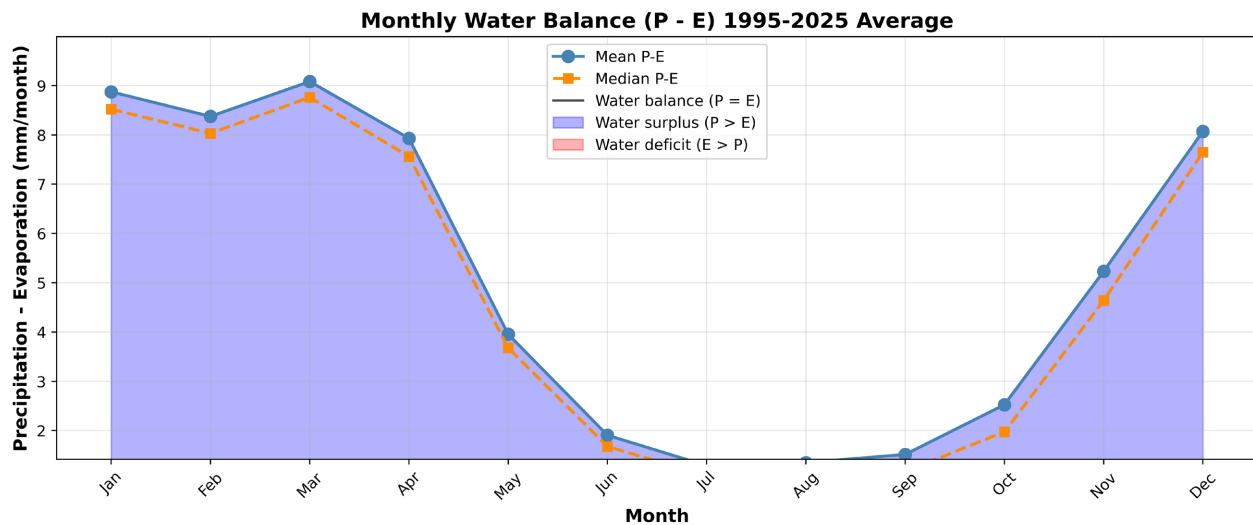
In the wet seasons, particularly during the long rains (March-May), widespread water surplus conditions emerge across much of the country. The southern highlands and lake zones exhibit strong positive P-E values, driven by sustained rainfall and comparatively lower evaporation rates associated with increased cloud cover. Dar es Salaam and the eastern coastal belt show a marked surplus during the peak of the long rains, with maximum values observed in April, consistent with the seasonal intensification of the Indian Ocean moisture flux. However, during the short rains (October-December), surplus conditions become more spatially heterogeneous, with deficits persisting in parts of the central and northern interior while surplus conditions re-establish along the coast and highland regions.

Notably, areas surrounding Mount Kilimanjaro display persistent water surplus throughout the year, underscoring the role of elevation-induced precipitation and reduced evaporative losses in sustaining positive moisture conditions. Similarly, the Lake Victoria basin experiences water surplus for nearly nine months annually, emphasizing its hydrological resilience and importance as a regional moisture source. Overall, the P-E patterns demonstrate that Tanzania's water balance is governed not only by rainfall seasonality but also by strong spatial controls related to topography, proximity to large water bodies, and regional climate dynamics.

#### 4.2.2. Seasonal Water Balance Dynamics

To further contextualize the monthly P-E dynamics, **Figure 5** presents the average water balance across Tanzania from 1995 to 2025, highlighting the seasonal interplay between precipitation and evaporation. The graph shows that from January to May and again from October to December, the country experiences a net water surplus ( $P > E$ ), while the period from June to September is marked by a pronounced deficit ( $E > P$ ). The surplus months align with the long and short rainy seasons, where increased precipitation and reduced evaporative demand due to cloud cover and elevated humidity contribute to positive moisture conditions. In contrast, the deficit observed during the dry season reflects suppressed rainfall and intensified evaporation driven by higher temperatures and clear-sky conditions.

The divergence between mean and median P-E values in certain months, particularly during transitional periods, suggests spatial heterogeneity in water balance across the country. Regions with persistent surplus, such as the Lake Victoria basin and highland zones, buffer national averages, while drier interior zones contribute to the observed deficits. These temporal patterns reinforce the spatial findings from the P-E maps and underscore the importance of seasonally adaptive water management strategies.



**Figure 5.** Monthly average water balance (P-E) for Tanzania from 1995 to 2025.

National-scale ERA5-Land analysis aligns closely with basin-level studies conducted across Tanzania, while also extending their insights to a broader spatial context. For instance, [Deus et al. \(2013\)](#) demonstrated strong evaporation and water balance variability in the semi-arid Lake Manyara catchment, with fluctuations linked to large-scale climate drivers such as the Indian Ocean Dipole. Similarly, [Mbanguka et al. \(2016\)](#) reported sensitivity of Lake Babati's water balance to hydroclimatic forcing, consistent with our finding of pronounced deficits in the central plateau. [Kisiki et al. \(2023\)](#) highlighted groundwater recharge variability in the Makutupora basin, which resonates with our interpretation of soil moisture memory sustaining evaporation during dry months. [Clement et al. \(2021\)](#) emphasized land-use and climate change impacts on water balance in the Sigi catchment, and our national results refine these conclusions by situating localized land-use effects within broader climatic controls. [Fischer \(2013\)](#) further demonstrated recharge sensitivity in the Kilombero Valley, corroborating our evidence of strong coupling between precipitation and evaporation during wet months. Taken together, these basin-scale studies confirm the coherence of our national findings, while our analysis provides a spatially explicit framework that integrates localized processes into Tanzania's broader evaporative and hydrological dynamics governed by both rainfall seasonality and evaporative stress, shaped by atmospheric circulation, topography, and land-surface feedback.

### 4.3. Correlation of Evaporation and Precipitation Temperature

#### 4.3.1. Evaporation vs Precipitation

**Figure 6** illustrates the monthly Pearson correlation coefficients between evaporation and precipitation across Tanzania, highlighting the seasonal variability in land-atmosphere coupling. Positive correlations dominate during the wet season months (January-April), particularly in the western interior and lake-adjacent regions. These patterns suggest that increased rainfall is closely linked to enhanced

evaporation, driven by greater soil moisture availability, elevated latent heat flux, and active vegetation transpiration. The strong coupling observed in these months reflects efficient moisture recycling under convective rainfall regimes, where precipitation inputs directly sustain evaporative processes.

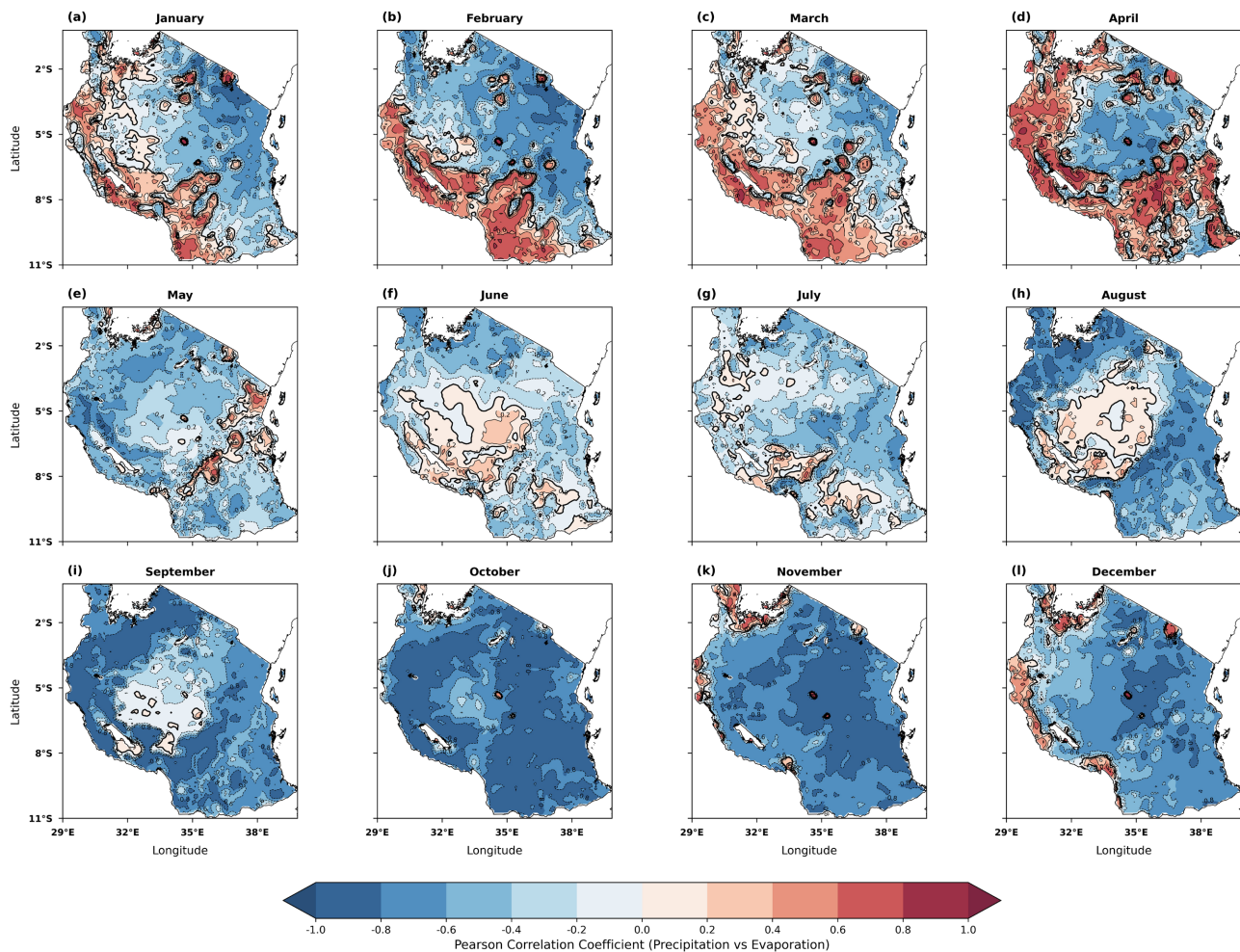
In contrast, the dry season (June–September) is characterized by widespread negative correlations, especially across central and southern Tanzania. Here, evaporation persists or intensifies despite minimal rainfall, indicating a decoupling between precipitation and evaporative demand. This behavior is consistent with semi-arid hydroclimates, where high net radiation, reduced cloud cover, and elevated vapor pressure deficits drive potential evaporation independently of rainfall inputs. The persistence of negative correlations underscores the dominance of atmospheric demand over moisture supply during prolonged dry periods, reinforcing regional aridity.

The persistence of evaporation during dry months, despite minimal rainfall, can also be attributed to soil moisture memory. Water stored in deeper soil layers from preceding wet seasons continues to support latent heat fluxes and vegetation transpiration even when rainfall inputs are absent. This residual storage sustains evaporation for several weeks to months, creating a lagged response between precipitation and evaporative flux. As a result, correlations between evaporation and precipitation become negative during dry periods: evaporation persists or intensifies while rainfall ceases. Such soil moisture memory effects have been documented in semi-arid hydroclimates, where groundwater recharge and subsurface storage act as buffers against short-term rainfall deficits. In Tanzania, these mechanisms are particularly relevant in regions with clay-rich soils and perennial vegetation, which enhance water retention and prolong evaporative activity during drought conditions.

Transitional months such as May and October–December exhibit mixed correlation structures, reflecting the interplay between residual soil moisture, vegetation phenology, and the seasonal migration of the Intertropical Convergence Zone. Regions surrounding Lake Victoria and Mount Kilimanjaro maintain positive correlations throughout much of the year, underscoring the buffering influence of large water bodies and orographic uplift in sustaining precipitation–evaporation coupling. These localized effects highlight the importance of topography and proximity to moisture sources in stabilizing hydroclimatic interactions.

Multiple scientific drivers shape the observed correlation structures. Variations in the surface energy balance, particularly the partitioning between sensible and latent heat fluxes, directly influence evaporation rates. Soil moisture dynamics and vegetation activity modulate the responsiveness of evaporation to rainfall inputs, while large-scale climate modes such as ENSO and the Indian Ocean Dipole alter rainfall distribution and temperature anomalies, thereby reshaping the strength and direction of correlations. Together, these findings emphasize that Tanzania's hydroclimatic regime is governed by both local land-surface processes and broader atmospheric circulation patterns.

Overall, the seasonal reversal in correlation patterns provides critical insight into the mechanisms controlling water availability and evaporative demand. The strong coupling during wet months and decoupling during dry months highlight the sensitivity of Tanzania's water balance to climatic variability. These results not only serve as a diagnostic tool for evaluating climate model performance but also underscore the importance of incorporating land-atmosphere feedback into hydrological planning and climate adaptation strategies.



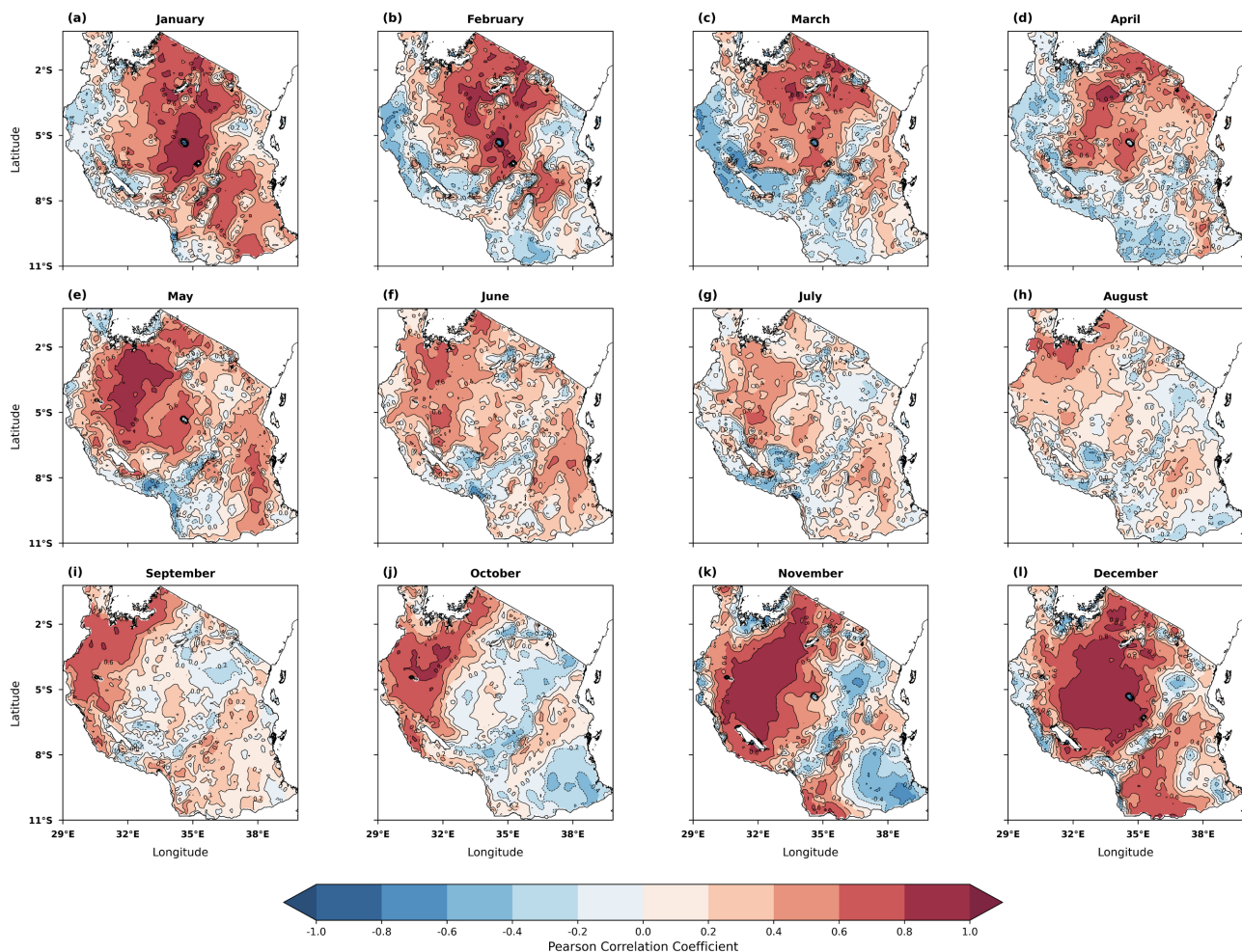
**Figure 6.** Monthly Pearson correlation coefficients between evaporation and precipitation across Tanzania (1995-2025).

#### 4.3.2. Correlation of Evaporation and Temperature

**Figure 7** presents the monthly Pearson correlation coefficients between evaporation and near-surface air temperature across Tanzania, revealing strong seasonal and spatial variability in land-atmosphere energy exchange. Correlation values range from  $-1.0$  (strong negative relationship) to  $+1.0$  (strong positive relationship), indicating how closely evaporation responds to temperature fluctuations across different regions and months.

Throughout most of the year, particularly during the dry season months (June-September), the country exhibits widespread positive correlations, with red tones

dominating central and western Tanzania. These patterns suggest that rising temperatures are closely associated with increased evaporation, consistent with the physical expectation that higher thermal energy enhances vapor pressure deficit and accelerates moisture loss from land surfaces. The strength of these correlations reflects the dominance of potential evaporation during dry periods, where atmospheric demand governs evaporative fluxes independent of precipitation inputs.



**Figure 7.** Monthly Pearson correlation coefficients between evaporation and near-surface air temperature across Tanzania (1995-2025).

During the wet season (March-May and October-December), the correlation patterns become more heterogeneous. In some regions, notably the southern highlands and coastal zones, correlations weaken or even turn negative. This decoupling may be attributed to increased cloud cover and reduced net radiation during peak rainfall months, which suppresses surface heating and limits evaporation despite elevated moisture availability. Additionally, the presence of saturated soils and high humidity can reduce the sensitivity of evaporation to temperature, leading to weaker or inverse relationships.

Regions surrounding Lake Victoria and Mount Kilimanjaro consistently show moderate to weak correlations throughout the year, underscoring the buffering influence of large water bodies and orographic precipitation. These areas maintain relatively stable moisture and energy balances, which dampen the direct impact of temperature variability on evaporation.

The observed correlation structures are governed by several physical and climatic mechanisms. The surface energy balance plays a central role, with net radiation and sensible heat flux driving temperature-induced evaporation. Soil moisture availability and vegetation cover modulate the efficiency of latent heat exchange. These interactions determine whether evaporation is energy-limited or moisture-limited, shaping the strength and direction of temperature-evaporation coupling.

The monthly correlation maps highlight the evolving nature of hydroclimatic sensitivity across Tanzania. The strong positive correlations during dry months emphasize the role of temperature as a key driver of evaporative demand, while the variable patterns during wet months reveal the complex interplay between energy availability and moisture conditions. These findings are critical for improving land-surface parameterizations in climate models and for anticipating shifts in water loss under future warming scenarios.

## 4.4. Trend Analysis

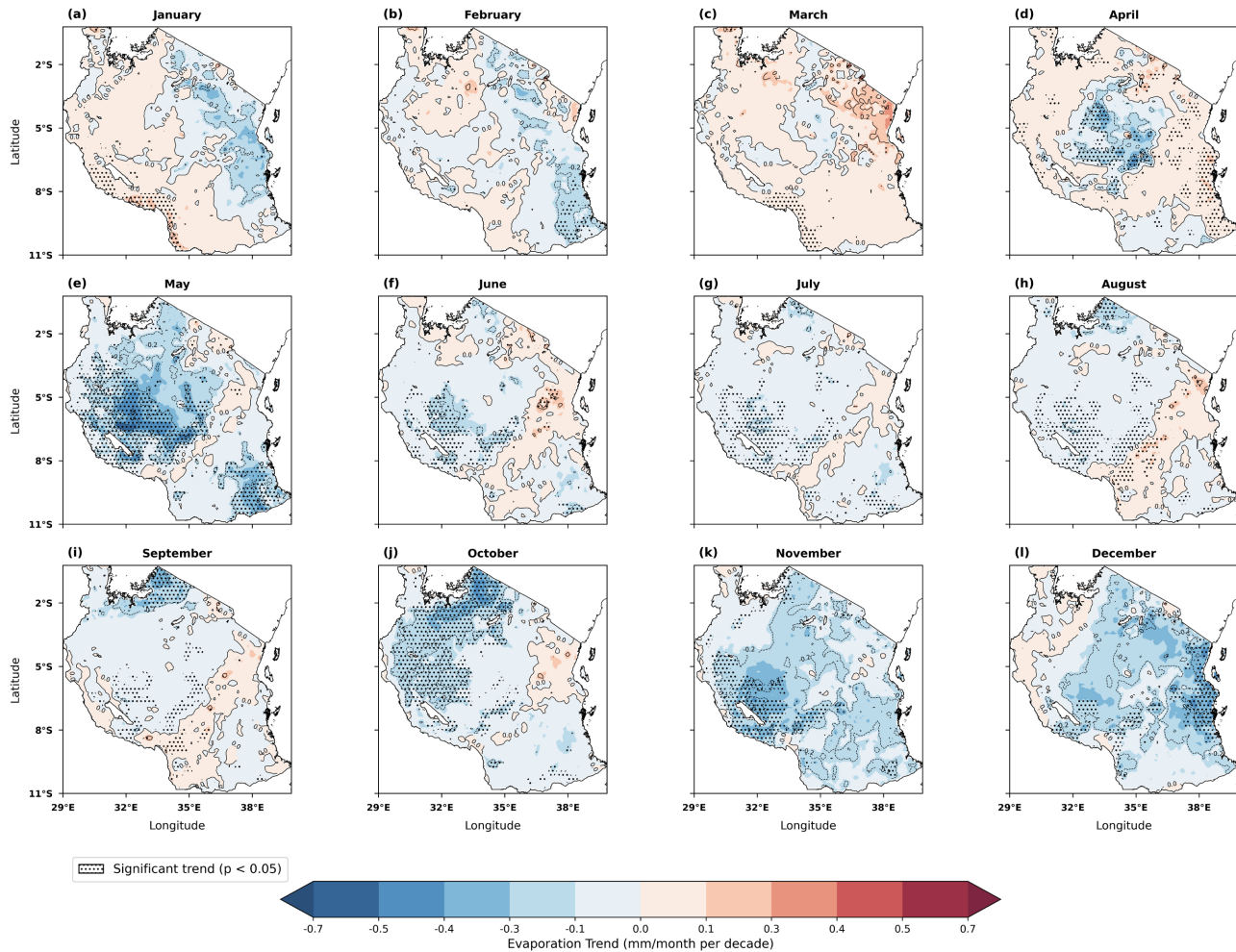
### 4.4.1. Monthly Evaporation Trend Analysis

**Figure 8** illustrates the spatial distribution of monthly evaporation trends across Tanzania from 1905 to 2025, with values ranging from  $-0.7$  mm/month (decreasing) to  $+0.7$  mm/month (increasing). Statistically significant areas ( $p < 0.05$ ) are marked with black dots, highlighting regions where long-term changes in evaporative flux are robust. These results provide insight into how atmospheric circulation, land-surface processes, and hydroclimatic variability interact to shape evaporation dynamics.

During the onset and cessation of the rainy seasons (March-May and October-December), widespread negative evaporation trends are evident, particularly across central and southern Tanzania. These declines are consistent with enhanced cloud cover, reduced incoming solar radiation, and elevated relative humidity, which collectively suppress potential evaporation. The significant negative anomalies suggest that rainfall seasonality and large-scale moisture convergence (e.g., the Intertropical Convergence Zone shifts) have increasingly moderated evaporative demand during these transitional months.

In contrast, the dry season months of January and February exhibit positive evaporation trends over western and central Tanzania. These increases are likely driven by rising near-surface air temperatures, reduced soil moisture availability, and stronger sensible heat fluxes, which amplify evaporative demand. The clustering of significant positive trends in these regions points to intensifying aridity, possibly linked to warming trends and land-atmosphere feedback that reinforce

## moisture stress.



**Figure 8.** Monthly trend of evaporation from 1995 to 2025.

The spatial and seasonal heterogeneity of evaporation trends reflects the combined influence of temperature variability, rainfall seasonality, atmospheric circulation patterns, and topographic controls. The suppression of evaporation during wet months and its intensification during dry months highlight the sensitivity of Tanzania's hydroclimatic regime to both local processes (soil moisture, vegetation cover, orography) and broader climate drivers (Indian Ocean dynamics, ENSO variability). These findings underscore the importance of integrating evaporation trends into water resource planning, as they signal evolving risks of moisture deficit and highlight regions where climate adaptation strategies may be most critical.

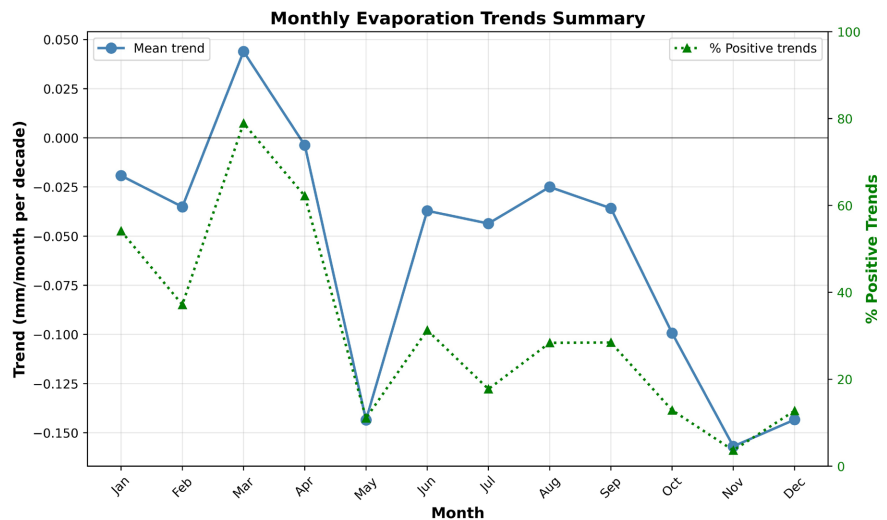
To account for potential serial correlation, we applied the non-parametric Mann-Kendall test with pre-whitening to monthly regional averages, as shown in **Table 1**, with  $p > 0.05$ . Results confirmed a statistically significant decreasing trend in May and a near-significant decline in November, consistent with regression slopes. Other months showed no significant trends.

**Table 1.** Mann-Kendall test results for regional monthly averages.

Months	January	February	March	April	May	June	July	August	September	October	November	December
<b>Slope</b>	-0.001	0.001	0.003	-0.001	-0.018	-0.006	-0.005	-0.004	-0.004	-0.007	-0.017	-0.016
<b>Tau</b>	-0.067	-0.011	0.103	-0.011	-0.274	-0.172	-0.14	-0.182	-0.205	-0.154	-0.251	-0.195
<b>p-value</b>	0.617	0.943	0.432	0.943	<b>0.035</b>	0.187	0.284	0.164	0.116	0.239	<b>0.054</b>	0.134

#### 4.4.2. Seasonal Modulation of Water Availability

To complement the spatial analysis of monthly P-E, the temporal summary of evaporation trends across Tanzania (Figure 9) provides further insight into the seasonal modulation of surface water availability. The dual-axis graph illustrates the mean evaporation trend (mm/month) and the percentage of grid cells exhibiting positive trends for each calendar month. Notably, May exhibits the most pronounced negative mean trend, coinciding with the peak of the long rains, where suppressed evaporation is likely driven by increased cloud cover, reduced net radiation, and elevated humidity. This aligns with the observed P-E surplus during the same period, reinforcing the role of atmospheric moisture convergence in enhancing water retention.

**Figure 9.** Monthly evaporation trends summary (1995-2025).

Conversely, months such as January and February show positive mean evaporation trends alongside elevated percentages of positive grid cells, particularly over western and central Tanzania. These increases suggest intensifying evaporative demand during the dry season, likely driven by rising temperatures and reduced soil moisture availability. The temporal pattern of evaporation trends thus mirrors the seasonal water balance dynamics, with negative trends reinforcing surplus conditions during wet months and positive trends amplifying deficits during dry periods.

The alignment between spatial P-E patterns and monthly evaporation trends

underscores the sensitivity of Tanzania's hydrological regime to seasonal energy-moisture interactions. These findings highlight the importance of integrating both spatial and temporal diagnostics when assessing climate impacts on water resources, especially in regions with complex rainfall regimes and strong land-atmosphere feedback.

#### 4.4.3. Competing Drivers of Declining Evaporation

The observed decline in evaporation during the rainy seasons reflects the balance between two opposing drivers: rising temperatures and reduced solar radiation. On one hand, warming trends across Tanzania enhance atmospheric evaporative demand, particularly during dry months when soil moisture is limited. This effect is evident in the positive evaporation trends observed in January and February, where higher near-surface air temperatures and stronger sensible heat fluxes amplify aridity. On the other hand, increased cloud cover during the onset and cessation of the rainy seasons reduces incoming shortwave radiation, lowers surface energy availability, and suppresses potential evaporation despite abundant moisture. Elevated humidity further dampens evaporative fluxes by reducing the vapor pressure gradient between the land surface and atmosphere.

The relative dominance of these drivers varies seasonally. In wet months, cloud-induced cooling and reduced radiation outweigh the warming effect, leading to widespread negative evaporation trends. In dry months, temperature increases and soil moisture depletion exert stronger control, resulting in localized positive trends. This dual mechanism underscores the sensitivity of Tanzania's hydroclimatic regime to both energy and moisture constraints, and highlights the importance of considering radiation-temperature interactions when interpreting evaporation dynamics. By explicitly weighing these competing effects, the results in **Figure 8** provide a better understanding of the drivers behind declining evaporation trends, with implications for anticipating future water balance shifts and designing climate adaptation strategies.

## 5. Conclusion and Recommendations

This study provides a detailed assessment of evaporation dynamics across Tanzania using long-term reanalysis data (1995-2025), combining spatial climatologies, temporal trends, and correlation analyses with key climatic drivers. The results reveal a coherent seasonal cycle in evaporation, with elevated rates during the rainy seasons (OND and MAM) under energy-limited conditions and suppressed evaporation during the dry season (JJAS) under moisture-limited conditions. Monthly and annual climatologies highlight the influence of temperature, net radiation, and moisture availability in modulating evaporative fluxes, with central and lowland regions consistently exhibiting stronger evaporation due to favorable energy conditions.

Trend analysis indicates a significant decline in evaporation during the onset and cessation of rainfall seasons, particularly in March-May and October-December.

ber. These negative trends are likely driven by increased cloud cover and humidity, which reduces atmospheric evaporative demand. In contrast, positive trends observed in January and February over western Tanzania suggest intensifying aridity and enhanced evaporative stress during dry months. The monthly summary of evaporation trends confirms this seasonal modulation, with May showing the strongest negative trend and January-February exhibiting elevated percentages of positive grid cells.

Correlation analyses further elucidate the drivers of evaporative variability. Evaporation-precipitation correlations reveal strong coupling during wet months, where rainfall enhances soil moisture and supports latent heat flux. During dry months, negative correlations dominate, reflecting a decoupling between moisture supply and evaporative demand. Evaporation-temperature correlations show widespread positive relationships during dry periods, confirming the role of thermal energy in driving potential evaporation. However, during wet months, these correlations weaken or reverse in some regions due to cloud-induced cooling and saturated soil conditions.

Together, these findings underscore the dual control of evaporation by both energy availability and moisture supply, with seasonal transitions governed by the migration of the Intertropical Convergence Zone, topographic influences, and large-scale climate modes such as ENSO and the Indian Ocean Dipole. The spatial and temporal heterogeneity in evaporation patterns has critical implications for water resource management, agricultural planning, and climate adaptation.

Recommendations include the need to:

1. Incorporate evaporation trends and land-atmosphere coupling metrics into regional hydrological models to improve water balance simulations.
2. Prioritize monitoring and adaptation strategies in regions showing increasing evaporative stress, particularly western and central Tanzania, during dry months.
3. Enhance observational networks and integrate satellite-derived evaporation products to validate reanalysis-based findings and improve spatial resolution.
4. Investigate nonlinear relationships and feedbacks using alternative correlation metrics (Spearman) and explore interactions with vegetation indices and soil moisture datasets.

Future research should explore the impact of land use change and vegetation dynamics on evaporation trends, and assess how projected warming scenarios may alter the balance between energy-limited and moisture-limited evaporation regimes across Tanzania.

### Authors' Contributions

All authors contributed to the study conception and design. M. M. A., J. U., and I. J. J. conceived the idea of the study; I. J. J. and M. M. A. work on the methodology and plot the figures; M. M. A. collected the preliminary data and wrote the manuscript. All authors read and agree to the published version of the manuscript.

## Data Availability statement

The datasets to train and prove the neural network were obtained from Copernicus Climate Change Service (C3S) on the website:

<https://cds.climate.copernicus.eu/datasets>.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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