Teleconnection between Atlantic Ocean and Local Hydroclimate: Case of Lake Hawassa and Abaya in Ethiopian Rift Valley Basin

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Abstract

Large scale atmospheric circulations exist over wide areas that affect regional climate conditions in adjacent or remote regions. Important aspect of climate change and variability is how these teleconnections are related to and influence local hydroclimate. In this regard, the hydroclimatic condition of East-Africa has frequently shown to have teleconnection with Indian and Pacific Oceans with little focus on the influence of Atlantic Ocean. This study investigated the likely association of Atlantic Ocean with the hydro-climate of two selected lakes in Ethiopian Rift Valley Basin (Lake Hawassa and Lake Abaya). The study employed three statistical techniques: Pettit's homogeneity test to compare significant points of change across time; coherence analysis to measure the frequency and strength of the association; and principal component analysis to identify patterns of variations. The homogeneity test revealed that the water level of Lake Hawassa and Abaya have experienced significant regime shifts at and around the period in which sea surface temperature (SST) of Atlantic Ocean significantly shifted. On the other hand, the coherence analysis confirmed that the local hydrology has significant coherence ($p<0.01$) with the corresponding sea surface anomalies of Atlantic Ocean. In addition, the principal component analysis traces out the role of Atlantic Ocean and Indian Ocean to significantly act in the same direction of influence. The findings provide strong bases to consider sea surface temperature of Atlantic Ocean as one of the potential predictor of local hydroclimate in East Africa in general and Ethiopia in particular.

Key words: Coherence analysis; Lake level variability; Principal component analysis; Regime shift index; Sea surface temperature
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INTRODUCTION

The nature and cause of East African hydroclimate variability is a subject of heightened concern because of the frequent flood and drought events with far-reaching economic and social consequences that are linked to oceanic phenomena. Large scale atmospheric circulations exist over wide areas that affect regional climate conditions in adjacent or remote regions. These anomalies are called teleconnections and refer to the climate anomalies being related to each other at large distance. They served as a building block for the understanding of climate variability. These are striking features of the Earth climate system (Herein et al., 2017). They transmit climate signals over very long distances to remote ecosystems (Gu and Philander, 1997; Alexander et al., 2004). An important aspect of climate change and variability is how these teleconnections are related to and influence local climate and ecosystems such as lakes (Ghanbari et al., 2009). The climate variability manifests itself on the local hydrology such as the dynamics of Lake Surfaces. For instance, Lake Victoria water level dropped by 1.1 meters in ten year averages out of which 45% is caused by climate variability (Kull, 2006).

In this regard, Indian and Pacific Oceans are shown to have remote connection with East African rainfall (Hastenrath et al., 1993; Ogallo et al., 1994; Latif et al., 1999; Saji et al., 1999; Black et al., 2003). Whereas Chiang and Sobel (2002) reported that El Niño-Southern Oscillation (ENSO) impacts Africa through Tropical Atlantic, Alexander et al. (2002) reported that this happens via Indian Ocean teleconnections. Other researchers considered Indian Ocean Dipole (IOD, representing Indian Ocean) and El Niño-Southern Oscillation (ENSO, representing Pacific Ocean) are separate modes of variability (Yamagata et al., 2003; Behera et al., 2003). Teleconnection of large scale variability of Atlantic Ocean to the local hydroclimate of East Africa in general and Ethiopia in particular is much less understood. This study attempted to investigate the fingerprints of Atlantic Ocean to the local hydroclimate by considering two selected lakes in the Ethiopian Rift Valley Lakes Basin (Lake Hawassa and Abaya).

MATERIALS AND METHODS

Description of the study area

Rift Valley Lakes Basin is one of the eleven major river basins in Ethiopia with a total area of approximately 52,000km^2 (MoWR, 2010). The basin is characterized by a chain of lakes varying in size, hydrological and hydrogeological settings (Alemayehu et al., 2006). The basin constitutes eight lakes: Lake Ziway, Lake Langano, Lake Abiyata, Lake Shalla, Lake Hawassa, Lake Abaya, Lake Chamo, and Lake Beseka (Fig. 1*)* where all are located south-west of the Ethiopian capital Addis Ababa.

Available data

The three major groups of data that were used in this study include: the local hydrology in terms of monthly lake level variability acquired from Ministry of Water, Irrigation, and Electricity; the local climate in terms of variability in rainfall acquired from Ethiopian Meteorological Agency; the sea surface temperature indices of the three Oceans acquired from NOAA (National Oceanic and Atmospheric Administration). The three oceanic indices include TNA (Tropical Northern Atlantic Index representing surface temperature variation at Atlantic Ocean in the region 5.5N to 23.5N and 15W to 57.5W); NINO3.4 index for surface temperature variation at Pacific Ocean in the region 5N to 5S and 120W to 170W); and DMI index for Indian Ocean. The period1986-2006 was considered due to the availability of common data shared by each of the study units.

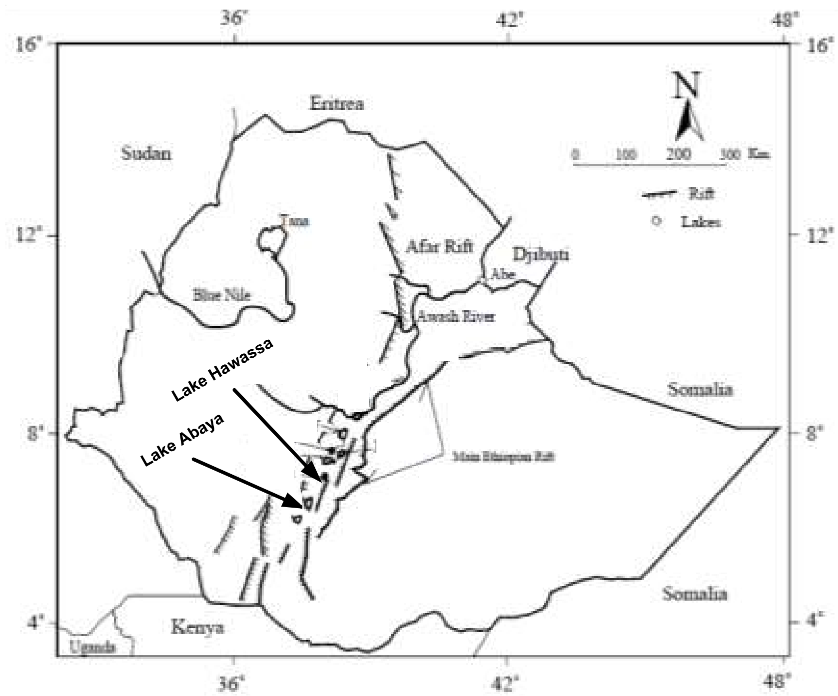

Figure 1. Location of Ethiopian Rift Valley lakes [Modified after Alemayehu et al. 2006]

Detection of regime shift (Pettit´s Homogeneity test)

In order to detect the significant regime shifts, the data sets were considered as a sequence of random variables $X_1, X_2, \ldots, X_T$ and said to have a change-point at τif X_t for t=1,…, τhave a common distribution function $F_1(x)$ and X_t for t =τ+1, …, T have a common distribution function $F_2(x)$, and $F_1(x) \neq F_2(x)$. The null hypothesis of "no change", H: τ=T is tested against the alternative hypothesis of "change", A: $1 \leq \tau < T$, using a non-parametric statistic.

Let $D_{ij} = sgn\,(X_i - X_j)$ where $sgn\,(x)$ =1 if x >0; 0 if x=0; -1 if x <0, then consider

$X_{t,T} = \sum_{i=1}^{t} \sum_{j=i+1}^{T} D_{ij}.$ ……………..……….… *(1)*

The statistic $U_{t,T}$ is then considered for values of t with $1 \leq t < T$ using the statistics:

$K_T = \max_{1\leq t<T} |U_{t,T}|$ …………………………..… *(2)*

and for changes in one direction, the statistics

$K_T^{+} = \max_{1\leq t<T} U_{t,T}$ ……………………….……..… *(3)*

$K_T^- = -\min_{1 \le t < T} U_{t,T}$ …………………….……..… *(4)*

Equivalently, the approximate significance probability p_{OA} associated with the value k+ of K_T^+ is given by

p_{OA}=exp [-2$(k^+)^2\{S_T(T^2 - TS_T)\}^{-1}$] …………… *(5)*

This approximation is conservative in that $p_{OA} \ge p$, where p is the exact significance probability.

Coherence analysis

The coherence, which is a measure of the correlation between two time series at each frequency, was made following Jenkins and Watts (1968) and Bloomfield (1976). A total of 252 pairs of monthly time series data of lake level variations and oceanic water surface temperature were analyzed for their coherence. Prior to the actual analysis, the time series data were de-trended using linear regression and autocorrelations were also removed by differencing techniques with order 1.

The cross-spectrum is then defined from the covariance function C_{xy}:

$$\Gamma_{xy}(\omega) = \sum_{\tau=-\infty}^{\infty} C_{xy} exp\{-2\pi i\tau\omega\},\ \omega \in \left[-\frac{1}{2},\dots,\frac{1}{2}\right] \text{….. (6)}$$

This is a complex function where the power is:

$$A_{xy}(\omega)^2 = Re(\Gamma_{xy}(\omega))^2 + \text{Im}(\Gamma_{xy}(\omega))^2 \text{……… (7)}$$

and the phase information is:

$$\Phi_{xy}(\omega) = tan^{-1}\left(\frac{\text{Im}((\Gamma_{xy}(\omega))}{Re(\Gamma_{xy}(\omega))}\right)^2 \text{…………….………(8)}$$

where $A_{xy}(\omega)$ is the modulus of the complex-valued cross spectrum, and $\Gamma_{xx}(\omega)$ and $\Gamma_{yy}(\omega)$ are the power spectra of processes x(t) and y(t) (Von Storch and Zwiers, 1999).
The coherence spectrum is then calculated as:

$$K_{xy}(\omega) = \frac{|A_{xy}(\omega)|^2}{\Gamma_{xx}(\omega)\Gamma_{yy}(\omega)} \text{………………… (9)}$$

Estimated coherences are considered significant at the 99% and 95% level of confidence when they are larger than the critical value T. In this study, Daniell´s window was used as smoothing techniques with window span of 5.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was employed by including time series of the lake level and rainfall time series data of other four lakes in the rift valley basin (Ziway, Langano, Abiyata, and Chamo) for the short rainy season (October-November-December) for this period is usually reported to experience teleconnections (Camberlin et al., 2009; Schreck and Fredrick, 2004).

With this method, the variables were transformed in a multivariate data set, $X_1, X_2, ..., X_p$, into new variables, $Y_1, Y_2, ..., Y_p$ which are uncorrelated with each other and account for decreasing proportions of the total variance of the original variables defined as:

$$Y_1 = a_{11}X_1 + a_{12}X_2 + ... + a_{1p}X_p \text{ …………… } (10)$$

$$Y_2 = a_{21}X_1 + a_{22}X_2 + ... + a_{2p}X_p$$

$$Y_p = a_{p1}X_1 + a_{p2}X_2 + ... + a_{pp}X_p$$

with the coefficients being chosen so that $Y_1,Y_2,...,Y_p$ account for decreasing proportions of the total variance of the original variables, $X_1,X_2,...,X_p$ (Everitt et al., 2001).

RESULTS AND DISCUSSION

Regime shift analysis

Lake Hawassa experienced regime shift in the annual average lake level in the year 1995-96 (from 20.44m to 21.14m), whereas Lake Abaya in the year 1993-94 (from 0.95m to 2.2m relative to the local bench mark) (Fig. 2). Correspondingly, the water surface temperature of Atlantic Ocean experienced the shift in the year 1994-95 (from -0.118 to 0.325 of the unit less index). The one year lag of Lake Abaya and an equivalent advance of Lake Hawassa from the driving teleconnection could be due to the local conditions on one hand and the involvement of other Oceans in influencing the circulation on the other hand. Similar justification could be applied for the contrasting results in the year 2000 and 2005. In addition, the 2004-2005 droughts (Ebei et al., 2008) that were associated to Indian Ocean (Hastenrath et al., 2007) might distort the teleconnection patterns. Generally, the result provides evidence to the likely linkage of local hydrology to the large scale phenomena of Atlantic Ocean in addition to the other Oceans.

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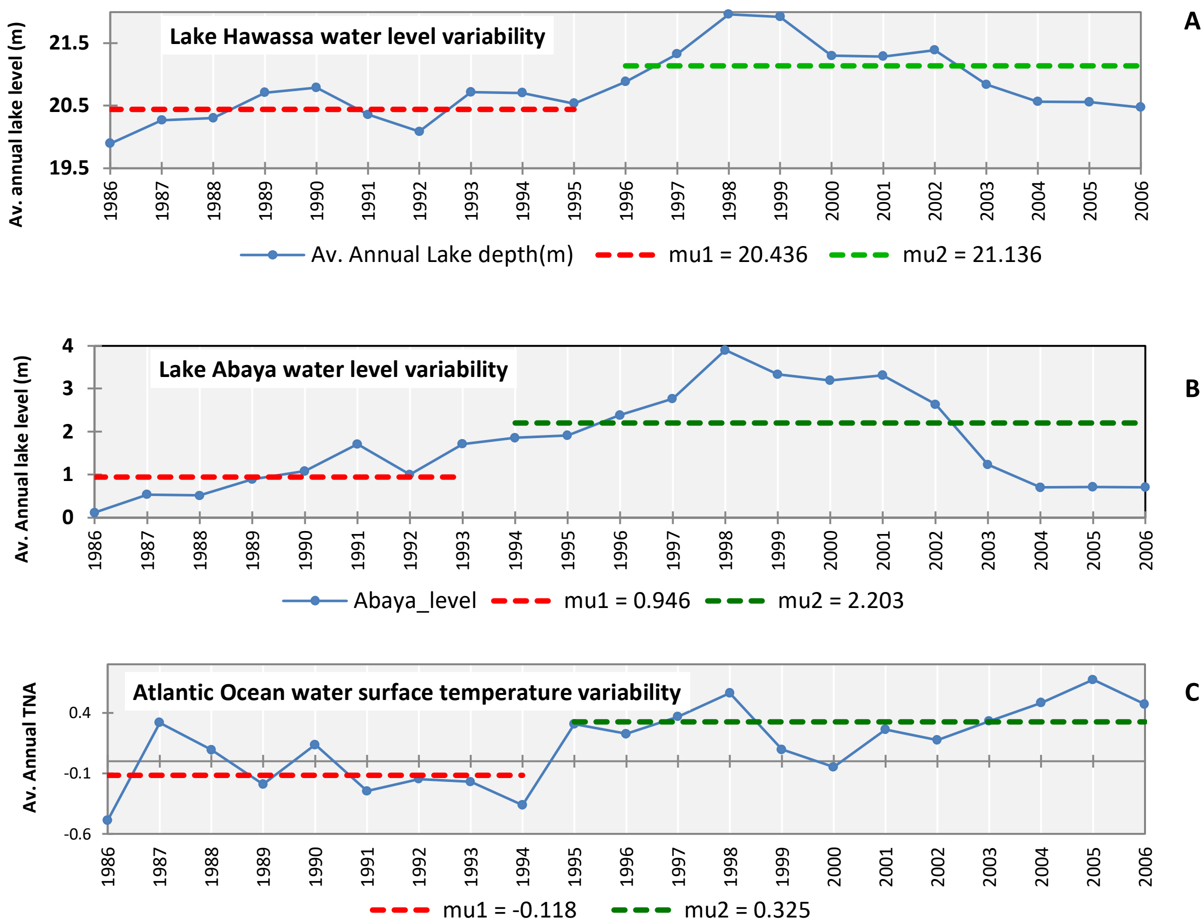

Figure 2. Dominant regime shift period of the local hydro-climate variables (NB: mu= μ=mean value)

Coherence analysis

The study indicated that the local hydrology has significant coherence with the corresponding distant signal at Atlantic Ocean as evidenced by the occurrences of significant peaks at 99%, 95% and 90% confidence limit (*represented by the three solid lines*) (Fig. 3). These high powers (significant peaks) in the same spectral frequency bands are statistical evidences for the significant interrelationship in the spectral domain at some specific frequencies where the peaks occurred.

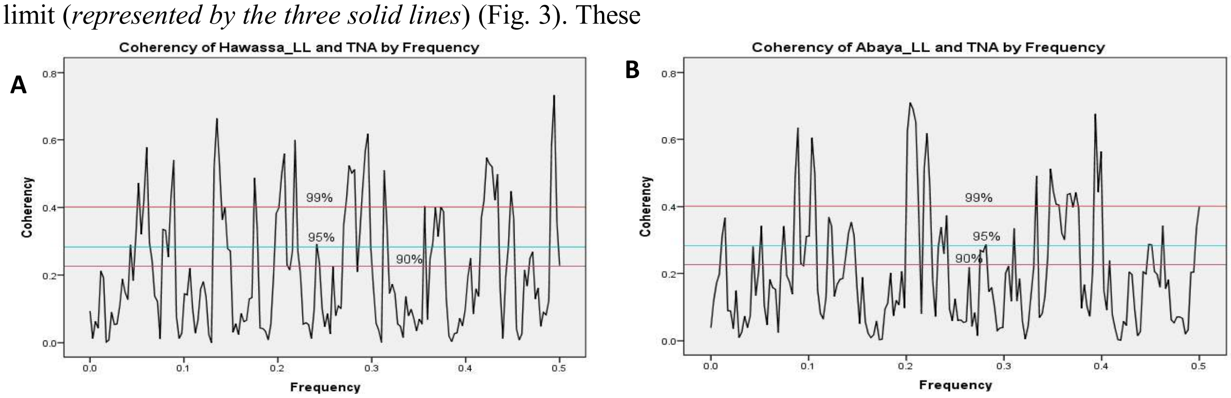

Figure 3. Relationship between SST of Atlantic Ocean and local lake level variability (A = Lake Hawassa; B = Lake Abaya)

Principal component analysis

The principal component analysis (PCA) traced out four important variabilities (Table 1). The first principal component (F1) which accounts for 26.2% of the total variation corresponds to the local rainfall and followed by the local hydrology (F2) which accounts for about 15.4%. The third component (F3) which explains the 11.5% of the vairiation is likely associated to the temperature variabilities in Indian and Atlantic Oceans. The fourth component (F4) with 9.8% of the total variation represents sea surface temperature (SST) variability at Pacific Ocean.

Table 2. Correlations between hydroclimatic variables and factors

Hydroclimate variables	F1	F2	F3	F4
Sea surface temperature variation: Indian ocean	0.1	-0.4	**0.6**	0.3
Sea surface temperature variation: Pacific ocean	-0.1	-0.5	0.1	**0.6**
Sea surface temperature variation: Atlantic ocean	0.2	0.2	**0.8**	0.1
Rainfall: Lake Hawassa	**0.7**	-0.4	0.1	0.1
Rainfall: Lake Abiyata	**0.8**	-0.2	-0.1	-0.2
Rainfall: Lake Ziway	**0.7**	-0.1	-0.3	0.0
Rainfall: Lake Abaya	0.2	-0.3	-0.1	0.3
Rainfall: Lake Chamo	**0.7**	-0.3	0.2	-0.1
Rainfall: Lake Langano	**0.8**	-0.2	-0.2	-0.3
Lake level variation: Lake Ziway	0.5	**0.7**	-0.1	0.4
Lake level variation: Lake Hawassa	0.5	**0.6**	0.3	0.3
Lake level variation: Lake Abaya	0.2	**0.6**	0.2	-0.2
Lake level variation: Lake Chamo	0.3	0.4	-0.5	0.5
Lake level variation: Lake Langano	0.0	0.2	0.3	-0.3

Though Indian Ocean has significant teleconnection, the case of Atlantic Ocean is shown to be stronger. The third principal component that shows the association between SSTs of Indian and Atlantic is in consistent with the findings of Chiang and Sobel (2002) who reported the impact of ENSO on Africa via tropical Atlantic. On the other hand Alexander et al. (2002) argued it to happen via Indian Ocean in which both oceans are likely to impact African hydroclimate.

CONCLUSION

The findings provide strong bases to consider Atlantic Ocean as a candidate predictor of local hydroclimate in East Africa in general and Ethiopia in particular. Such findings with further future researches on the modes of variabilities in Atlantic Ocean will improve the predictability of hazardous hydroclimatic events such as flood and drought. The finding also implies the importance of considering the sea surface temperature (SST) variability of Atlantic Ocean in future modeling of local hydroclimate in addition to the frequently employed Indian and Pacific SSTs. Such conditions provide opportunities to make use of better predictability of tropical sea surface temperatures up to two years ahead of time (Chen et al., 2004) that potentially be transferred to forecasting the local hydroclimate. Moreover, the argument on the primary impact of Indian Ocean on East African hydroclimate requires reconsideration due to the significant share of Atlantic Ocean to influence the local hydroclimate.

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