

Influence of Hydrological Fluxes and Temperature Dynamics on Sub - Saharan Africa Hydro-Climatology

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Abstract: Hydrological fluxes and temperature dynamics are emerging as key drivers of hydro- climatology variability across sub-Saharan Africa. As climate change intensifies, these factors exert growing influence on the frequency, intensity and spatial-temporal distribution of hydro climate extremes such as flood and drought. Understanding their complex interactions is critical for improving predictive capabilities and informing adaptive strategies for improved agricultural production, water resources management, climate risk mitigation and resilience across the region. In this study, hydrological and temperature variables from Global Land Data Assimilation System (GLDAS) were optimized using Principal Component Analysis (PCA) thereafter their Anomalies were computed and generated for spatial trend averages of changes to be visualized and investigated, furthermore Decomposition Analysis Technique integrated with Empirical Orthogonal Function (EOF) was implemented on PCA to unravel the significant influence of hydrological fluxes and temperature on the hydro-climatology variability across the region. Results of the spatial-Temporal distribution of these variabilities were depicted in respective interpret-able maps. Study recommends that the Regional Climate and hydrological monitoring networks should be expanded and modernized and secondly, Promoting the development of a coupled hydrological-climate modeling that can better simulate the interaction between hydrological fluxes, temperature dynamics and extreme events such as flood and drought.

Keywords: Hydrological-fluxes, Temperature-dynamics, GLDAS, Decomposition, Hydro-climatology

I. Introduction

Background to the study

Sub-Saharan Africa is a region characterized by diverse climatic zones ranging from humid equatorial forests to semi-arid Sahelian plains, where the interaction between hydrological processes and climate variables is both complex and region-specific (Nicholson, 2013). Hydrological fluxes (comprising precipitation, evapotranspiration, runoff, and soil moisture dynamics) and temperature significantly influence hydro-climatology by modulating the water cycle and consequently climate system across sub-Saharan Africa (SSA) particularly phenomena such as flood and drought.

In SSA, the water cycle is strongly influenced by the Inter-tropical Convergence Zone (ITCZ), monsoonal circulation patterns, and land-atmosphere feedback mechanisms (Williams *et al.*, 2012). Variations in hydrological fluxes and temperature are known to modulate regional climate extremes such as droughts and floods, which are becoming more frequent under the pressure of anthropological climate change (Taylor *et al.*, 2017). Hence this study which aims at investigating the influence of key hydrological fluxes and temperature on the hydro-climatology of sub-Saharan Africa is with a view to enhancing the knowledge and understanding of future hydro-climatic extreme occurrences in the region.

II. Literature Review

Study Area

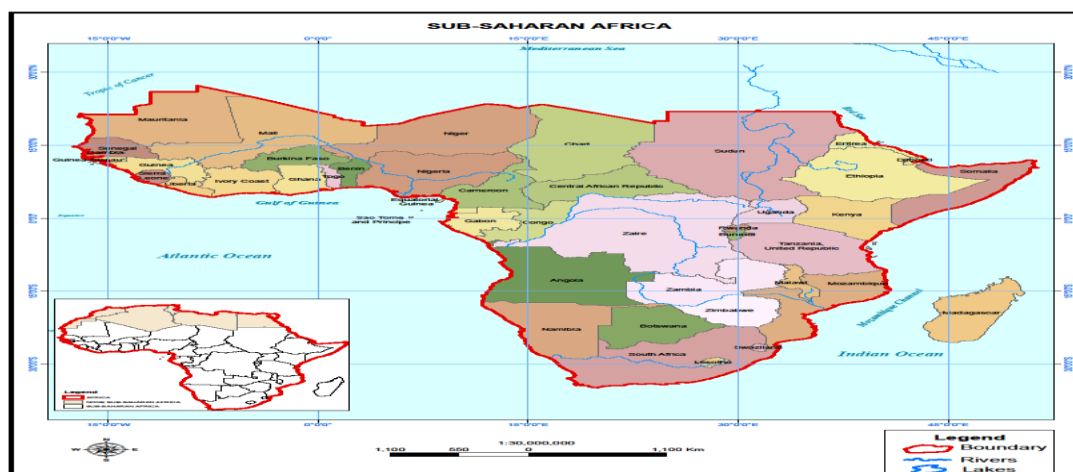


Figure 2.1: Map of the study area: Sub-Saharan Africa

Sub-Saharan Africa which is commonly referred to as black Africa is geographically located between latitude 27° 25'N and 34° 5' S and longitude 51° 28' E and 17° 39' W. Study Area is made up of countries and territories that is lying wholly or partially south of Sahara. The region has been characterized as an endangered geographical area due to negative consequences of climate change (WMO Report, 2021), also inherent dependence on rain sustain agriculture makes the region very susceptible to variations in rainfall and temperature. The Region is inundated with a number of basins and plateaus. Four main rivers systems bisect the region plain and large lakes constitute the rift valley of eastern Africa. There are major geographical features in SSA; these include tropical rainforest, Savannah and the Sahel region. The annual average rainfall over sub-Saharan Africa ranges from 151mm to 3200mm and the annual average temperature range of 15°C to 33.9°C in summer (Nwaerema, *et al.*, 2019; Stockdale, 2017). Separated by seven tropical climate zones including monsoon, rain-forest, middle latitude dry, wet and dry, dry Mediterranean, and humid sub-tropical (Thoithi *et al.*, 2021). Past studies have shown appreciable progress in observing the diverse climatic effect from regional hydrology through applying integrated association between enclosing Atlantic-Ocean, Indian-Oceans and TWS (Kalu *et al* 2022.,; Ndehedehe *et al.*, 2017).

Hydro-Climatology and its Relevance

Defined as the interdisciplinary study of cyclical, multi-directional interactions between the climate system and the hydrologic cycle on a variety of spatial and temporal scales. Hydro-climate, encompassing water availability and its variability due to climate patterns, is critically relevant in sub-Saharan Africa due to the region's reliance on rainfall for agriculture, hydro-power, and overall water resources. Hydro-climate plays a crucial role in sub-Saharan Africa, impacting agriculture, energy production, water resources, ecosystems, and the overall well-being of the population. (Serdeczny *et al*, 2017; Lamptey, 2022).

III. Methodology

Input from Global Land Data Assimilation System (GLDAS):

Land Surface Modeling process utilizing Global Land Data Assimilation System (GLDAS) involves driving numerous offline Land Surface Models (LSMs) with a large amount of land observation-based data, made possible through accurate Geographic Information System. GLDAS operate four Land Surface Models including Noah, Mosaic, Community Land Model (CLM), and Variable Infiltration Capacity (VIC). Regular monthly products are produced as a function of time-based assemblage of 3-hourly production utilized for excellent estimates of land surface condition and variability. Investigating climate variability is made possible by this valuable water and energy storage (Rodell *et al.*, 2009). Currently, these products with revisit time gap of every three hours and geographical resolution of 0.25° and 1° for Mosaic, Noah, CLM, and VIC models are readily available on demand. For this study, the two versions of GLDAS products were spatially interpolated to become homogeneous and were averaged to propagate uncertainties in the datasets used for this study.

Technique of Data Processing and Analysis

The following processing and analysis were implemented in Matlab software environment:

Input Data Optimization Procedures using Principal Component Analysis aimed at data dimensionality reduction, interpretability upgrade and noise removal to enhance the capabilities of discerning underlying pattern and relationship in data analysis,

Computation and Generation of Anomalies (Long term averages) for all hydrological and temperature variables : The exercise was key to avoid inaccuracies commonly associated with the application of absolute data for a very large area in climate data processing. This was executed through subtracting the long term mean of 2004 to 2009 out of monthly data value covering study period as shown in equation 3.1

$$Pr_{(i)} = Pr_{(i)} - \text{mean } Pr(2004:2009) \quad \text{Equation 3.1}$$

Where, **Pr** represents the selected variable.

Spatial Patterns were thereafter generated from the Anomalies, showing estimated trend averages of changes in hydrological and temperature variables and used efficiently for hydro-climate variability trend analysis.

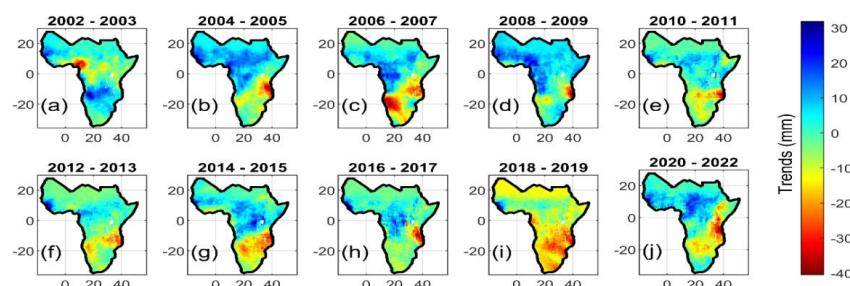


Figure 3.1: Anomalies in precipitation patterns across sub-Saharan Africa (Estimated trend averages of changes)

Figure 3.1 shows the Anomalies (estimated trend averages of changes) in precipitation over sub-Saharan Africa. The bi-annual trend results show that 2018 to 2019 (Figure 3.1(i)) was a relatively dry year for nearly all of sub-Saharan Africa and accounted for driest year in the study period. For the changes in precipitation patterns, strong declines in precipitation was observed in southern Africa, from 2002 to 2003 (Figure 3.1(a)), from 2010 to 2011 (Figure 3.1(e)), from 2012 to 2013 as shown in Figure 3.1(f), from 2014 to 2015 as shown in Figure 3.1(g) and from 2020 to 2022 as shown in Figure 3.1(j) corresponding to depletion of land water storage. Declines in precipitations observed in these regions can be attributed to joint actions of climate changes, atmospheric dynamics, deforestation and other anthropological factors. The action is largely owing to the fact that referred regions usually experience above normal precipitation patterns as evidenced in 2004 to 2005 (Figure 3.1(b)), 2008 to 2009 (Figure 3.1(d)) and 2016 to 2017 (Figure 3.1(h)). Deforestation reduces evapotranspiration rates and disrupt atmospheric moisture dynamics, potentially leading to decreases in precipitation over affected areas. Furthermore, changes in oceanic and atmospheric circulation patterns, including shifts in subtropical jet streams and trade winds, can influence moisture target and precipitation patterns in the deficient regions (Butt *et al.*, 2023). Figure 3.2 depicts Anomalies (estimated trend averages of changes) in evapotranspiration while Figure 3.3 is the Anomalies (estimated trend averages of changes) in runoff pattern across the study region. Climate change is a prominent factor that can exacerbate precipitation anomalies in the study region. While the specific impact of climate changes on precipitation patterns in study region are complex and multifaceted, some studies suggested climate change could steered shifts in precipitation spread and intensity, potentially resulting in more frequent and prolonged dry periods (Smith *et al.*, 2023). These changes pose significant challenges for water resource management, agriculture, and ecosystem resilience in southern Africa.

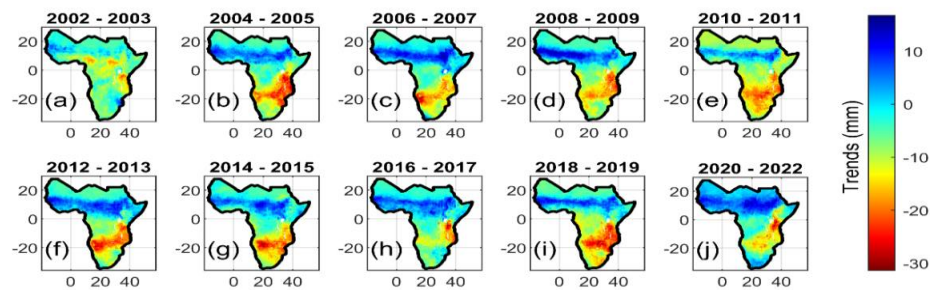


Figure 3.2: Anomalies in evapotranspiration patterns across sub-Saharan Africa (Estimated trend averages of changes)

For Evapotranspiration, strong positive changes were experienced between 2002 and 2003 (Figure 3.2(a)) and 2008 to 2009 (Figure 3.2(d)). This was in agreement with the strong amplitudes of rainfall observed during study period at the time, corresponding to flood trend (Figure 3.1 and 3.2). However, it was further observed that strong declines in 2006 to 2007 (Figure 3.2(c)) and 2010 to 2011 (Figure 3.2(e)) occurred and this trend was noticed throughout the study period. However, the influence of hydrological-fluxes in these observations cannot be rule out considering noticeable alterations in temperature-intensity, long term rainfall patterns and evapotranspiration rates.

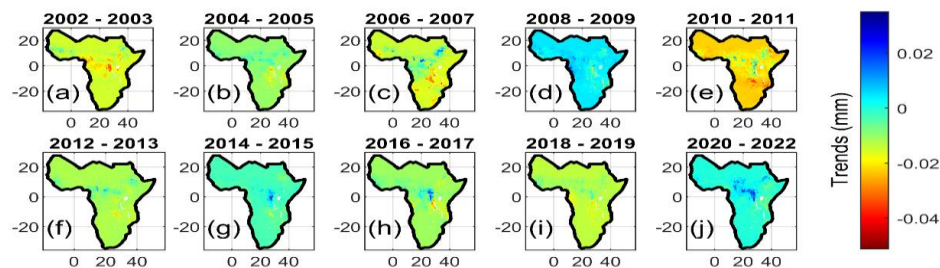


Figure 3.3: Anomalies in runoff patterns across sub-Saharan Africa (estimated trend averages of changes)

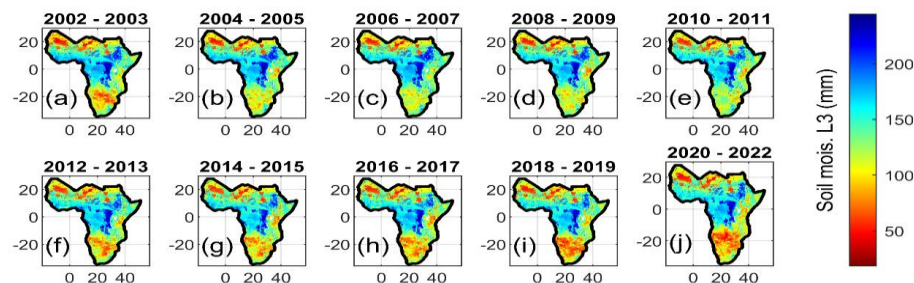


Figure 3.4: Anomalies in soil moisture across sub-Saharan Africa (estimated trend averages of changes)

Consequently, changes in precipitation patterns such as decreased rainfall or shifts in seasonal distributions can reduce soil moisture availability and limit plant transpiration resulting in lower evapotranspiration rates. This is plausible because increase in precipitation leads to increased evapotranspiration and vice versa. These actions were also observed in the simulation of runoff changes, which is a major constituent of the region's hydrological fluxes as presented in Figure 3.3 and whose amplitude was strongest over the Central African region where the Congo Basin exists. Congo basin and other basins in the region exhibits a significant role in replenishing aggregate content of soil, Figure 3.4 shows very strong amplitude of available soil moisture contents over large part of West Africa, the Sahelian region, Central Africa, and most part of South Africa.

Decomposition of Hydrological Fluxes and Temperature Integrated with Empirical Orthogonal Function: To unravel significant of each hydrological and temperature component influencing the climatology of the study region and to understand the impact of the spatial-temporal trend and seasonal signal variability. The Principal Component Analysis (PCA) was used for statistical decomposition method and integrated with Empirical Orthogonal Function (EOF) for the analysis. Figure 3.5 demonstrated how temporal components of input variables are being statistically decomposed into precipitation, evapotranspiration, runoff, soil moisture and Land surface temperatures (LST)

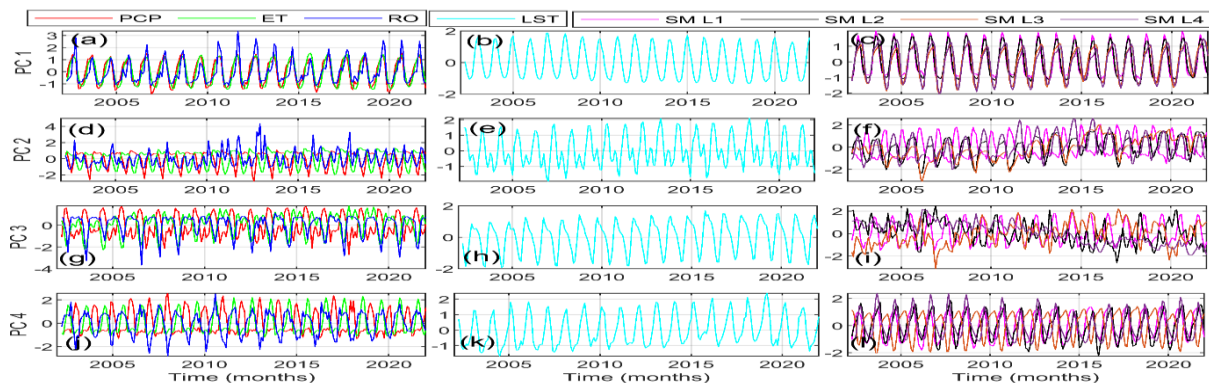


Figure 3.5: PCA decomposition of water budget terms (a),(d),(g),(j), Land Surface Temperature (LST) (b),(e),(h),(k) and soil moisture components (c),(f),(i),(l) after rotation.(Temporal Evolution)

The temporal resolutions of the PCs Figure (3.5) is characterized by Annual hydrological signals for the first PCs depicted as follows:Figure 3.5 (a), (b) and (c) . Inter annual hydrological signals for the second and third PC's depicted as follows: Figure 3.5 (d), (e), (f), (g), (h) and (i)), and finally Intra-annual hydrological signals for the fourth PC's depicted as follows:Figure 3.5 (j), (k) and (l)), It was observed that Western Africa together with Central African regions contributed the most to hydrological signals of sub-Saharan Africa. However, this was anticipated as majority of river basins that contribute greatly to fluctuation in water resources of sub-Saharan Africa are located in that sub-region. This was used in the integration process between PCA – EOF (Empirical Orthogonal Function) for all hydrological fluxes and Land surface temperature and is discussed in what follows for the spatial patterns spread: The 1st independent PC mode before and after rotation, explains 35.24% total variation described yearly precipitation changes across study region in the course of study. Spatial spread of the first PC (Figure 3.7(a)) mode indicated Annual intensity of change to be most positively dominant across Western African and Sahelian sub-region (encompassing Senegal, Niger, Nigeria, and Volta River basin). An alternative negatively dominant spatial pattern is observed over the Central African region towards South Africa. The same trend is observed for the PCs after rotation (Figure 3.7e), however, with less magnitude and spatial spread.

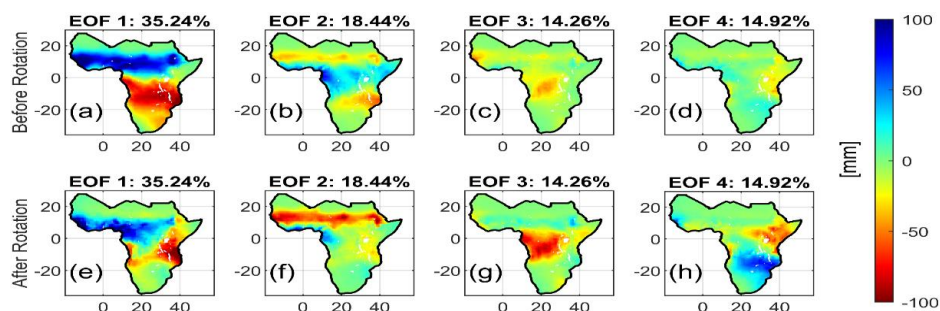


Figure 3.7: PCA decomposition of precipitation changes. Showing spatial patterns of variations

The 2nd PC modes of precipitation trends hold Inter-annual changes which are positively active in wider Western African region. The trend for before and after rotation homogeneously characterizes a net precipitation loss over the highlighted region (Figure 3.7(b), and f). This explains 18.44% total variation over the study region. The 3rd PC mode (Figure 3.7(c)) explains least variation

with 14.26% total variation in study region. The spatial distribution pattern demonstrated intensity of inter-annual variability to be most influential in far West Central African region with a net precipitation loss. This trend is made more prominent after the rotation of the PCs as shown in Figure 3.7(g). The fourth PC (Figure 3.7(d) and(h)) which accounts for all the Intra-annual signals captures 14.92% total variation depicting strong amplitude in southern Africa. This was attributed to a net precipitation gain of the Orange and Okavango basins which drive the TWS signals in the region. However, over East Africa, a net precipitation loss is observed, and this is more prominent after the rotation of the PCs in (Figure 3.7(d)). These four PC modes are statistically significant as they account for the overall fluctuation patterns in the entire study region, they denote signals constituting over 90% total precipitation dynamics in the study region. For example, in the PC decomposition of the Evapotranspiration (ET) fluxes shown in Figure 3.8, PC1 to PC4 accounts for 47.20%, 19.58%, 5.63%, and 17.07% total ET variation in study region. The signals mirror those from the precipitation trends, where the Congo River basins is seen to cause massive and dominant increase in ET while the southern African region witness significant ET losses. For Land surface temperature (Figure 3.10 (a) and (e)), having strong declines about north western part of study region, accounted for 60.20% of total variance. The second, third and fourth PC modes were given as 10.29%, 18.56%, and 6.69%, respectively. Result for soil moisture variability in aggregated layer is presented in Figure 3.11 for PCA decomposition . All soil moisture layers for PCs 1 to 4 is as presented in Table 3.2

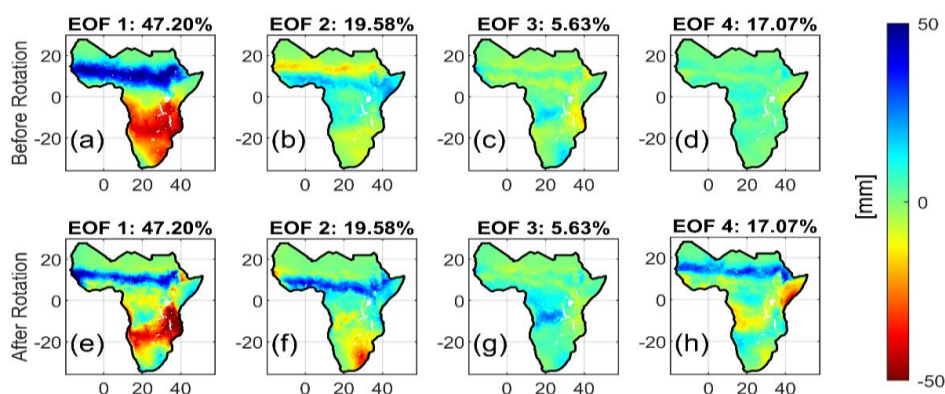


Figure 3.8: PCA decomposition of evapotranspiration changes Showing spatial patterns of variations

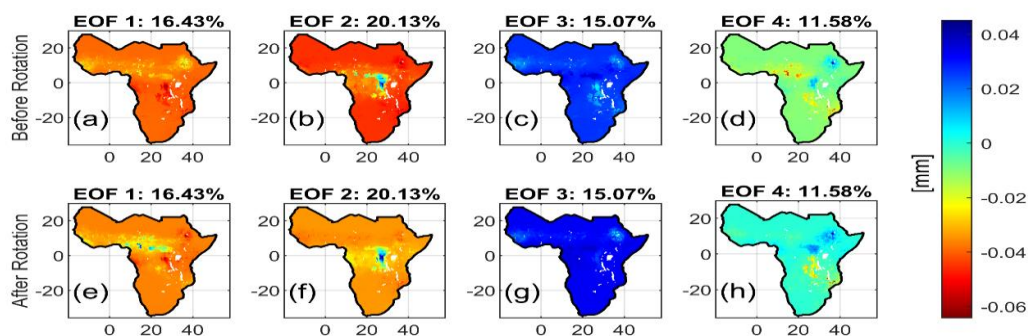


Figure 3.9: PCA decomposition of runoff changes. Showing spatial patterns of variations

Figure 3.9 present runoff variability which accounted for PC1: 16.43%, PC2: 20.13%, PC3:15.07%, PC4: 11.58% in tandem with the other flux variables.

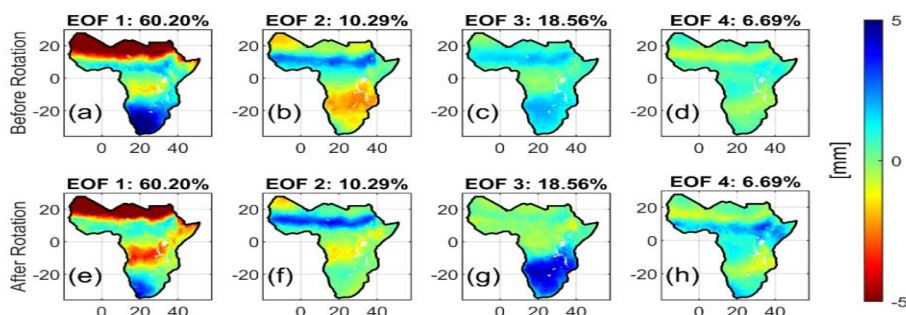


Figure 3.10: PCA decomposition of land surface temperature changes Spread before and after rotation.

Table 3.2: Percentage variance of the four soil moisture layers

PCA - Rotation (%)				
PC's	PC1	PC2	PC3	PC4
Layer 1	28.51	20.85	8.70	30.24
Layer 2	42.46	20.97	4.49	11.30
Layer 3	36.10	10.11	5.54	24.38
Layer 4	31.40	13.19	7.56	24.39

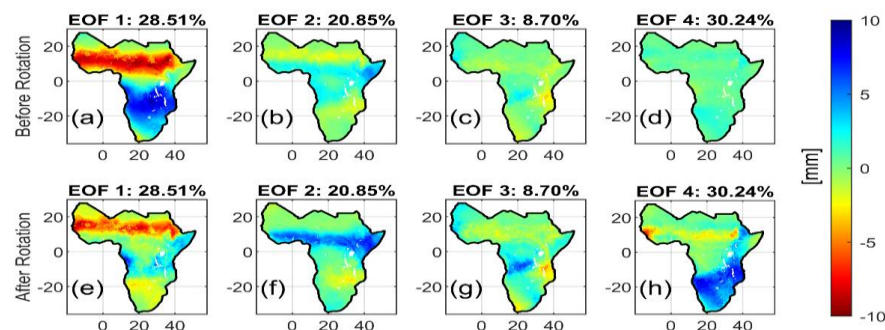


Figure 3.11: PCA decomposition of soil moisture

Limitations and Uncertainties:

Empirical Orthogonal Function (EOF) and Principal Component Analysis (PCA)

EOF and PCA are widely used to extract dominant spatial and temporal pattern from climate dataset. However their application in sub-Saharan Africa (SSA) hydro-climatology faces several limitations and uncertainties as follows:

Linear Assumptions: Both EOF and PCA assume linear relationship between variables, however, hydrological processes in SSA often exhibit non-linear interactions due to Land-Atmosphere feedback, Vegetation cover and land-use changes (Hannachi *et al.*, 2007 and Monahan *et al.*, 2009)

Mode Mixing: EOF are sensitive to domain size and can mix physical modes (e.g , rainfall variability with soil moisture pattern) which obscures interpretation of physical processes (Hannachi *et al.*, 2007)

Orthogonality Constraint: The orthogonality component (Principal Components) may not represent physically independent modes in climate systems especially where the interaction are strong (Monahan *et al.*, 2009)

Sampling bias: In region like SSA where data gaps and limited stations coverage exist EOF result may be bias or unstable especially in noisy or sparse datasets (Hannachi *et al.*, 2007)

Decomposition Methods (Trend, Seasonal and Residual Analysis)

Assumption of Additivity: Standard time series decomposition assume that the observed series can be split into additive or multiplicative components (Trends + Seasonality + Noise). in some cases the interaction may be non-linear and dynamics (Das, *et al.*, 2025)

Temporal Resolution Sensitivity: Decomposition accuracy depends on temporal resolution (monthly, seasonal or annual). High variability in rainfall and temperature dynamics across SSA limits the robustness of seasonal signals (Liebmann *et al.*, 2013)

Climate Shifts: Sudden climatic regime shift such as prolonged drought or extreme flooding may not be well captured by traditional decomposition technique which assume relative stationarity

Global Land Data Assimilation Systems (GLDAS)

GLDAS provides land surface data by integrating satellite observations and numerical models, often used for studying water and energy cycles. however several challenges arise when applying GLDAS to SSA.

Sparse Ground Validation: SSA has limited ground based meteorological and hydro-logical observations resulting in uncertainty in GLDAS model calibration and validation (Rodell *et al.*, 2004).

Temporal Aggregation Effect: Monthly or seasonal averaging can mask extreme short duration events such as flash floods and short-term drought spell (Rodell *et al.*, 2004).

IV. Discussion of Results

Investigation of the Influence of Hydrological Fluxes and Temperature dynamics on the Climatology of sub-Saharan Africa

This exercise is important to understand how hydrological fluxes and temperature influence land water storage dynamics and climate change throughout study period. Analysis showed that precipitation, evapotranspiration, runoff, soil moisture and land surface temperatures were mostly influencing hydro-climatology over Central, Eastern and parts of Southern Africa (Figures 3.5 to 3.11). This is to be expected as these regions are known to have strong anthropological influences and contains major River Basins.

Analysis unravels the drought event of 2018/2019 over some part of southern Africa and drier season's across SSA in 2002. (Figure 3.1), this was influenced by precipitation deficit and increase temperature intensity impacting on evapotranspiration variability (Figures 3.1, 3.2 and 3.10). Below-average rainfall often leads to drought susceptibility across the region, especially over West, Central and East Africa. It was also found that the increase rainfall changes in 2004, 2005, 2008, 2009 and 2016 -2017 (Figure 3.1) had led to incessant flooding events in Central Africa region, West Africa and southern Africa. This finding is corroborated by the result reported in Forootan *et al.*, (2014).

V. Conclusion and Recommendation

The study investigated the influence of hydrological fluxes and temperature on hydro-climatology of sub-Saharan Africa. Data optimization procedures using Principal Component Analysis (PCA) was followed by computation and generation of Anomalies (Long term averages) for all hydrological and temperature variables, the spatial patterns and trend generated from the anomalies was used in the analysis of hydro-climatic variability. Furthermore, decomposition analysis technique integrated with Empirical Orthogonal Function was implemented to unravel significant influence of each hydrological fluxes and temperature variable, the spatial-temporal trend and seasonal signal variability on the regional hydro-climatology was evaluated and presented in respective resultant maps. Based on the results exhibited and visualized in respective maps it is concluded that the actions of hydrological fluxes and temperature effectively influence the variability of hydro-climatology such as flooding and drought across sub-Saharan Africa. The recommendations are summarized as follows: Regional Climate and hydrological monitoring networks should be expanded and modernized and secondly, Promoting the development of a coupled hydrological-climate modeling that can better simulate the interaction between hydrological fluxes, temperature variability and extreme events such as flood and drought.

Region Specific and Actionable Strategies for Improving Monitoring Network and Implementing Coupled Models

Strengthening Hydrological and Meteorological Monitoring Networks

Region Specific Approach: In the Sahel rainfall variability is among the highest globally, yet rain gauge density is critically low (Nicholson, 2013): Expanding Automatic Weather Station (AWS) network is crucial for capturing hydrological fluxes and temperature variability.

In Central Africa, dominated by Congo Basin monitoring, evapotranspiration and soil moisture is essential for understanding land-atmosphere coupling (Pokam *et al.*, 2014).

The Horn of Africa faces recurrent drought, making groundwater Observation stations and temperature logging indispensable (Funk *et al.*, 2015).

Southern Africa especially the Zambezi Basin would benefit from hydro-metric upgrade integrated with Climate-Smart-Agricultural Monitoring

Actionable Strategies: Digitize and harmonize historical datasets via national meteorological and hydrological services (NMHS) (WMO, 2021).

Deploy low-cost AWS and community-based monitoring systems (McMillan *et al.*, 2012).

Implement Mobile Phone-Enabled Logger for near real-time data transfer (Tadesse *et al.*, 2020). Strengthen regional sharing via ACMAD AGRHYMET and SASSCAL Framework

Implementing Coupled Land-Atmosphere Models

Why Coupled Models? Hydrological fluxes and temperature dynamics are deeply interconnected in SSA where soil moisture-precipitation feedbacks can intensify both flood and drought (Seneviratne *et al.*, 2010). Fully coupled models (e.g., WRF-Hydro, RegCM and CLM) simulate these feedbacks more accurately (Giongi *et al.*, 2012).

Model Implementation Strategies: Calibrate models for major SSA basins (e.g., Niger, Nile, Zambezi) using multi-source data assimilation (Rodell *et al.*, 2004). Integrate remote sensing datasets such as GLDAS, CHIRPS, MODIS (Sefield *et al.*, 2006). Use multi-model ensembles to quantify uncertainty (Sylla *et al.*, 2016). Customize systems for seasonal forecasting to improve drought and flood early warning (Kumar *et al.*, 2014).

Capacity Building: Regional hubs such as ICPAC (East Africa) and WASCAL (West Africa) should host cloud-based modeling platforms (Google Earth Engine, ClimateSERVE) for training and operational use. Integration of Indigenous Knowledge and Practices Influencing Hydro-Climatology: Merge community observations (particularly in agricultural practices such as irrigation and land-use) with formal datasets for model validation (Nyong *et al.*, 2007). Engage local knowledge to interpret anomalies in flood and drought patterns particularly in data scarce regions

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