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Use of Wavelet Transform to Analyse Observed Precipitation at Bukoba, Tanzania to Recognize Impacts to Hydrological Response in Lake Victoria Basin

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Abstract: This research exploited seventy years of daily precipitation data from Bukoba, Tanzania to understand precipitation variability and change important for water resource management. Morlet Wavelet Transform was applied to discriminate the distinct time-frequency rainfall variability in the 92 days long MAM ((March and May)) and OND (October to December) primary rainfall seasons for intraseasonal characteristics over the periods 1931-1960, 1961-1990 and 1971-2000. The time-frequency analysis yielded wavelets outlining the intraseasonal nature of sporadic wet and dry spells in each epoch. The characters of the spells designate changing distribution, intensity and frequency of occurrence across the three epochs. The profile of the erratic wet and dry spells speculates shift change and fading of high frequency, quasi biweekly and low frequency oscillations. The oscillations which act together across atmosphere, oceans and land surfaces through convective processes are likely to influence seasonal precipitation anomalies at intraseasonal scale. The variability of the observed daily precipitation is thus hypothesized to be linked to the fading oscillations in the later two epochs particularly during the main MAM season and thus the declining precipitation in the study domain. Global increased atmospheric carbon dioxide concentration could catalyze this process.

Key words: Wavelets, daily precipitation, hydrologic response across Lake Victoria.

1. Introduction

A warming world is expected to continue to alter the occurrence and magnitude of climate extremes including droughts, heavy precipitation and floods, as well as the geographic distribution of precipitation [1]. Such changes are highly correlated to an acceleration of the hydrological cycle and circulation changes and directly impacting atmospheric water vapor amounts and rainfall intensity. Availability of high frequency datasets including those at daily timescales and use of new techniques of data transformation and assimilation are gradually becoming important to properly characterize challenges and opportunities in water cycle research. Previous studies including Ref. [2-5] have suggested that interannual variability of the oceanic stratification could modulate the SST signature of the MJO (Madden Jullien Oscillation) and may be both high and low frequency oscillations associated with MJO itself. Santos, C. A. G. et al. [6] used wavelet transform using rainfall time series for studies concerning soil erosion and land degradation for runoff-erosion simulations.

While estimating rainfall using a water balance model from Lake Victoria, Yin and Nicholson [7] have demonstrated that LVB (Lake Victoria Basin) which is mainly atmosphere controlled is an important indicator of environmental and climatic change on long time scales and indeed an indicator of climatic change. On the other hand, Awange et al. [8] suggested that Lake Victoria water levels have varied drastically both on an annual and a monthly basis due to a combination of meteorological and water management factors since the 1950s. It has also been shown by Ref. [9] that Lake Victoria generates its own climate (rainfall) through precipitation–evaporation–precipitation recycling boosted by large-scale moisture transported via the

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prevailing easterly trades.

This investigation used wavelet analysis to examine the time-frequency domain approach to show how the recurring characteristics of seasonal rainfall at intraseasonal scales in three thirty year period have evolved during the primary precipitation seasons in LVB. The study is also expected to recognize likely characters to the hydrological cycle during the period in the respective basin.

2. Study Area, Data and Method

2.1 Study Area

Lake Victoria is the largest lake in Africa and the second largest in the world. The lake is located between latitudes 0°20’N–3°S and longitudes 31°40’E–34°53’E (Fig. 1). The lake basin area is about 193,000 square kilometers and the lake surface covers an area of about 68,800 square kilometers or 35% of the basin. The lake surface is shared between Kenya (6%), Uganda (43%) and Tanzania (51%) while its basin includes parts of Burundi and Rwanda. Precipitation profile over Lake Victoria is bimodal in nature and varies significantly from its eastern, western and southern parts [14] consistent with findings by Ref. [9]. The eastern and southern parts of the lake basin receive annual average precipitation of between 500 and 750 mm and 750 to 1,100 mm respectively, while the western part around Bukoba, receives annual average rainfall of over 2,000 mm as provided in Ref. [12]. Two main precipitation seasons associated with the migration of the ITCZ (Inter Tropical Convergence Zone) about the equator are distinguished around Lake Victoria basin. The long rains occur between MAM (March and May) as shown by Ref. [10]. On the other hand, the short rains prevail between OND (October and December) as outlined by Ref. [11]. ENSO (El Niño–Southern Oscillation) and the Indian Ocean Dipole have been demonstrated to be of much influence to the OND rainfall seasons as also shown by Refs. [11, 12] among many. The two seasons common over Lake Victoria basin are also typical over the northern coast bounded approximately by latitudes (4-8)° S and longitudes (38.5-41)° E as well as regions around Mount Kilimanjaro. Mt Kilimanjaro is the tallest freestanding mountain in tropical Africa.

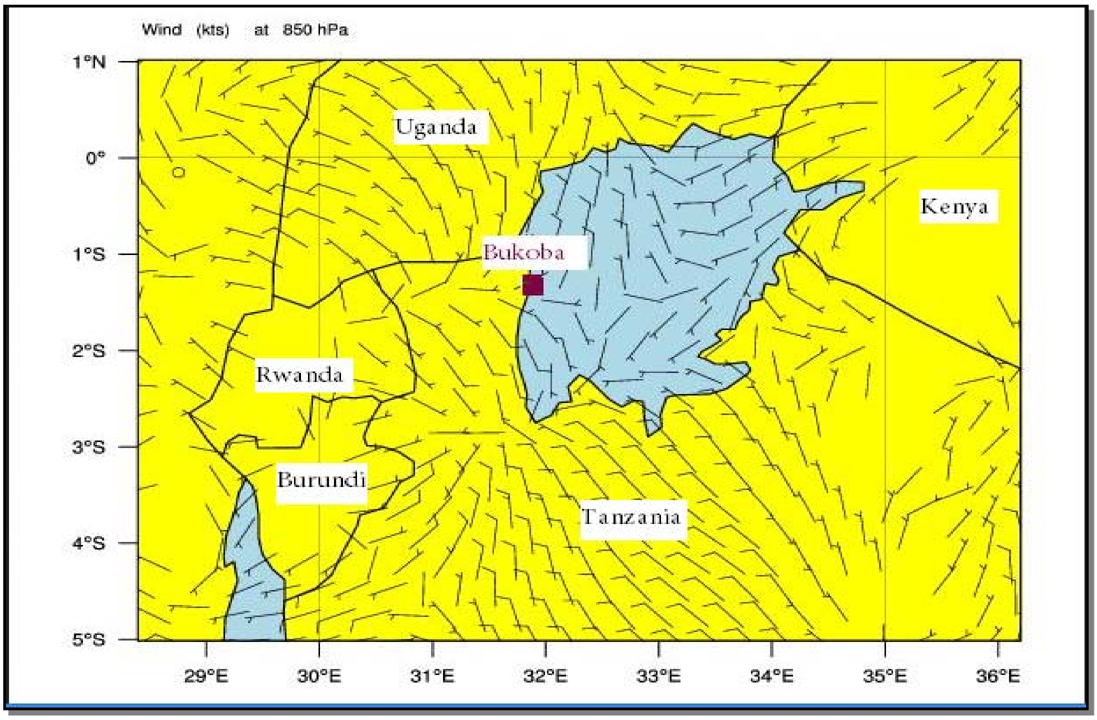

Fig. 1 Location of Bukoba rain gauge over north west of Lake Victoria in Tanzania.

2.2 Data

Seventy years of good quality daily rainfall data from Bukoba meteorological station constituting the wettest location in Lake Victoria (Fig. 1) was used in the research.

2.3 Method

Wavelet transform delineated by Ref. [13] was engaged. Wavelet analysis has advantage over other methods since it is able to identify temporal variability in the periodic nature of the time series as shown by Refs. [6, 15, 16]. While spectral analysis reduces information to ensemble averages, wavelet analysis technique categorizes the information in terms of time—frequency modes, decomposing the signals into localized oscillations and achievable through isolating short processes embedded in highly structured harmonic phenomena, analyze the progression of time signals or track the characteristics of an event or feature over a wide range of scales. Expected oscillations tend to dominate in bandwidths with periods of between 3 and 7 days, 10 and 20 days and beyond 20 days, which describe mode of intraseasonal precipitation variability. The less than 10 day, about 15 days and more than 20 day are respectively likely to be linked to synoptic scale disturbances, quasi-biweekly period westwards moving disturbances in south west Indian Ocean as suggested by Ref. [17, 18, 20, 21] and Madden Julian oscillation as recommended by Ref. [19] and many others. Method entailed several steps. First step was to satisfy the basic requirement for a time series X_n with equal time spacing δ_t and $n = 0,1,..., N-1$. This was comprehended as data used was available on daily timescale whereby N is 92 (length of time series between October 1 to December 31). From this match X_n was admissible to a wavelet function $\psi_0(\eta)$ with non-dimensional time parameter η with zero mean localized in both time and frequency space as required by the Morlet wavelet:

$$\psi_0(\eta) = \pi^{0.25} e^{i\omega_0\eta} e^{-\eta^2/2} \qquad (1)$$

where ω_0 is the non-dimensional frequency.

Second step was to define scale variable s, an integer that scales the wavelet function to generate wavelets. The scale index S indicates the wavelet's width. The wavelet functions are rescaled or dilated by powers of two and translated by integers. The scaled translated version of $\psi_0(\eta)$ becomes

$$W_n(s) = \sum_{n}^{N-1} X_{n'} \psi^* \left[\left(n' - n \right) \delta_t / s \right] \qquad (2)$$

where, $(*)$ and S indicate complex conjugate and scale respectively. Since climatic time series are categorized as non-orthogonal in wavelet analyses, the scales S_j are written in fractional powers of two such that

$$s_j = s_0 2^{j\delta j} \qquad (3)$$

for $j = 0,1,2,..., J$ where, $s_0 = 2\delta_t$ the smallest resolvable scale and $j = \delta j^{-1} \log_2 \left(N\delta_t / s_0 \right)$ which determines the largest scale. By varying the wavelet scale S and translating along the localized time index *n* a picture showing the way amplitude varies with time against scale is constructed. The wavelet transform $W_n(s)$ was run 92 times (N =92) for each scale in a Fourier space using a DFT (Discrete Fourier Transform). Convolution in the time domain was also specified to obtain the wavelet coefficients. A convolution in the time domain is a multiplication in the frequency domain, which zooms the signal. The inverse Fourier transform of the product $W_n(s)$ was thus computed from the relation:

$$W_n(s) = \sum_{k=0}^{N-1} X_k \psi^* (s\omega_k) e^{i\omega kn\,\delta t} \qquad (4)$$

where, the angular frequency defined as $\omega_k = \left[-2\pi k / N\delta_t \; fork < \frac{N}{2} \right]$ and $\omega_k = \left[-2\pi k / N\delta_t \; fork > \frac{N}{2} \right]$

The coefficients act as filters. The filters or coefficients are placed in a transformation matrix, which is applied to a raw data vector. The coefficients are ordered using two dominant patterns, one that works as a smoothing filter or like a moving average and one pattern that works to bring out the data's detail information. The wavelet coefficients are arranged so that odd rows contain an ordering of wavelet coefficients that act as the smoothing filter, and the even rows contain an ordering of wavelet coefficient with different signs that act to bring out the data's detail. The matrix was first applied to the original, full-length vector. Then the vector was smoothed and decimated by half and the matrix applied again. Then the smoothed, halved vector was smoothed and halved again and the matrix applied repeatedly until each matrix application brought out a higher resolution of the data while at the same time smoothing the remaining data. To maintain that the wavelet transforms at each scale (k) are directly comparable to each other and to the transforms of other time series, the wavelet function at each scale was normalized to ensure unit energy. The so obtained Morlet wavelets were identified by varying colors representing various concentrations of power. Concentration of power is marked by red to maroon colors and extreme reduction in power by blue to dark blue to correspond to wet and dry spells respectively.

3. Results

Morlet wavelets tool has demonstrated usefulness in extracting information from the time series with frequency-time decomposition as shown in Figs. 2-7. Obtained information included temporal distribution of alternating wet and dry spells across the 92 days of both MAM and OND seasons for the three epochs. The spells are observed to dominate in bandwidths with periods of between 3 and 7 days, 10 and 20 days and beyond 20 days, which describe mode of intraseasonal precipitation variability. The transform also indicated shift of band widths marked by changing concentration of power from the first to second and eventually the third epoch marked within the season and looked upon as high natural variability on different time scales. The shifts, which were noted, mainly from quasi biweekly to longer periods or lower frequencies were imminent particularly in MAM precipitation season as shown across Figs. 2-4. The shifts in the mean state of the observed precipitation across the three epochs are likely due to change in the changed climatic dynamics that influence precipitation. Another observation worth pointing out includes the reduced concentration of power in the intraseasonal distribution of wet and dry spells in the same season. Reduced concentration of

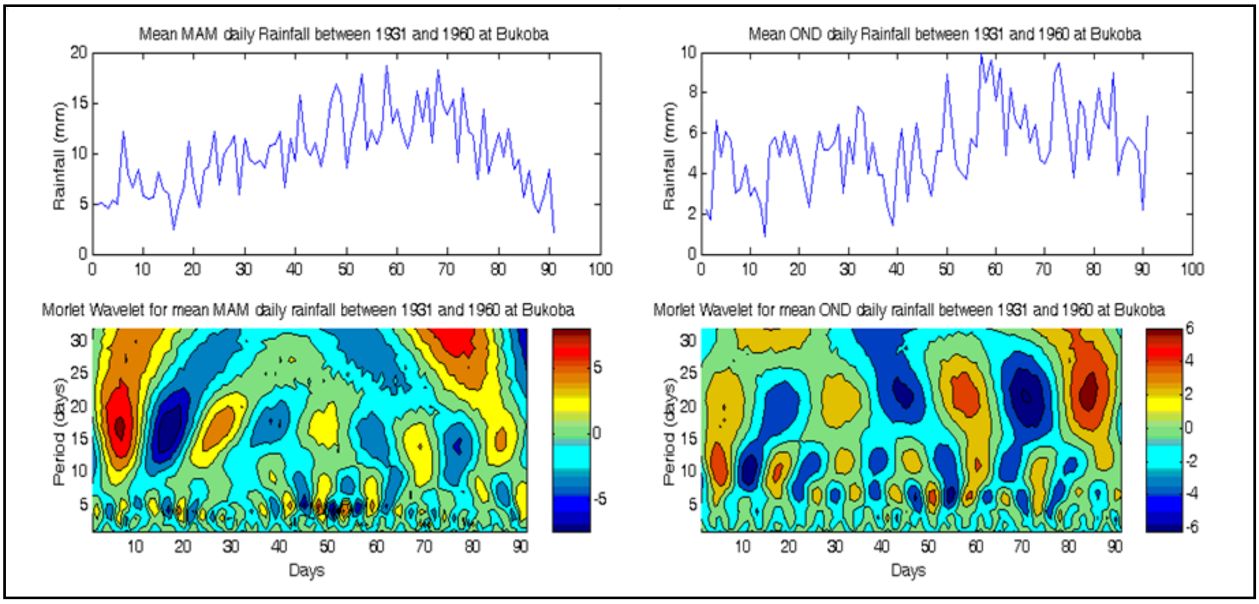

Fig. 2 Mean MAM and OND precipitation season between 1931 and 1960 at Bukoba.

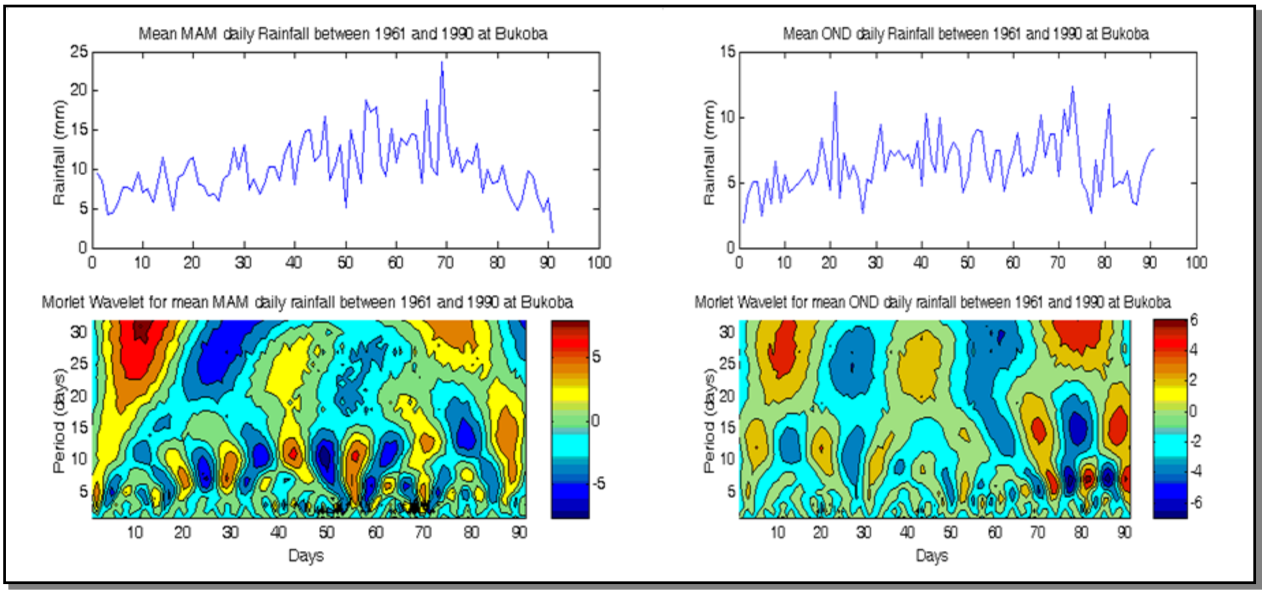

Fig. 3 **Mean MAM and OND precipitation season between 1961 and1990 at Bukoba.**

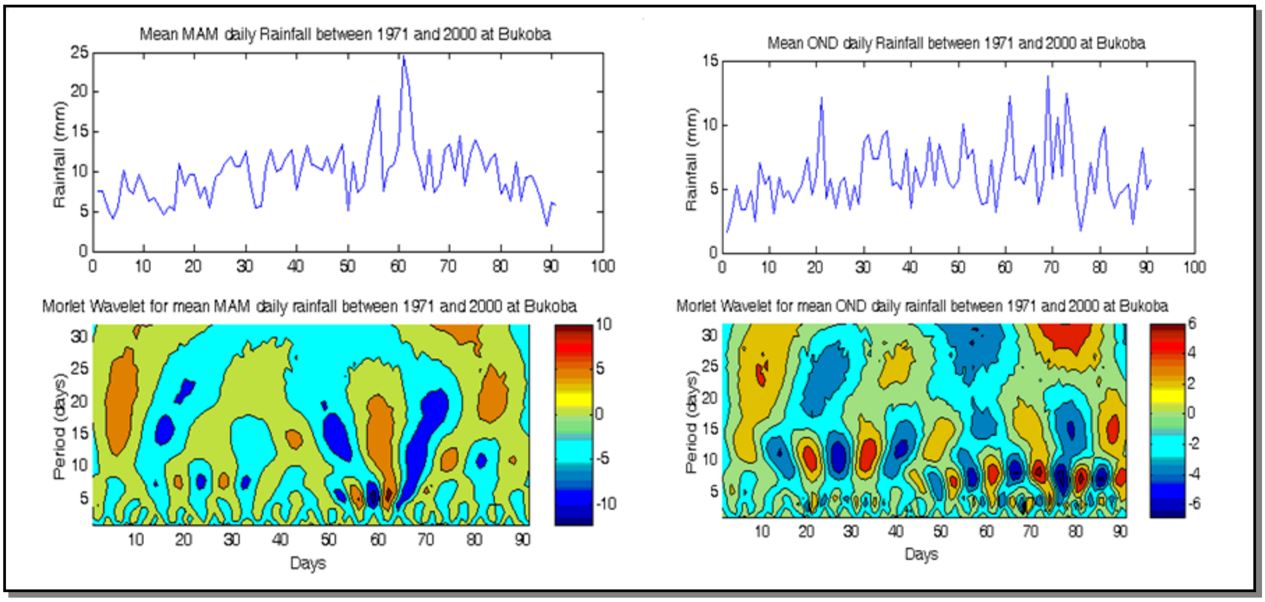

Fig. 4 **Mean MAM and OND precipitation season between 1971 and 2000 at Bukoba.**

power like in Fig. 4 may be associated with gradual reduced intensities of the alternating wet and dry spells hypothesizing overall reduced precipitation. MAM revealed characteristics of both low and high frequency mode of variability in the second and third epochs unlike the first epoch. Dominance of low frequency mode of variability typical of more than 20 days is depicted to occur at beginning and end of MAM season and likely to influence start and end of the season respectively. High frequency mode of variability indicated by less than 10 days seems to remain dominant in the middle of the season. Nevertheless, unlike MAM the transform did not pick much shift change or significant change in the concentration of power across the three epochs in the OND sister season suggesting that mode of variability remained almost uniform across the whole period of analysis. These changes are vibrantly observed in the trend investigation, which was made to MAM precipitation trends in each of the three epochs as shown in Fig. 5.

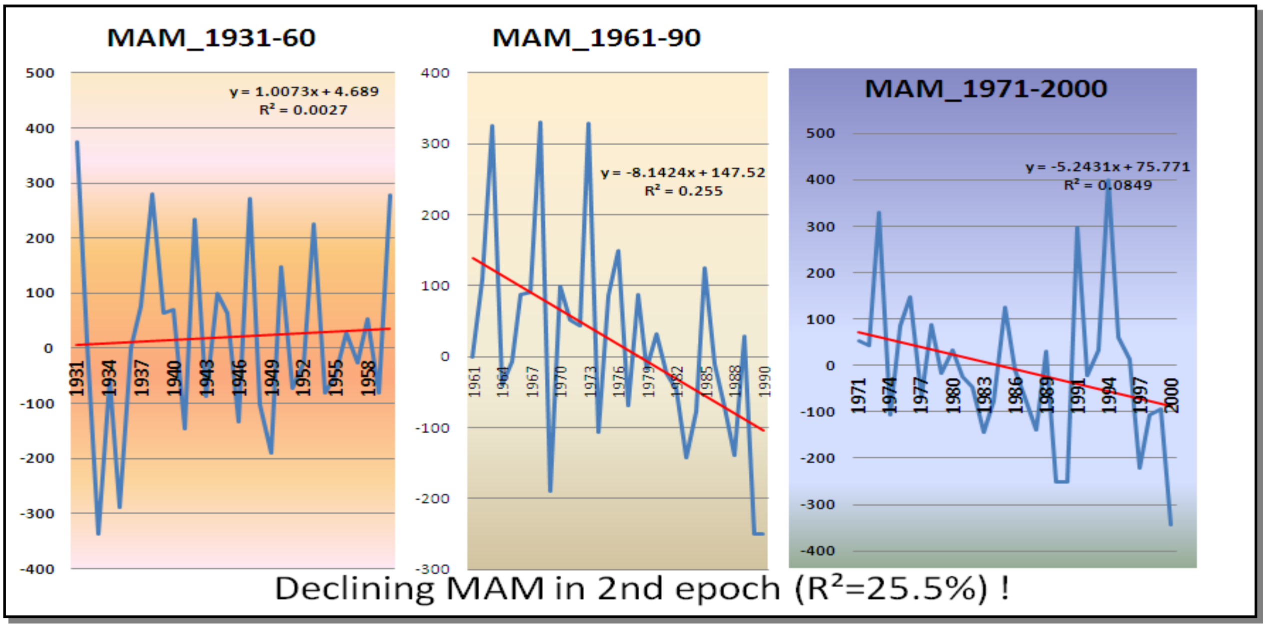

Fig. 5 Comparison of seasonal precipitation trend during MAM in the three epochs.

Declining trend was much more significant in the second epoch. Trend on OND in the three periods was insignificant.

4. Conclusion

Morlet wavelet transform was used in this investigation to extract dominant oscillations from the long-term behavior of daily precipitation data at Bukoba, Tanzania. Detected oscillations or variations were noted to be associated mainly with high frequency, quasi biweekly and low frequency oscillations with respective periods of about 5, 15 and above 20 days. The oscillations as a result of interactions between the atmosphere, oceans and land surfaces through convective processes are likely to influence seasonal rainfall anomalies in Lake Victoria basin. The shift change and fading oscillations distinguished by this study particularly during MAM precipitation season, are likely to be linked to climate dynamics change that have and likely to continue to influence characteristics of precipitation distribution, amount, intensity, frequency, duration and type recorded at Bukoba and Lake Victoria at large. MAM season contributes more than two thirds of annual precipitation recorded in the lake. The observed changes are suggested to excite understanding of the complex processes and their interactions in climate system and hence improved knowledge to enhanced hydrological processes in the past and future changes to falling lake levels and thus water availability and security in Lake Victoria basin.

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