# Spatiotemporal Variability of Rainfall in Connection with Ocean-Atmosphere Coupling in the Lake Tana Basin

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**Abstract:** Spatiotemporal precipitation variability in Lake Tana basin was assessed at four locations using Empirical Orthogonal Function (EOF). This study was mainly aimed to investigate the linkages to large-scale ocean–atmosphere drivers associated with precipitation variability and spatial difference in rainfall statistics in the Lake Tana basin. To identify the driving forces of temporal rainfall variability in the study region with global monthly Sea Level Pressure (SLP) and Sea Surface Temperature (SST), correlation analyses were employed. Further investigations to support the obtained correlations were made using a total of eight climate indices. The result revealed that, precipitation has strong connection to the Indian and Pacific Oceans with respect to the summer season. In view of the directions of relationship, the annual precipitation variability has positive linkages with SLP of Pacific and most parts of Indian Ocean in spring season whereas SLP has negative linkages with Atlantic Ocean and Asian Peninsulas during summer season. In relation to SST, rainfall variability is positively linked to SST at Atlantic and Indian Ocean during summer season and negatively correlated with southern parts of India and Pacific Oceans. This study is spatially important under conditions of data scarcity, which is a typical of the Lake Tana Basin for water management and planning.

**Key words:** Spatiotemporal · Correlation · Coupling · Variability · Precipitation

## INTRODUCTION

Rainfall is a crucial climatic factor for society, agriculture and environment which varies considerably over space and time. Rainfall variability also connects extreme wet and dry events, floods and droughts, which pose threats to the environment and society [1]. A minor change in rainfall intensity or amount imposes a severe challenge on the rural peoples of developing countries like Ethiopia. The main livelihood of Ethiopian people is depends on seasonal rainfall which mostly relies on summer monsoon [2, 3]. In the country, whenever there is a change in rainfall pattern during summer season, especially, due to small or large scale drivers [4], it become

a threat for the agricultural products and goes to food insecurity. Among the dominant local and global driver distance from the ocean, ocean currents, direction of prevailing winds, shape of the land/topography/, distance from the equator, El Nino events and human activities can be listed. The upper Blue Nile, where the Lake Tana Sub basin is found in; is one of the greatest river basins in Ethiopia, highly susceptible for rainfall variability [5, 6]. Though, investigating any linkages to small and large-scale drivers associated with rainfall variability and spatial difference in rainfall statistics in the basin is vital for improving predictions for climate patterns and related hydro-meteorological processes. This is used to enhance agricultural production, decision making and to mitigate

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impacts of extreme departures from normal rainfall [7]. Therefore, the main objective of this study is to understand spatiotemporal variability of rainfall over the Lake Tana Basin in relation to large-scale ocean–atmosphere interactions.

## MATERIALS AND METHODS

**Description of the Study Area:** Lake Tana Basin (Fig. 1; hereafter called the Basin) is located in northwestern Ethiopia (latitude 10.95° and 12.78°N and longitude 36.89° and 38.25°E), shared by three administrative zones of Amhara Region, North Gondar, South Gondar and West Gojjam, with a drainage area of about 15, 000 km². The Basin consist of the third largest lake in Nile Basin which has an elevation of 1786 m.a.s.l. out of more than 40 rivers feeding the Lake, Gilgel-Abay, Reb, Gumara and Magetch contribute more than 93% of the inflow. The only surface outflow is the Blue Nile, which comprises 7% of the Blue Nile flow at the Ethio-Sudanese border [8].

Climate of the Basin is tropical highland monsoon with an air temperature shows large diurnal but small seasonal changes with an annual average of 20°C. The seasonal distribution of rainfall is controlled by the movement of inter-tropical convergence zone (ITCZ) which is northward and southward. The mean annual rainfall of the Basin varies from 1, 200 to 1, 600 mm [9, 10]

and, the mean actual evapotranspiration of the Basin is 773mm. Generally, the southern part of the Basin is wetter than the western and the northern parts.

**Data Collection:** The observed daily rainfall data from 1985 to 2015 for four (Gondar, Debre Tabor, Bahir Dar and Dangila) independent weather stations were obtained from the Ethiopian National Meteorological Agency (NMA) and eight climate indices from global sites [10, 11]. Based on quality, long range data and representation of various climate zones in the basin, the stations were selected [12]. Some station selection criteria justify that, the study of historical climate variability and change should utilize reliable data that are free of artificial trends or changes. Artifacts of measurement caused by changes in observation practice, equipment, site exposure and location can lead to misleading results when used in trend analyses [9]. To enhance the acceptability of the research findings, long-term rainfall series of length not less than 31 years and missing data points not more than 10% were used. And also climate data indices from Sea Surface Temperature (SST; including Atlantic Multi-Decadal Oscillation Index (AMO), Pacific Decadal Oscillation Index (PDO), Indian Ocean Dipole (IOD) and Area averaged Niño SST Indices) and Sea Level Pressure (SLP; including North Pacific Index (NPI) and Southern Oscillation Index (SOI)) [11] were employed.
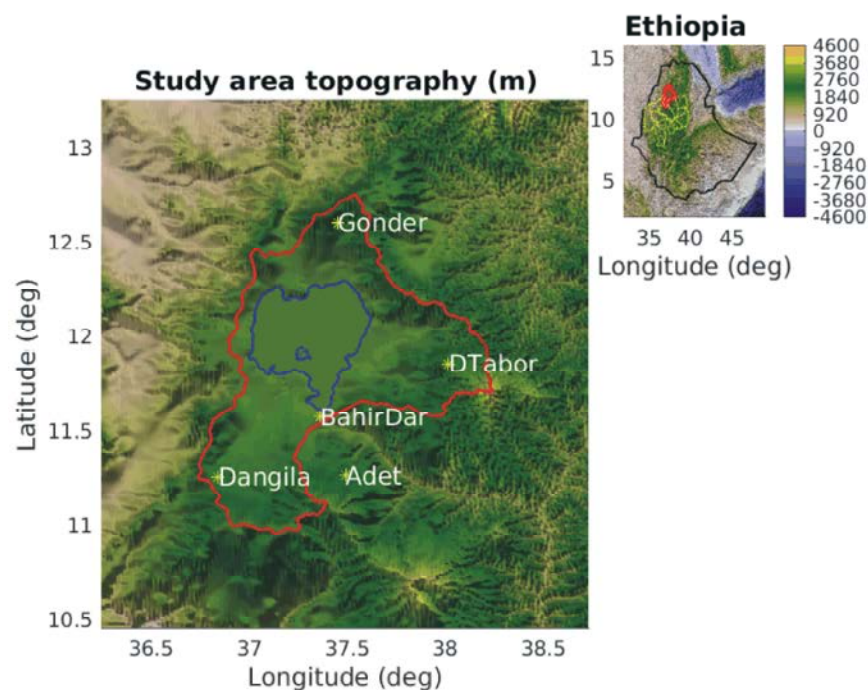


Fig. 1: The location of Tana Basin (red color) out side Lake Tana (blue color).

**Data Analysis with Empirical Orthogonal Functions (EOF):** The data were analyzed using Empirical Orthogonal Function (EOF) Methods [13]. EOF has a potential of yielding substantial insights into both the spatial and temporal variations exhibited by the field or fields being analyzed and new interpretations of the original data $X$ can be suggested by the nature of the linear combinations that are most effective in compressing those data. The EOF based method applies principal component analysis to a group of rainfall time series data to extract coherent variations that are dominant. It entails computation of eigenvectors and eigenvalues of a covariance or correlation matrix which was obtain from selected groups of original rainfall time series data's. There were studies on rainfall of the Nile Basin that were used this method, [e.g., 5, 14] and they found the technique is satisfactory over a wide range of data structures. Lately, however, EOF analysis has been used to extract individual modes of variability such as Pacific Oscillation (PO), Arctic Oscillations (AO) and Indian Ocean [3]. It's mainly based on using spatial and temporal correlations.

To do so, from the measurements of variable at locations $x_1, x_2, x_3 \ldots \ldots \ldots x_p$ taken at time $t_1, t_2, t_3, \ldots \ldots \ldots t_n$ we tried to store in a matrix X as n maps each being p points long.

$$X = \begin{bmatrix} x_{11} & x_{12} & .. & . & x_{1p} \\ x_{21} & . & & \ddots & . & . & . \\ . & . & & \ddots & . & . \\ . & & & & . \\ . & & & & . \\ x_{n1} & & & & x_{np} \end{bmatrix}$$

Then, using anomaly data matrix, covariance matrix can be defined using equation (1);

$$S = \frac{1}{n-1} X'^T X' \tag{1}$$

where $X'$ id anomalie value $X^T$ is projection of the anomalies $\wedge$n is sample Which contains the covariance between any pair of grid points and then to find the linear combination of all the variables that explains maximum variances. That is to find a direction, $a = (a_1, \ldots , a_p)^T$ such that $X'a$ has maximum variability. The variance of the (centered) time series $X'a$ was calculated using,

$$var\left(X'a\right) = \frac{1}{n-1}\left(X'a\right)^2 = \frac{1}{n-1}\left(X'a\right)^T\left(X'a\right) = a^T S a \tag{2}$$

And then, by considering unitary vector of $a$, simple eigen value problem (EVP):

$$\Sigma a = \lambda a \tag{3}$$

where $\lambda$ is eigenvalue and $a$ eigenvector [13]. For each eigenvalue $\lambda_i$ chosen we find the corresponding eigenvector $a_i$. These eigenvectors are the EOFs we were looking for. In what follows we always assume that the eigenvectors are ordered according to the size of the eigenvalues. Thus, EOF1, is the eigenvector associated with the biggest eigenvalue and the one associated the second biggest eigenvalue is EOF2, etc. Each eigenvalue $\lambda_i$, gives a measure of the fraction of the total variance in $\Sigma$ explained by the mode.

With this mathematical description, differences between rainfall intensity at the selected stations were assessed in terms of patterns of their long-term monthly mean and temporal variability [3]. For each month in the entire series, an average of the rainfall was calculated. By repeating the procedure for all months, indication of which months fall in the wet or dry seasons was obtained. The temporal pattern of anomaly in the rainfall of the different selected stations was also compared.

Lastly, possible linkage of rainfall variability into large scale ocean–atmosphere interactions were pursued using correlation analysis [9]. This was important to locate parts of the world over which the driving influence for temporal variability in rainfall over the basin. The correlation pattern for time series Principal Component (PC) for Lake Tana rainfall in both spring and summer seasons using SLP and SST as driving factors were evaluated.

## RESULTS AND DISCUSSION

Fig. 2 shows rainfall intensity for 31-year mean monthly and temporal variability for the selected stations. The rainfall pattern at all stations exhibit mono-modal with the main wet season occur during June-to-September which is in agreement to [11] findings. According to [3], large variations in long term mean rainfall statistics across the Upper Blue Nile were due to its great latitudinal and longitudinal extents [15], but in our study the complex topography and altitude is also the dominant driving factor for having such statistics.
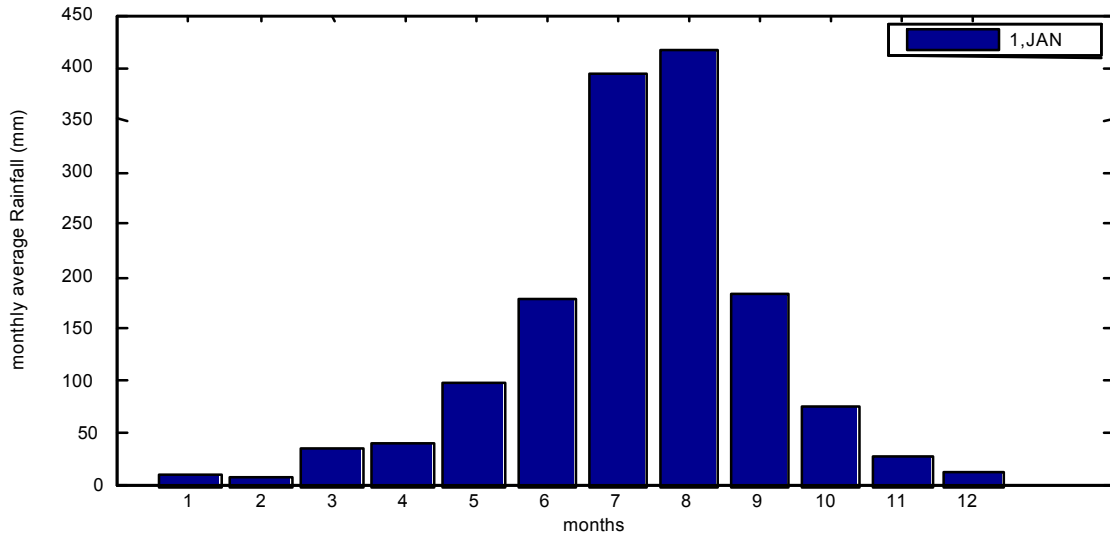
Fig. 2: Rainfall intensity for 31-year monthly mean and temporal variability
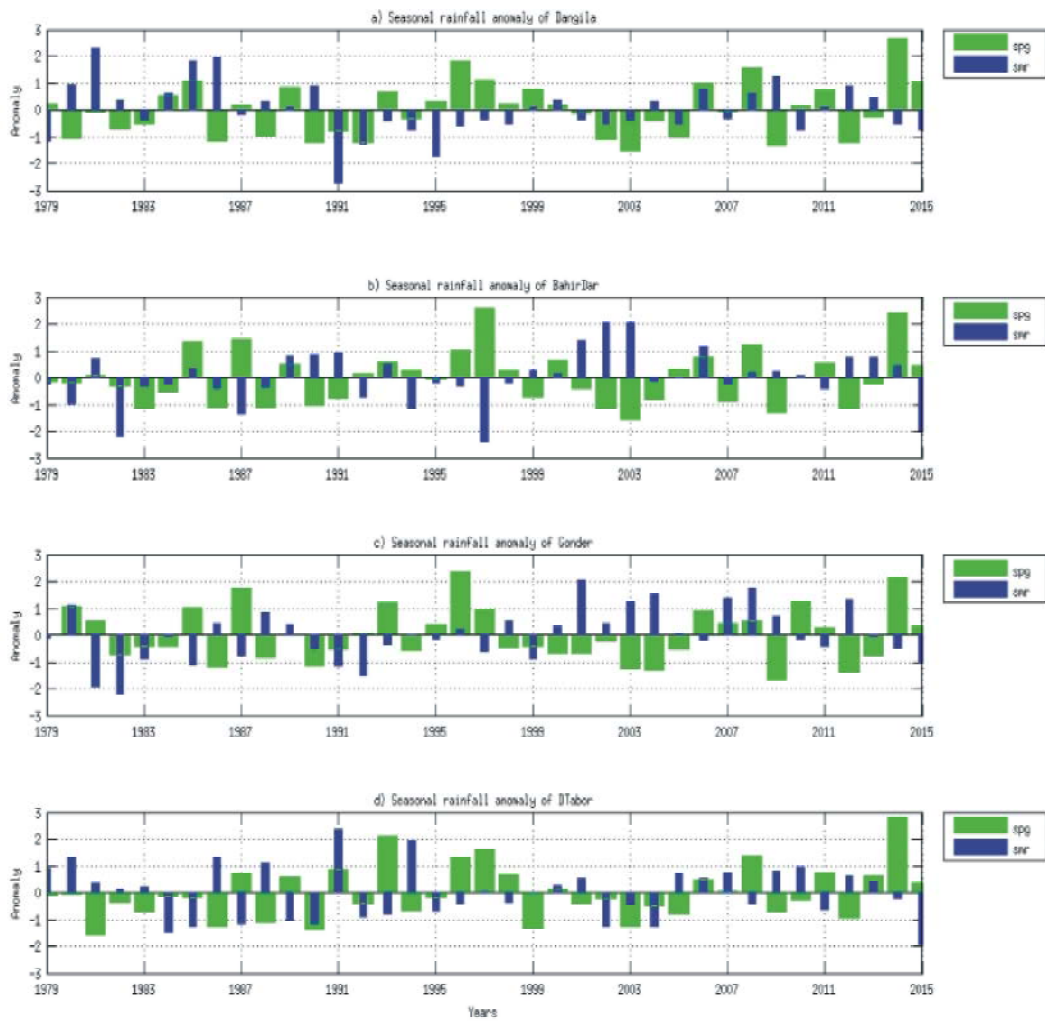


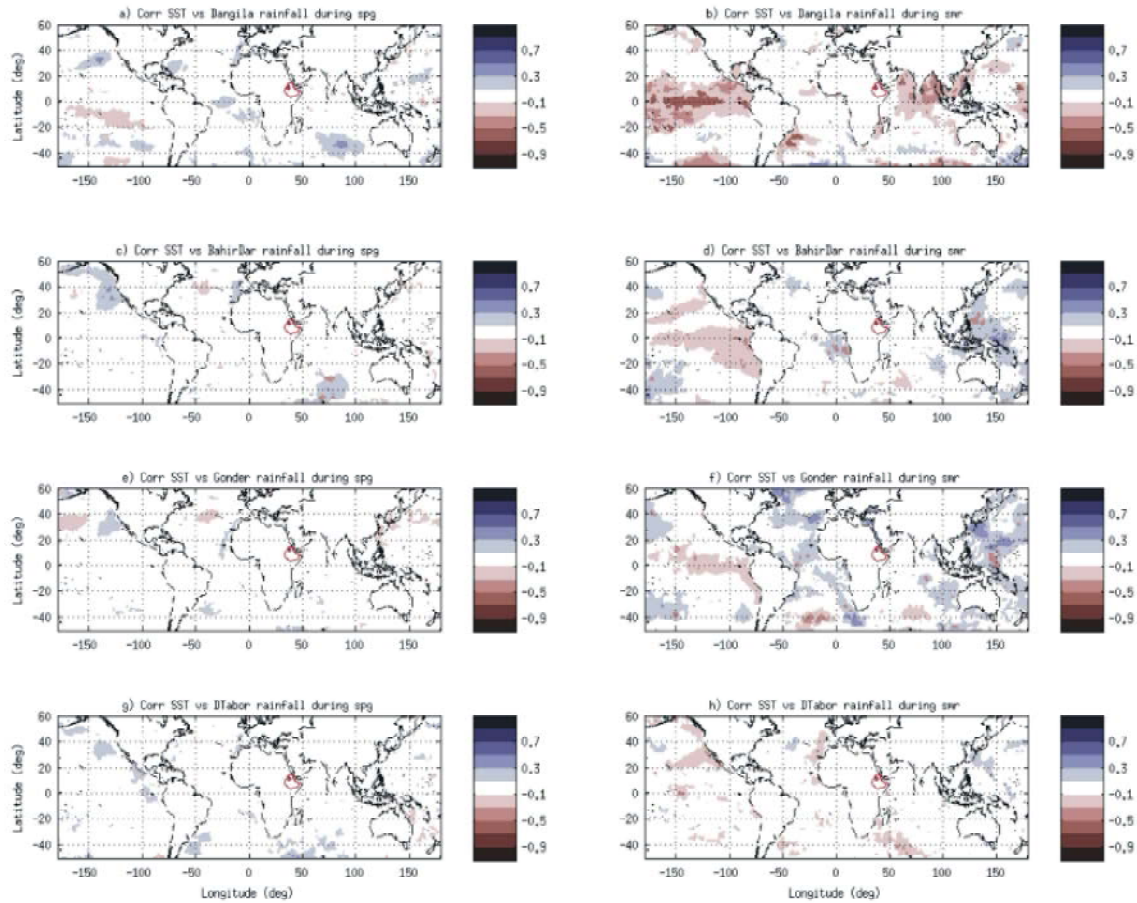Fig. 3: Temporal variability of annual rainfall anomalies at each station

Fig. 4: Correlation pattern for time series PC of EOF1 for Lake Tana Basin rainfall in both spring and summer season

Table 1: Correlation between climate indices from HadSST2 and HadSPL2 with rainfall anomalies of        selected stations.

| | Climate indices and/or time series | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NAO | NPI | PDO | SOI | IOD | AMO | Nino 1+2 | Nino 3 | Nino 3.4 | Nino 4 |
| Gondar | -0.364* | 0.217 | -0.030 | 0.292 | 0.113 | -0.343 | 0.217 | -0.260 | -0.294 | -0.143 |
| D/Tabor | -0.121 | -0.074 | -0.212 | 0.151 | 0.504* | -0.182 | 0.336 | 0.112 | -0.125 | -0.117 |
| B/Dar | -0.014 | -0.155 | -0.137 | 0.183 | -0.207 | -0.300 | -0.039 | -0.222 | -0.256 | 0.115 |
| Dangila | 0.076 | -0.193 | -0.138 | 0.288 | 0.062 | -0.242 | 0.421* | -0.085 | -0.165 | -0.009 |

**Spatial Difference in Rainfall Statistics:** Fig. 3 illustrates temporal variability of annual rainfall anomalies at the selected stations for spring and summer seasons. The spatial rainfall anomalies loaded over all stations as negatively and positively are described for both spring and summer seasons. The spatial differences in the EOF factor loadings indicate how the influence from the large-scale Ocean-Atmosphere interactions on the rainfall variability may slightly vary in strength from one part of the station to another as Zeleke [16] studied. For instance, the migration of the Intertropical Convergence Zone (ITCZ) leads to latitudinal difference in the rainfall [17]. Furthermore, the influence from the

difference in the microclimate can also lead to the spatial variation of rainfall across the stations. Other factors which could lead to heterogeneity in rainfall across the study area include the influences from regional features, for example, topography and water bodies and so forth [15]. There are similarities in the co-occurrences of the High Oscillation (in 1982, 1990, 1991, 2006, 2008 & 2014) and Low Oscillations (in 1985, 2000 & 2001) of rainfall variability in spring and summer seasons for most of the stations. Strong spatial differences of these rainfall statistics could indicate difference in possible driving forces of temporal variability across the study area.
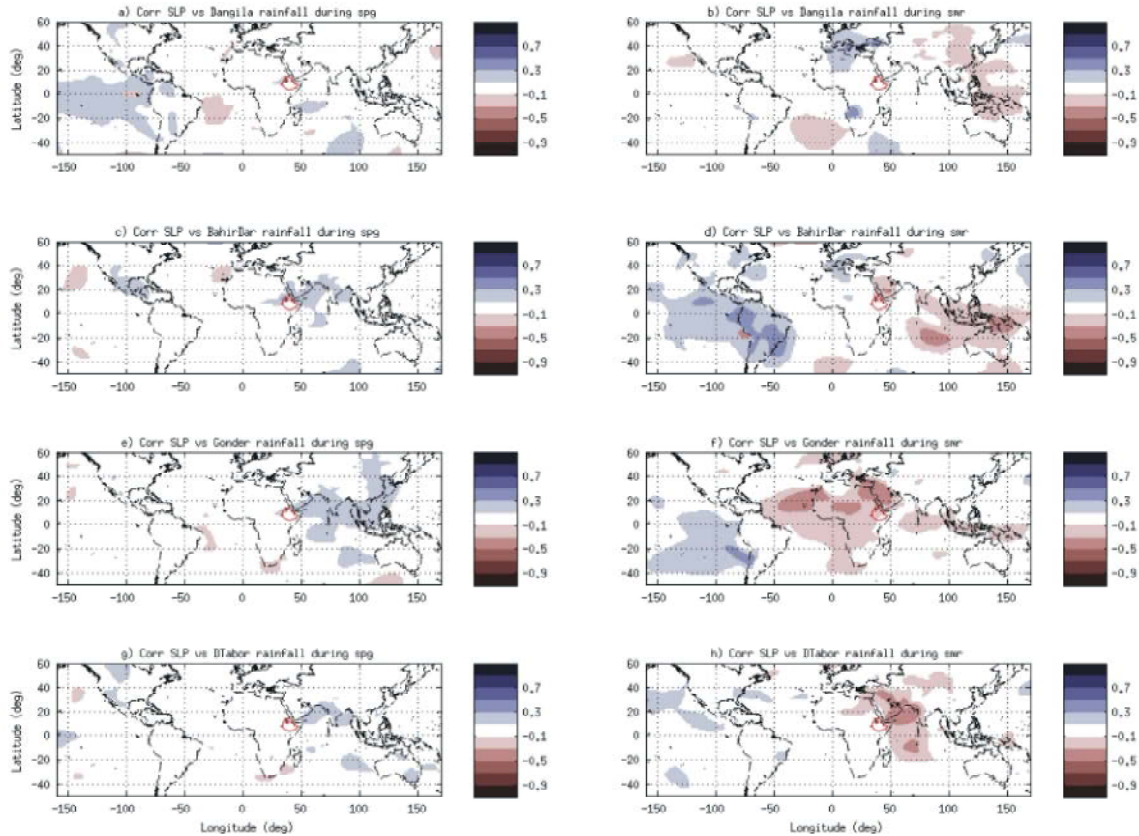
Fig. 5: Correlation Pattern for time series PC of EOF1 for SLP with Lake Tana Basin rainfall during spring and summer seasons

**Identification of Drivers for the Rainfall Variability:** Fig. 4 shows locations over which possible influences for temporal variability of rainfall in the Lake Tana Basin originates as determined using HadSST1.1 data. For the spatial coherence of the driving force of rainfall variability [17], correlation analysis for Lake Tana is obtained over the whole statistical period for each stations.

The significant correlation pattern between SST and the first dominant PC's of EOF1 shows northwest Pacific, southwest Pacific, central Atlantic and Mascarene high are associated positively, whereas central Pacific, northern Atlantic and central India Oceans are associated negatively during spring season. Similarly during summer season, significant correlations between SST and the first dominant PC's of EOF1 shows tropical pacific, central Atlantic and tropical India ocean associated negatively, whereas north & southern Pacific, Asia Gulf (Fig. 4d & 4f), eastern India and central Atlantic (except Fig. 4b & 4h) are associated positively. So, those all regions with positive correlations are responsible for producing short term rainfall over the Lake. The highest negative anomaly over tropical pacific in summer season, significantly affect

rainfall producing mechanisms in the study region. The negative/positive anomaly over Asian Gulf and east parts of Indian Ocean affect low-level circulations and induce contemporary rainfall scarcity and rich over the basin respectively.

Fig. 5 shows locations over which possible influences for temporal variability of rainfall in the basin originates as determined using HadleySLP2 data. During spring season, the correlation between precipitation in the Lake Tana basin and concurrent SLP anomalies over central Pacific (Fig. 5a), west central Pacific (Fig. 5g), gulf of Mexico & Caribbean sea (Fig. 5c & 5a), Asia gulf (except Fig. 5a) and central India oceans are associated positively, whereas north & south Pacific, Atlantic and farther north & south India ocean are associated negatively. Similarly, during summer season the correlation between in the Lake Tana basin on concurrent SLP anomalies over Pacific (except Fig. 5d, 5f & 5h), Atlantic, Asia Gulf and Indian oceans are associated negatively, whereas central Pacific (Fig. 5d), southern Pacific (Fig. 5f), northern Pacific (Fig. 5h), southwest India, regions of Amazon (Fig. 5d) and Mediterranean sea

(Fig. 5b & 5d) are associated positively. Low SLP in the Arabian Peninsula is associated with enhanced moisture transport from west parts of all sources [18, 19], whereas the reverse is true. Therefore, from this study we can infer that the positive or negative seasonal SST and SLP anomaly of all oceans are strongly linked with Lake Tana Basin climate in both spring and summer seasons via large scale circulations.

In addition to the above discussion, the possible linkage of rainfall variability to large scale ocean–atmosphere interactions is fully understood using correlations between climate indices and stations rainfall. This was enabling us to locate parts of the world over which the driving influence for temporal variability in rainfall over the basin [11]. Hence, Table 1 shows that positive influence for anomaly rainfall variability in the region originates from Indian Ocean Dipole, Southern Oscillation Index and Nino regions mainly.

For all stations, the correlation sign is positive with Southern Oscillation index and Indian Oceanic Index, except B/Dar. On the other hand, the correlation sign with Northern Atlantic Oscillation Index (except Dangila) Pacific Decadal Oscillations and Atlantic Multi-Decadal Oscillations were negative. Both the negative and positive correlations can have significant impact on rainfall variability of the Basin. Which were enhanced due to the oceanic pattern in warm and cool phase, agree with Jury's [20] study. And it also shows that significant positive driving forces originate from Indian oceans while negative driving forces were originated from Atlantic Ocean.

## CONCLUSION AND RECOMMENDATIONS

This study examined the association of seasonal and annual variability of rainfall over the Lake Tana Basin Using Empirical Orthogonal Function (EOF) method of global drivers SST, SLP and eight climate indices. We have found heterogeneity in rainfall distribution across the basin due to those global drivers. The co-occurrences of rainfall oscillations as high and low for a specific periods in 1982, 1990, 1991, 2006, 2008 &2014 and in 1985, 2000 & 2001 were explained respectively.

In spring season, the rainfall variability is positively associated to SLP at the Pacific and most of Indian Ocean but negatively associated to Atlantic Ocean. Generally, considering the entire Lake Tana Basin, EOF reveals that, the rainfall was found significantly correlated to those of SLP and SST over Atlantic, Indian and Pacific oceans. Apart from seeking links to large-scale atmosphere –ocean interactions, other causes of rainfall variability should be investigated, like influence of regional features such as topography, water bodies, or transition in land cover and/or use.

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