SMITH, KARA ANN. The Role of the Dominant Modes of Climate Variability over Eastern Africa in Modulating the Hydrology of Lake Victoria. (Under the direction of Fredrick Semazzi).

Previous water budget studies over the Lake Victoria basin have shown that there is near balance between rainfall and evaporation and that the variability of Lake Victoria levels is determined virtually entirely by changes in rainfall since evaporation is nearly constant. It is also well known that the variability of rainfall over East Africa is dominated by ENSO. However, the dipole mode is the second most dominant rainfall climate mode also accounts for significant variability across the region. The hydrologic adjustment time of the lake is also on a decadal scale.

Based on this knowledge, we hypothesize that ENSO dominates the variability of Lake Victoria levels. We further hypothesize that the dipole mode and hydrologic adjustment also play significant roles but we are uncertain which of these two is more significant. The relationship between the ENSO and dipole mode with Lake Victoria levels is nonlinear and a key objective in this study is to estimate the relative contributions of these modes in modulating Lake Victoria levels to test our hypothesis.

We find that the sudden significant increase in lake levels from 1961-64 was mainly caused by consistent above average precipitation during those years, while the decline from 1965-2005 was due to the lake reaching a new equilibrium level. The first EOF mode of annual precipitation variability (ENSO) accounts for the highest impact on the annual variability of Lake Victoria levels. While the second annual EOF mode accounts for approximately 10 percent of the variability, its affect on the variability of lake levels is nearly negligible because the loadings are very small over the lake.
Lake Victoria levels could reach 14 meters under IPCC AR4 A2 scenario projections. We map the potential flooding from these increased levels using GIS. This information is potentially highly valuable in assessing future use of hydroelectric dams and other applications such as land use and infrastructure planning over the Lake Victoria basin.

The annual variability in precipitation in terms of the seasonal variability from station gauge precipitation over Uganda, Kenya and Tanzania is investigated by performing seasonal EOF analysis on station gauge precipitation for the October-December (OND), March-May (MAM), January-February (JF) and June-September (JJAS) seasons. The EOF time series of the dominant modes are correlated with SST anomalies for each season to help determine their sources of variability. The first annual mode is correlated with the first modes of OND and MAM seasons, while the second mode is correlated with the second modes of MAM and JJAS seasons.

We then perform EOF analysis on a ten year running mean of 1961-90 OND season station precipitation to investigate decadal variability. Correlation of the time series of the first EOF mode with SST anomalies gives a ‘ENSO-like’ signal pattern consistent with recent studies.

We recommend that there is a definite need for sustained and improved monitoring of the lake and its basin, to compile high quality monthly observations for all the factors in the water balance model including information on water taken from the lake and its tributaries for human use. We further recommend the use of a dynamical hydrological model for use in projections of lake levels for climate change scenarios. Such a model would have more reliability outside of the regimes under which the model used in this study was calibrated. Future studies would benefit from an estimation of the cascade of uncertainty over the entire chain of steps involved from data collected to impact modeling.
The Role of the Dominant Modes of Climate Variability over Eastern Africa in Modulating the Hydrology of Lake Victoria

by
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A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science Marine, Earth and Atmospheric Sciences

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Biography

Kara Ann Smith was born January 16, 1981 in Takoma Park, Maryland. Shortly thereafter, her family moved to Fishers, Indiana. After graduating from Hamilton Southeastern High in 1999, she attended Indiana University in Bloomington, Indiana where she earned a Bachelor of Science in Geography - Atmospheric Science in 2003. While a student at North Carolina State University, Kara was on the Department of Marine, Earth, and Atmospheric Sciences Connectivity Committee in 2007 and helped organize the first annual MEAS Research Symposium. She was president of the Central North Carolina Chapter of the American Meteorological Society during the 2008-2009 academic year.
Acknowledgments

I would like to thank my committee members Dr. Semazzi, Dr. Hanna, Dr. Liu and Dr. Nelson for all of their guidance. I am especially grateful to my advisor and committee chair, Dr. Semazzi, for his patience, guidance and motivational support. Finally, I would like to thank the present and former members of CML and friends I have met while at NC State who have helped me along the way with coding problems, background information on East Africa and Lake Victoria, and everything else.
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List of Abbreviations

CRU: Climate Research Unit
ENSO: El Niño-Southern Oscillation
EOF: Empirical Orthogonal Function
ERSST: Extended Reconstruction Sea Surface Temperature
FFT: Fast Fourier Transform
FvGCM: NASA Finite Volume Global Climate Model
GIS: Geographic Information System
IOZM: Indian Ocean Zonal Mode
IPCC: International Panel on Climate Change
JF: January-February season
JJAS: June-September season
MAM: March-May season
NBS: Net Basin Supply
OND: October-November season
RegCM3: ICTP REGional Climate Model system version 3
SO: Southern Oscillation
SOI: Southern Oscillation Index
SSTs: Sea Surface Temperatures
TS: Time Series
WBM: Water Balance Model
Chapter 1

Introduction

Lake Victoria and Nile River Basins

Lake Victoria is one of the sources of Nile River which is the lifeblood of the ten African nations of Egypt, Sudan, Rwanda, Uganda, Tanzania, Zaire, Ethiopia, Kenya, Eritrea, and Burundi. With a population of less than 10 million, the great ancient civilizations along the Nile valley relied on the abundance of Nile’s water supply to thrive. Despite the low population at that time, it is believed that failure of the Nile discharge to deliver sufficient water due to climatic fluctuations may have resulted in the collapse of several ancient Egyptian dynasties of the great Pharaohs. The Nile has annual flow in normal years of about 84 billion cubic meters at Aswan in southern Egypt. Of this, about 85 percent is from the Blue Nile, the Atbara and the Sobat rivers, originating in the Ethiopian highlands. The rest originates from the Great Lakes region of which Lake Victoria is the most important source. Records show that from 1870 to 1899, the average annual flow at Aswan was 110 bcm, and declined to 83 bcm from 1899 to 1954 and 81.5 bcm from 1954 to 1988. Consequently, the demand for accurate projections of future fluctuations in the Nile flow and its sources has become a matter of very high priority for the Nile basin countries. The Anglo-Italian Agreement of 1891 and
subsequent treaties are the basis for the sharing of the river’s water by the ten countries. The main treaties include, the Anglo-Italian Protocol of April 15, 1891; the Treaty between Great Britain and Ethiopia of May 15, 1902; the Tripartite (Britain-France-Italy) Treaty of December 13, 1906; the Agreement between Egypt and Anglo-Egyptian Sudan of 7th May 1929; & the post-colonial agreements (the 1959 Nile Agreement between the Sudan and Egypt). These agreements and the latest plans to redress the Nile water treaties do not adequately take into account the projected impacts of climate change on water supplies. This is a serious shortcoming since some estimates indicate that climate changes in the next few decades could reduce run-off over the arid regions by up to 40-70%. Compounding the problem even further, current estimates of climate change which are primarily based on global climate models do not have sufficient geographical detail required for the application of hydrological models at catchments spatial scales. There are significant socio-political issues associated with water resources over the Lake Victoria Basin, yet currently there is limited science behind water policy within countries of the region. Its water sharing also presents significant trans-boundary environmental challenges. Basic research addressing variability and predictability of river basin regimes, and implications for major climatic phenomena such as climate change, El Nino and other complex climatic phenomena on watersheds is needed. The science is still in its infancy as the translation even of such a major phenomenon as an El Nino into its implications for a watershed is complex and for lesser climatic phenomena even more difficult. The science and data are both clearly inadequate.

**ENSO and Dipole Climate Modes**

It is well known that El Niño-Southern Oscillation (ENSO) and the Indian Ocean Zonal Mode (IOZM) dominate the interannual climate variability of Eastern Africa (Ogallo [1979], Ogallo et al. [1988], Nyenzi [1992], Nicholson [1996], Latif et al. [1998]). More recently Schreck
and Semazzi (2004) unveiled a new mode represented by the second most important regional precipitation EOF mode characterized by decadal variability and a dipole rainfall loading pattern (Fig. 1.1). The spatial distribution of rainfall over Lake Victoria Basin (LVB) is complex as shown in figure 1.2. It consists of a wave-like dry-wet-dry-wet climatological rainfall pattern. During previous ten years significant progress has been made in understanding the physical mechanisms which determine its characteristics (Anyah et al., 2009; Bowden and Semazzi, 2007; Anyah and Semazzi, 2007; Anyah and Semazzi, 2006; Anyah et al., 2006; Anyah and Semazzi, 2004; Song et al., 2004). Over the eastern sector of the lake rainfall is minimum & less than 800mm per year (Asnani, 1993, 2005); over the western sector of the lake rainfall is maximum and over 2000 mm per year; there is a well-marked rainfall maximum (more than 1500mm) over land immediately to the east the lake; and a rainfall minimum (less than 1000mm) immediately to the west of Lake Victoria. This climatic pattern, its variability & associated atmospheric & marine conditions determine the performance of the primary social-economic activities across the Lake Victoria basin including agriculture, fisheries, hydroelectric power generation. Global climate models with resolution of 100km and coarse cannot resolve the important features of the distribution of rainfall in figure 1.2 and regional climate models with resolution of 10s of km in resolution would be required. Equally important, these models should adequately represent several critical mechanisms including basin-scale orographic-dynamic forcing, interaction of large scale prevailing flow & lake-land breeze mesoscale circulation, and the role of lake surface temperature gradient.
Figure 1.1: (left top) EOF1 based on CMAP rainfall data set (1979-1999); (left bottom) EOF1 time series, red line corresponds to station gauge EOF 1, solid blue is East African regional CMAP EOF1; (top right) EOF2 loading based on CMAP rainfall data set (1979-1999); (right bottom) red line corresponds to eastern Africa CMAP EOF2, solid blue is CMAP global EOF3, and dotted is global average surface temperature time series based on HadCRUT data set, an indicator of global warming.
Hydroelectric Power Plants

Nalubaale Dam (originally called Owen Falls Dam), located at the Jinja Lake Victoria coastal city in Uganda (at source of the Nile), was the first major hydroelectric plant to be constructed in Uganda. It was opened in 1959 to provide hydroelectric power for the region. Kiira Dam was commissioned in 2000 to generate more electricity from the excess water being spilled by the sluices of Nalubaale (Kull 2006a). The Bujagali dam, 250 Megawatts (MW), is expected to be commissioned in 2011. The Murchison Falls dam in Uganda and several other plants in Sudan are in the planning phase. The flow of the White Nile, and hence the productivity of these dams are primarily determined by the level of Lake Victoria (Fig. 1.3). The temporal variability of the level of the lake is in turn primarily determined by the rainfall
variability. Other factors including, evaporation, fluctuations in the area of the lake, play some but less important roles.

![Historical Water Level Elevations for Lake Victoria](image)

Figure 1.3: Recent Lake Victoria water levels (from USDA (2005)).

### 1.1 Variability of Lake Victoria Hydrology

Lake Victoria the third largest lake in the world, is approximately 67,000 km² in area, but shallow with an average depth of only 40 m. It is territorially administrated by Tanzania, Uganda, and Kenya and is a major source of income in those countries producing $3-4 billion annually. The lake basin provides fresh water and hydroelectric power for the over 30 million people who live in the Lake Victoria basin, as well as supporting agriculture, fisheries, trade and tourism. The lake is the primary source of the White Nile, which flows through Lake
Kyoga in Uganda and Lake Albert into Sudan where it joins with the Blue Nile at Khartoum to form the Nile River, which supports the livelihood of over 300 million people. The climate of the lake basin is dominated by the bimodal signature of the Intertropical Convergence Zone (ITCZ).

After a long period of near constant levels in the early part of this century, Lake Victoria levels rose by almost 2.5 m between 1961 and 1964. This has been explained by a strong Indian Ocean Dipole in 1961 and unusually high precipitation in East Africa in late 1961 and 1962 (Piper et al., 1986; Sene and Plinston, 1994; Kite, 1981). The lake levels remained above the previous average, decreasing slightly over time until 2002 when the rate of decrease more rapidly (Fig. 1.3). From late 2003 through 2005, Lake Victoria’s water level dropped over 1.1 m from it’s 10 year average (Fig. 1.3). As of December 2005, it was approximately 10.69 m, reaching the lowest level since 1951 (USDA, 2005). Various studies have investigated this drop (Kull, 2006(a, Sutcliffe and Petersen, 2007; Mangeni, 2006), attributing the drop to various combinations of over-release from Nalubaale and Kiira dams and a drought which affected the area for several years. While there is not enough data currently to study this drop in lake levels, we plan to study the slow drop from 1965-2005 and the sudden increase in levels from 1961-64 which preceded it. These abrupt changes in level and the resulting changes in lake outflow have important impacts on the hydrology of the Nile River and hydropower generation at Jinja, Uganda.

In order to understand the effect of climate on the level of the lake, especially the sharp rise during the early 1960’s, several water balance models have been developed for the lake (Kite, 1981; Piper et al., 1986; Yin and Nicholson, 1998; Tate et al., 2004). These models have been based on a simple hydrological balance model,

\[ \Delta S = P - E + \frac{Q_{in} - Q_{out}}{A} \]  (1.1)
where $\Delta S$ is the change in water stored by the lake, $P$ is precipitation directly over the lake, $E$ is evaporation, $Q_{in}$ is inflow from the catchment $Q_{out}$ is outflow from the lake, $A$ is the surface area of the lake. The effect of groundwater is assumed to be negligible (Krishnamurthy and Ibrahim, Piper et al., 1986) and is not included in the model. Many models assume evaporation and the surface area of the lake to remain constant from year to year (Piper et al., 1986; Sene, 2000; Tate et al., 2004). Precipitation and evaporation are almost in balance (Table 1.1) (Sutcliffe and Petersen, 2007). Precipitation over the lake accounts for about 84% of the total lake inflow. However, inflow from tributaries is subject to greater interannual variability, 30% compared with 10% variability for rainfall (Sutcliffe and Petersen, 2007). The surface area of the lake is held constant at 6800 km$^2$ (Piper et al., 1986; Sene, 2000; Tate et al., 2004). Studies have shown that the local lake breeze circulation enhances precipitation over the lake, predominantly at night (Flohn and Fraedrich, 1966; Nicholson, 1998). Piper et al. (1986) included a scaling factor to the average precipitation at stations around the lake to account for the enhanced precipitation over the lake, which was part of the first water balance model to realistically reproduce the large lake level increase in the early 1960’s. Since then, other studies have focused on improving the water balance model, especially the inflow and precipitation terms. Table 1.1 shows the observations various studies used to determine the parameters of eq 1.1. In each of the studies it was assumed that the outflow followed a version of the Agreed Curve.

The Agreed Curve was created to approximate the natural release of water over Ripon Falls when the Owens Falls Dam was built in 1954. After the increase of levels in 1961, the lake levels were higher than accounted for by the original Agreed Curve and a straight line extension was used for several years (Sene and Plinston, 1994). Starting around 1968, an extended Agreed Curve was adopted based on the results of hydraulic modeling studies of Ripon Falls (Hydraulics Research Station, 1966). Sene and Plinston (1994) have shown that the Agreed
Curve has been followed, with compensatory releases made at later dates when it hasn’t, from the time operations started at Owen Falls dam through 1994. Kite (1981) and Sene and Plinston (1994) both note that the effect of any departures on lake levels has been small through 1994. Outflow is considered the most understood part of the water balance equation since it can be assumed to follow the Agreed Curve through 1994. Since the Agreed Curve approximates the amount of water that would naturally flow out of Lake Victoria if there were no dams, the lake can be treated like an open lake and the amount of time it takes the lake to reach an equilibrium level can be found. The adjustment time to reach equilibrium is different for individual lakes based on their size (Sene, 1998). This adjustment time and resulting equilibrium level do not depend on starting level. Salas et al. (1982) found an adjustment time of approximately 10 years. Sene and Plinston (1994) found the adjustment time to be 19 years for levels to reach 1 cm from equilibrium for an initial departure from equilibrium of one meter. While their calculations give different results, it is clear that the adjustment time is on a decadal time scale. Evaporation is also consistent between studies with only small changes between the values used. Yin and Nicholson (1998) investigated using energy balance and Penman methods of calculating evaporation before settling on using a constant 1532 mm/yr. This term is the least understood due to a lack of observations which would allow an accurate estimation of its value (Yin and Nicholson, 1998). The precipitation and tributary inflow terms differ the most between different models. Piper et al. (1986), Sene and Plinston (1994) and Tate et al. (2004) rely on the eight lakeshore stations that have a complete record starting from 1925. They then use a multiplier to adjust for lake enhancement, although they each use a slightly different multiplier. Yin and Nicholson (1998) used 19 stations and derived a multiplier from satellite analysis from Ba and Nicholson (1998). Inflow varies the most between different studies. All studies used a combination of observed and modeled inflow. Tate et al. (2004) used the most advanced inflow. They calculated the precipitation over the lake, and then segmented the
basin into five main sub-catchments. They then used a non-linear function, explained further in section 3.5, to relate the inflow from each sub-catchment to the precipitation over the lake.

Table 1.1: Orders of magnitude for water balance equation. PL is rainfall over Lake Victoria, E is evaporation, Qin is tributary inflow and Qout is outflow from Owen Falls dams.

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL</td>
<td>~2000 mm/yr</td>
</tr>
<tr>
<td>E</td>
<td>1595 mm/yr</td>
</tr>
<tr>
<td>Qin</td>
<td>$2 \times 10^{19}$ mm$^3$/yr (Volume) = 200-500 mm/yr (height)</td>
</tr>
<tr>
<td>Qout</td>
<td>$4 \times 10^{19}$ mm$^4$/yr (Volume) = 400-700 mm/yr (height)</td>
</tr>
</tbody>
</table>
Table 1.2: Data used in water balance models of Lake Victoria for previous studies adapted from Davis (2007a)

<table>
<thead>
<tr>
<th>Source</th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Inflow</th>
<th>Outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tate et al. (2004)</td>
<td>Extended rainfall series developed by Sene &amp; Plinston (1994) using remaining 6 stations.</td>
<td>1595 mm/yr</td>
<td>Subcatchment rainfall estimated using regressions of annual rainfall over lake, runoff from 5 tributaries estimated from subcatchment rainfalls by linear regression. Total inflow estimated using tributary multipliers.</td>
<td>Agreed curve used on an annual basis to find lake level and calculate revised outflow.</td>
</tr>
</tbody>
</table>
1.2 History of Lake Victoria and Nile Basin

1.2.1 Egypt

Egypt, the most dependent nation on Nile waters, depends on the Nile for irrigation (Waterbury, 2002). Egypt receives about 98 percent of its fresh water from the Nile, which satisfies more than 95 percent of their water requirements (Tvedt, 2009). Egypt has entered many contracts with other countries including the 1929 Agreement, the Owen Falls Dam agreements with Britain on behalf of Uganda and the 1959 Agreement for full utilization of Nile Waters with Sudan. The main goal of these agreements is to prevent any construction along the Nile River which would modify the flow in any way which would be detrimental to Egypt. Water from Lake Victoria minus evaporation losses in the Sudd region, contributes between 20% and 25% of the total Nile flow to Egypt (Howell and Allan, 1994; Garretson, 1967). While the largest contribution comes from the Blue Nile, its contribution is less steady due to seasonal and annual fluctuations in its tributaries.

1.2.2 Sudan

All major tributaries of the Nile, the White Nile, Blue Nile and Atbara join in Sudan to form the main Nile. The economy of Sudan depends heavily on agriculture, most of which is not farmed under irrigation from the Nile. The 1929 Nile River agreement did not define water rights in quantitative terms, however the 1920 report of the Nile Projects Commission suggested that Egypt should be guaranteed sufficient water to irrigate the maximum 5 million feddans cultivated up to that time. Quantitative estimates were derived which gave Egypt
rights to 48 bcm and Sudan 4 bcm (Tvedt, 2003). The 1929 agreement stated that Sudan could take water from the Nile and its tributaries from July 15 to December 31 each year without limitations, enough to irrigate 38,500 feddans from January 1 to February 28, and enough to irrigate 22,500 feddans from March 1 to July 15 (Tothill, 1948). When Sudan gained independence in 1956, they declared that they did not have to take over the 1929 agreement between Egypt and the British colonies and prepared to negotiate a new agreement (Howell and Allan, 1994). The 1959 agreement with Egypt allowed Sudan 19.5 billion cubic meters per year as measured at Aswan, or about 20.5 billion cubic meters in the area north of where the White and Blue Niles merge in Khartoum (Waterbury, 2002).

### 1.2.3 Uganda

Uganda receives enough precipitation during the year that it does not depend on Lake Victoria for irrigation. However, it does depend on the hydroelectric power plant at Owen’s Falls for electricity. Owen’s Falls dam, renamed Nalubaale, and the newer Kiira dam control outflow of Lake Victoria at Jinja, Uganda. A series of agreements between Egypt and Britain acting on behalf of Uganda lead to the construction of Owen Falls dam. The agreement stated that the Uganda Electricity Board could take any action in regard to the dam only after consultation and agreement with the Egyptian government. The agreements dated between 1949 and 1954 are considered binding upon Uganda as long as Uganda uses the power supplied by the dam, there are no new agreements and neither country renounces this agreement (Howell and Allan, 1994).
1.2.4 Tanzania

The government of Tanzania sent diplomatic letters to the governments of Britain, Egypt and the Sudan on July 4th, 1962 outlining the policy of Tanzania on the use of Nile waters. In these letters, the Tanzanian government stated that since the 1929 agreement applied to territories under British administration, the treaty lapsed when Tanzania became independent. This became known as the Nyerere Doctrine (Howell and Allan, 1994). On November 21, 1963, Egypt replied that “pending further agreement, the 1929 Nile Waters Agreement...remains valid and applicable” (Seaton and Maliti, 1974).

1.2.5 Kenya

Even though six major tributaries of Lake Victoria flow through Kenya, two thirds of the country is classified as semi-arid or arid (Howell and Allan, 1994). Kenya contributes 8.4 km³ per year of water to Lake Victoria (Tvedt, 2009). Kenya adopted a position similar to the Nyerere Doctrine which indicates that the 1929 agreement ceased to apply to Kenya starting December 12th, 1965.

1.3 Contribution of Lake Victoria to Upper Nile River

Since 1959, the Nalubaale Dam (originally called Owen Falls Dam) at Jinja, Uganda has effectively turned Lake Victoria into a reservoir. The agreement since the dam was built is the Agreed Curve that mimics the natural variability of the flow that went over Ripon Falls, the natural rock weir submerged during the dam construction (Kull, 2006(a). This ranges between 300 and 1700 cubic meters per second depending on the level of the lake. While Nalubaale dam was originally designed to provide 150 MW of energy when it was completed in 1954, it
has since been refurbished to provide 180 MW. Construction of Kiira dam was started in 1993 with plans for five hydroelectric turbine generators, which would each provide 40 megawatts. The Bujagali dam, 250 MW is expected to be commissioned in 2011 further upstream, while the Murchison Falls dam in Uganda and several other hydroelectric plants in Sudan are in the planning phase. The flow of the White Nile, and hence the productivity of these dams are primarily determined by the level of Lake Victoria.

1.4 Climatology & variability of the climate of Eastern Africa

The general climate over Lake Victoria basin is characterized by a bimodal regime, the long rains of March-May and the short rains of October-December. The October-December season contributes disproportionately to the interannual variability of rainfall even though there is more precipitation during the March-May season (Fig. 1.4). The seasonal cycle of rainfall is mainly controlled by the north-south migration of the Intertropical Convergence Zone (ITCZ) across the region, while the diurnal cycle is dominated by lake/land breeze circulations (Asnani, 2005). Earlier studies (Indeje et al., 2000; Asnani, 2005; Ogallo et al., 1988; Janowiak, 1988) have established that the warm phase of ENSO causes greater precipitation over Eastern Africa. Indeje et al. (2000) studied the evolution of ENSO modes in the seasonal rainfall patterns over East Africa from 1961-1990 using empirical orthogonal function (EOF) and correlation analysis to delineate a network of 136 stations over East Africa into eight homogeneous rainfall regions to form rainfall indices. Other studies have noted that strong Indian Ocean zonal mode events also cause an increase in precipitation in the area (Ummenhofer et al., 2009; Clark et al., 2003).

Schreck and Semazzi (2004) performed an empirical orthogonal function (EOF) analysis of gauge precipitation data and CPC Merged Analysis of Precipitation (CMAP) data which is
derived from rain gauge observations and satellite estimates. Their investigation covered the October through November season from 1961-2001. Using Kendall’s (1980) criterion for distinctly separated EOFs, they determined that the first two EOF modes were significant. The most dominant mode of variability based on CMAP data over eastern Africa corresponds to El Niño-Southern Oscillation (ENSO) climate variability. The second eastern Africa EOF mode was found to be a decadal trend with a loading characterized by a dipole pattern with positive rainfall anomalies over the northern section of eastern Africa and negative rainfall anomalies over the southern section which correlated significantly with a global warming index constructed by globally averaging surface temperature data from CRU archives. Their combined analysis of their time series and loading indicate that northern areas of eastern africa are getting wetter, while southern areas are drying up during the time period 1961-2001.
1.5 Hypotheses

Based on previous water budget studies over the Lake Victoria basin we recognize that there is near balance between rainfall and evaporation. However, these studies have also shown that the variability of Lake Victoria levels is determined virtually entirely by changes in rainfall since evaporation is nearly constant. It is also well known that the variability of rainfall over East Africa, with Lake Victoria at the center of the region, is dominated by ENSO. However, the dipole mode (Schreck and Semazzi 2004) which is the second most dominant rainfall
climate mode also accounts for significant variability across the region with the Lake Victoria Basin becoming more dry from 1961-1990. The hydrologic adjustment time described by Sene (1998) and Sene and Plinston (1994) is also on a decadal scale.

Based on this knowledge, we hypothesize that ENSO dominates the variability of Lake Victoria levels. We further hypothesize that the dipole mode and effects of the hydrologic adjustment time of the lake also play significant roles but we are uncertain which of these two is more significant. The relationship between the ENSO and dipole mode with Lake Victoria levels is nonlinear and a key objective in this study is to estimate the relative contributions of these modes in modulating Lake Victoria levels to test our hypothesis.
Chapter 2

Data

2.1 Lake Victoria Level Combined Data Set

The lake level data is based on a data set of lake level observations from January 1949 to May 1998 at a gauge at the main river outlet in Jinja, Uganda obtained from an archive at the Ministry of Water Resources in Uganda (Davis, 2007b). This data set was extended through November 2007 using TOPEX/POSEIDON and Jason-1 altimetry satellite data (USDA, 2007). Since the heights obtained by satellite altimetry are an average of all topography within the instrument footprint further averaged in the direction of the satellite motion, these values differ from traditional gauge measurements which are at specific points. Therefore, the TOPEX/POSEIDON and Jason-1 altimetry data was supplied as a lake height variation with respect to TOPEX/POSEIDON 10 year mean level. The climatological mean was found by subtracting the satellite data from the observations for the time period the two data sets had in common to determine the difference between the two. From this a mean was chosen and added to the satellite anomalies. The mean was adjusted until bias and error were reduced to $-4 \times 10^{-4}$ and 0.0585 respectively (Davis, 2007b). The remaining satellite altimetry time series was then
added to the resulting mean, creating a combined data set for January 1949 to November 2010. The lake levels at the end of each year from this data set can be seen in figure 1.3.

2.2 Lake Victoria rain gauge precipitation

de Baulny and Baker (1970) originally used eight rain gauge stations (Jinja, Entebbe, Kalangala, Bukoba, Kagondo, Mwanza, Musoma and Kisumu) around the shore of Lake Victoria to determine precipitation over the lake for use in modeling the lake levels. The eight stations were chosen since they were found to be the only lake shore stations to have good quality records over long durations. Piper et al. (1986) and Sene and Plinston (1994) followed de Baulny and Baker (1970) in using the eight stations while using a water balance model to model Lake Victoria levels. All eight stations have records that date back to 1925, however we were only able to obtain data from 1961-19990. Tate et al. (2004) extended the rainfall series of Sene and Plinston (1994) omitting rainfall from Kalangala and Kagondo due to a lack of data in recent years. In this study, we follow Tate et al. (2004) in using precipitation from Jinja, Entebbe, Bukoba, Mwanza, Musoma and Kisumu to estimate precipitation over Lake Victoria. The location of the six stations relative to Lake Victoria is shown in figure 2.1. For the EOF analysis, we used a dataset of monthly precipitation for 136 stations unevenly distributed over Uganda, Kenya and Tanzania from 1961-90. The six stations used to calculate precipitation over the lake were included in this dataset.
2.3 Climate Research Unit (CRU) TS 3.0 Precipitation

We used the Climate Research Unit’s CRU TS 3.0 to study the use of the water balance model with data other than the stations mentioned in Section 3.3 since station data is not always easily available. CRU TS 3.0 is a monthly climatology of station data from 1901 through 2005. Station data is collected from several sources to form a global data set, which is checked and corrected using an automated process. After the correction, a reference series is found for a chosen baseline period (1961-1990). Anomalies are then found from the baseline climatological normal and interpolated using angular distance-weighted (ADW) interpolation to a 0.5 degree grid (New et al., 2000). The gridded anomalies are then added back to the baseline
period climatological normal to create the grids (Mitchell and Jones, 2005). Unlike previous versions of CRU, no homogenization is performed in CRU TS 3.0. Homogenization is a procedure used to correct any inhomogeneities in a station record caused by changes in instrumentation, station moves, or a change in observing practices (Peterson et al., 1998). For this study we use data from 1950-2005 because Lake Victoria levels are available starting in 1949.

2.4 NASA Finite Volume Global Climate Model (FvGCM)

We used data from the NASA Finite Volume global climate model (FvGCM) used in the PRUDENCE international model inter-comparison project, where two sets of FvGCM model runs for present-day and A2 scenario runs were conducted. The model has a mass-conserving finite-volume dynamical core (Lin et al., 2004). It was run at 1° latitude x 1.25° longitude resolution with 18 vertical hybrid coordinate levels using the NCAR CCM3 physics package (Kiehl et al., 1996). The model was forced by observed SSTs, sea ice distribution and greenhouse gas concentrations for the reference run (1961-1990) and a spatially varying monthly SST perturbation calculated from corresponding experiments with the Hadley Center coupled model HADCM3 was added to the reference run values to obtain SSTs for the A2 scenario experiment (2071-2100) (Coppola and Giorgi, 2005). This is important because the model variability in the coupled experiments does not have perfect SST boundary conditions and can be an additional source of error.

2.5 RegCM3

We use model precipitation from the RegCM3 model runs performed by Bowden (2008). He adopted the regional climate modeling approach to downscale present (RF, 1961-1990) and
a future (IPCC-A2, 2071-2100) climates generated by the NASA Finite Volume General Circulation Model (FvGCM) using the ICTP REGional Climate Model version 3 (RegCM3). The model is an updated version of the model previously customized for East Africa by Sun et al. (1999) and Anyah and Semazzi (2007). The RegCM3 model is coupled to a one-dimensional lake model which permits realistic vertical diffusion of heat energy. The domain has resolution of 40km with lateral and boundary conditions for RF and A2 constructed from the corresponding FvGCM runs. This domain is approximately 16.3° S to 20.7° N and 21.3° E to 55.1° E and encompasses the countries of Burundi, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania and Uganda.

2.6 IPCC Ensemble

In order to examine the potential effect of climate change on Lake Victoria levels, we used precipitation from an ensemble of IPCC AR4 models. The global climate model simulations were obtained from Coupled Model Inter-comparison Project (CMIP; http://www-pcmdi.llnl.gov). The subset of models used had 20th century simulations and A2 simulations run with comparable model physics with a resolution of 2.8 degrees or finer. This criteria provided us with 9 IPCC AR4 models out of the 23 models available, table 2.6 (Bowden, 2008). Horizontal resolution for the IPCC AR4 models varies from 1.4 to 2.8 degrees. The finer models were interpolated to the courser 2.8 degree resolution using a bi-linear interpolation to create the IPCC ensemble. The ensemble has all of the 35 ensemble members for each GCM included.
Table 2.1: Summary of selected IPCC AR4 models, their resolution and number of ensemble members used in the ensemble average for each model from Bowden (2008).

<table>
<thead>
<tr>
<th>Short name</th>
<th>CMIP3-ID</th>
<th>Resolution</th>
<th># ensemble members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian</td>
<td>CGCM</td>
<td>2.8 x 2.8</td>
<td>5</td>
</tr>
<tr>
<td>CCSM3</td>
<td>CCSM3</td>
<td>1.4 x 1.4</td>
<td>8</td>
</tr>
<tr>
<td>ECHAM</td>
<td>ECHAM/MPI-OM</td>
<td>1.9 x 1.9</td>
<td>4</td>
</tr>
<tr>
<td>FRANCE</td>
<td>CNRM-CGCM3</td>
<td>1.9 x 1.9</td>
<td>1</td>
</tr>
<tr>
<td>GFDL</td>
<td>GFDL-CM2.0</td>
<td>2 x 2.5</td>
<td>4</td>
</tr>
<tr>
<td>JAPAN</td>
<td>MRI-CGCM3.2</td>
<td>2.8 x 2.8</td>
<td>5</td>
</tr>
<tr>
<td>PCM</td>
<td>PCM</td>
<td>2.8 x 2.8</td>
<td>4</td>
</tr>
<tr>
<td>UK</td>
<td>HADGEM1</td>
<td>1.3 x 1.9</td>
<td>2</td>
</tr>
</tbody>
</table>

2.7 Extended Reconstruction Sea Surface Temperature Version 3 (ERSST.v3)

Sea surface temperature (SST) observations from the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder day and night satellite from 1985-2006 have been merged into the ERSST.v3 dataset (Smith et al., 2008). Satellite data biases are normally associated with aerosols and clouds, both of which cause a cold bias. The satellite SST bias is adjusted relative to the merged ship and buoy SSTs before being incorporated into the dataset (Smith et al., 2008).
Chapter 3

Method of Analysis

The primary method of investigation is a water balance model in combination with application of EOF analysis of the regional Eastern Africa rain gauge rainfall. The water balance model employs rainfall at six discrete locations around the lake to construct the Lake Victoria levels. We adopt the EOF approach to isolate the contribution of individual significant EOF mode and reconstruct the lake levels based on the water balance model. The results are compared with the Lake Victoria levels constructed by using the total rainfall.

We compare the performance of the water balance model with observed Lake Victoria levels and investigate the feasibility of the water balance model for the study. Since the water balance model is based on stations, we first computed the dominant modes of variability based on station data over Eastern Africa. Unfortunately the station data we obtained does not cover precipitation more recent than 1990. We have used CRU data, after checking that it reproduces salient features consistently, to model a longer time period.
3.1 Empirical Orthogonal Function (EOF) Analysis

Empirical orthogonal function analysis was performed on precipitation in Eastern Africa in order to examine the effect of different modes of precipitation variability on rainfall over eastern Africa and compare the modes derived from various data sets. Empirical Orthogonal Function is a statistical tool used to explain the variance-covariance of geophysical data fields through a few modes of variability. Two modes are spatially and temporally uncorrelated due to the orthogonal nature of the EOF.

To calculate the EOFs the observational data is expressed in a \( n \) by \( p \) matrix where \( n \) is the number of stations and \( p \) is the number of years, eqn. 3.1. Temporal anomalies, eqn. 3.2, are found for the variable of interest for each station. The variance, eqn. 3.3, is also calculated to standardize the data matrix, eqn. 3.4. The correlation matrix, eqn. 3.5, is then constructed in order to form a non-dimensionalized version of the data such that the data has unit variance (Wilks 1995). We then generate eigenvalues by solving the characteristic equation determinant, eqn. 3.6, for \( \lambda \). The eigenvalues, \( \lambda_i \) correspond to the variance explained by each EOF mode, \( EOF_i \). Once \( \lambda \) is known, the eigenvectors are found by solving eqn. 3.7 for \( x \). The eigenvectors give the spatial pattern for each EOF mode. Finally, we construct the EOF time series for each mode using eqn. 3.8 where \( e_i \) is the eigenvector for \( EOF_i \) and \( Z_k \) is the standardized data at time \( t \).

\[
X = \begin{pmatrix}
x_{11} & x_{12} & \cdots & x_{1p} \\
x_{21} & x_{22} & \cdots & x_{2p} \\
\vdots & \vdots & \ddots & \vdots \\
x_{n1} & x_{n2} & \cdots & x_{np}
\end{pmatrix}
\]

(3.1)

\[
X' = X - \bar{X}
\]

(3.2)
\[
S = \sum_{j=1}^{n} \frac{(X'_j)^2}{n}
\]  

(3.3)

\[
D = \begin{bmatrix}
Z_{11} = \frac{x_{11} - \bar{x}}{\sqrt{S_{11}}} & \cdots & Z_{1k} = \frac{x_{1k} - \bar{x}}{\sqrt{S_{1k}}} & \cdots & Z_{1n} = \frac{x_{1n} - \bar{x}}{\sqrt{S_{1n}}} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{t1} = \frac{x_{t1} - \bar{x}}{\sqrt{S_{t1}}} & \cdots & Z_{tk} = \frac{x_{tk} - \bar{x}}{\sqrt{S_{tk}}} & \cdots & Z_{tn} = \frac{x_{tn} - \bar{x}}{\sqrt{S_{tn}}} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{p1} = \frac{x_{p1} - \bar{x}}{\sqrt{S_{p1}}} & \cdots & Z_{pk} = \frac{x_{pk} - \bar{x}}{\sqrt{S_{pk}}} & \cdots & Z_{pn} = \frac{x_{pn} - \bar{x}}{\sqrt{S_{pn}}} 
\end{bmatrix}
\]  

(3.4)

\[
R = \begin{bmatrix}
\frac{S_{11}}{\sqrt{S_{11} \sqrt{S_{11}}}} & \cdots & \frac{S_{1p}}{\sqrt{S_{11} \sqrt{S_{pp}}}} \\
\frac{S_{i1}}{\sqrt{S_{i1} \sqrt{S_{i1}}}} & \cdots & \frac{S_{ip}}{\sqrt{S_{i1} \sqrt{S_{pp}}}} \\
\vdots & \ddots & \vdots \\
\frac{S_{pi}}{\sqrt{S_{pi} \sqrt{S_{pp}}}} & \cdots & \frac{S_{pp}}{\sqrt{S_{pp} \sqrt{S_{pp}}}} 
\end{bmatrix}
\]  

(3.5)

\[det(\lambda I - R) = 0\]  

(3.6)

\[Rx = \lambda x \equiv (R - \lambda I)x\]  

(3.7)

\[
[e_{i1}, e_{i2}, \ldots, e_{ip}]^* \begin{bmatrix}
Z_{1k} \\
\vdots \\
Z_{pk}
\end{bmatrix} = \text{amp}(EOF_{i,t=k})
\]

(3.8)

There are many ways to determine how many principal components can be retained without discarding important information [North et al. (1982); Kendall (1980); Preisendorfer and...
Barnett (1977). We test for significance of the modes using Kendall’s criterion for distinctly
separated EOFs, for sample size N, that sampling error \( \delta \lambda = \lambda (2/N)^{1/2} \), associated with a
given eigenvalue \( \lambda \), must be smaller than its spacing from the neighboring eigenvalue. We then
relate the spatial patterns to known physical properties, such as ENSO and IOZM.

3.2 Reconstruction of data excluding selected EOF modes

Reconstruction of variables utilizing a systematic inclusion of a subset of eigenmodes
which account for most of the data variability has been used to filter out statistical noise by
reconstructing the data using a reduced number of EOF modes which explain most of the
variability in the dataset. In this study, we reconstructed rainfall over the lake basin without
various modes of variability to examine the contributions of the modes on Lake Victoria levels.
Our data reconstruction procedure is similar to the approach used in Weickmann and Chervin
(1988) and Semazzi et al. (1996). Since the EOF analysis was calculated based on the corre-
lation matrix, we first denormalize the data by multiplying the data by the standard deviation
for each grid point and add the resulting anomalies to the mean. The reconstruction was then
performed using the equation,

\[
q_j(\lambda, \phi) = \bar{q}(\lambda, \phi) + \sum_{i=1}^{M} g_{ij} e_i(\lambda, \phi) s(\lambda, \phi)
\]  

where \( \bar{q}(\lambda, \phi) \) is the time mean vector, M is the number of the selected set of EOFs used in
the reconstruction, \( g_{ij} \) is the principal component at time j for the eigenvector i, \( e_i(\lambda, \phi) \) is the
ith eigenvector and \( s(\lambda, \phi) \) is the standard deviation. The annual mean for the reconstructed
data is identical to the corresponding mean for the reconstructed data, independent of the num-
ber of modes used in the reconstruction or the percent of variability covered by the modes.
3.3 Reconstructed data demonstration

We demonstrate how the method described in Section 3.2 works in practice using only 3 stations. The original standardized data can be reconstructed by multiplying the EOF time series and the eigenvectors. We will use an example proof to demonstrate the EOF and its reconstruction. The proof is based on standardized data for three stations for four years. There can be $p$ number of stations for $t$ years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Jinja</th>
<th>Musoma</th>
<th>Bukoba</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>1.1194156; $Z_{11}$</td>
<td>-1.0331278; $Z_{12}$</td>
<td>1.4768055; $Z_{1p}$</td>
</tr>
<tr>
<td>1962</td>
<td>-1.1506984; $Z_{21}$</td>
<td>-0.1551227; $Z_{22}$</td>
<td>-0.2496618; $Z_{2p}$</td>
</tr>
<tr>
<td>1963</td>
<td>0.4751598; $Z_{31}$</td>
<td>1.3695650; $Z_{32}$</td>
<td>-0.6570106; $Z_{3p}$</td>
</tr>
<tr>
<td>1964</td>
<td>0.4751598; $Z_{t1}$</td>
<td>-0.1813145; $Z_{t2}$</td>
<td>-0.5701331; $Z_{tp}$</td>
</tr>
</tbody>
</table>

Using the EOF method, we can generate the Eigenvectors for $p$ number of points and $i$ number of modes; $E_{pi}$.

<table>
<thead>
<tr>
<th>mode 1</th>
<th>mode 2</th>
<th>mode 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jinja</td>
<td>-0.466419; $E_{11}$</td>
<td>0.7725303; $E_{12}$</td>
</tr>
<tr>
<td>Musoma</td>
<td>0.5502730; $E_{21}$</td>
<td>0.6347719; $E_{22}$</td>
</tr>
<tr>
<td>Bukoba</td>
<td>-0.6924196; $E_{p1}$</td>
<td>-0.0161711; $E_{p2}$</td>
</tr>
</tbody>
</table>

From the eigenvectors we can generate the EOF time series by multiplying the eigenvectors and the standardized data. For example, the EOF time series for 1961 can be constructed as follows where $A_{1i}$ is the mode $i$ 1961 EOF time series:

$$E_{11}Z_{11} + E_{21}Z_{12} + E_{p1}Z_{1p} = A_{11}$$
\[-0.466419 \cdot 1.1194156 + 0.5502730 \cdot -1.0331278 + -0.6924196 \cdot 1.4768055 = -2.113188\]

\[E_{12}Z_{11} + E_{22}Z_{12} + E_{p2}Z_{1p} = A_{12}\]

\[0.7725303 \cdot 1.1194156 + 0.6347719 \cdot -1.0331278 + -0.0161711 \cdot 1.4768055 = 0.1851004\]

\[E_{1i}Z_{11} + E_{2i}Z_{12} + E_{pi}Z_{1p} = A_{1i}\]

\[0.4306300 \cdot 1.1194156 + -0.5424613 \cdot -1.0331278 + -0.7213138 \cdot 1.4768055 = -0.0227544\]

The time series for all three modes are,

Table 3.3: Time series for three modes of variability for the three stations.

<table>
<thead>
<tr>
<th>MODE</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>-2.113188; ( A_{11})</td>
<td>0.1851004; ( A_{12})</td>
<td>-0.0227544; ( A_{1i})</td>
</tr>
<tr>
<td>1962</td>
<td>0.6244748; ( A_{21})</td>
<td>-0.98337934; ( A_{22})</td>
<td>-0.23129253; ( A_{2i})</td>
</tr>
<tr>
<td>1963</td>
<td>0.9868323; ( A_{31})</td>
<td>1.2470613; ( A_{32})</td>
<td>-0.06440734; ( A_{3i})</td>
</tr>
<tr>
<td>1964</td>
<td>0.5021304; ( A_{i1})</td>
<td>-0.44878821; ( A_{i2})</td>
<td>0.31845428; ( A_{ii})</td>
</tr>
</tbody>
</table>

To reconstruct the data, we multiply the EOF time series and the eigenvectors. For example, we can reconstruct the data for Jinja for 1961. This is the same as the rainfall for Jinja in 1961 (Table 3.1).

\[A_{11}E_{11} + A_{12}E_{12} + A_{1i}E_{1i} = Z_{11}\]

\[-2.113188 \cdot -0.466419 + 0.1851004 \cdot 0.7725303 + -0.0227544 \cdot 0.4306300 = 1.118828\]
3.4 Correlation

Linear correlation is a well-known statistical tool within climatology. Our study uses linear correlations to determine relationships between EOF mode time series from different seasons and data sets. Grid point correlations between SST anomaly fields and EOF mode time series were also calculated to help determine their sources of variability.

3.5 Water Balance Model

Tate et al. (2004) and others (Sene and Plinston 1994; Sene 2000), developed a water balance model to estimate the level of Lake Victoria at the end of a given year ($L_n$) by calculating the change in lake level during the year ($\Delta L$) and adding it to the projected level for the previous year ($L_{n-1\text{(estimated)}}$).

The change in lake level is calculated as:

$$\Delta L_n = \left[ P - E + \frac{Q_{in} - Q_{out}}{A} \right]_n$$  

(3.10)

Where $P$ and $E$ are precipitation and evaporation over the lake, respectively, $Q_{in}$ is inflow to the lake from tributaries, $Q_{out}$ is outflow from the dams at Jinja, and $A$ is the surface area of Lake Victoria. Evaporation is assumed constant at 1595 mm/year. Precipitation over the lake, the dominant source of water for Lake Victoria, is assumed to be a linear function of the average annual rain gauge precipitation at eight stations (Jinja, Entebbe, Kisumu, Musoma, Bukoba, Mwanza, Kalangala and Kagondo) along the perimeter of the lake. When gridded precipitation datasets are used (CRU, FvGCM, RegCM3, IPCC ensemble), the precipitation is first interpolated to the six station using WENO interpolation, and then the interpolated station precipitation values are used in place of station gauge precipitation. The inflow, $Q_{in}$, from five
tributaries (Nzoia, Yala, Sondu, Awach Kaboun, and Kagera) is a non-linear function with $P$ as the input. Subcatchment rainfalls, $P_c$, for each of the five tributaries were estimated using regressions of annual total data for the period 1965-1990 (table 3.4). The runoff coefficient for each catchment is then estimated from the subcatchment rainfall by linear regression derived by Sutcliffe and Parks (1999) as:

$$r_c = 0.0002P_c - 0.1386$$

(3.11)

The runoff from each subcatchment to Lake Victoria is then estimated by multiplying each subcatchment’s rainfall by the runoff coefficient and the subcatchment area. The total inflow to Lake Victoria is estimated as the runoff of Nzoia, Yala, Sondu and Awach Kaboun scaled up by a factor of 2.7 on an annual basis, plus the flow of the Kagera increased by 10% to account for the flow of the Ngono tributary, which joins it downstream of the gauging station (Tate et al., 2004; Institute of Hydrology, 1985). The outflow, $Q_{out}$, is calculated from the Agreed Curve which has the form:

$$Q_{out_n} = \alpha(L_n - \beta)^\gamma$$

(3.12)

where $\alpha$ and $\gamma$ are empirical coefficients, and $\beta$ is a datum value, or reference point against which measurements are made (Sene, 2000). Substituting (Eq. 3.12) into (Eqn 3.10) produces:

$$\Delta L_n = \left[ \left( P - E + \frac{Q_{in}}{A} \right)_n - \left( \alpha \left( L_{(n-1)observed} + \Delta L_n - \beta \right)^\gamma \right) /A \right]$$

(3.13)

where $\alpha = 70.332$ (or 66.3); $\beta = 8.058$ (or 7.96); and $\gamma = 2.00$ (or 2.01) depending on the equation used (Koren, 1995; Sene, 2000). Since $\Delta L_n$ appears as a term on the left hand side and in the nonlinear term on the right hand side of (Eqn. 3.13), the equation must be solved iteratively. This procedure is executed using two iterations setting $\Delta L_n = 0$ on the first iteration.
Figure 3.5 summarizes the algorithm for estimating the lake level using Tate’s (2004) method.

Table 3.4: Regressions of rainfall for 1956-1990. $P_c =$catchment rainfall; $P_l =$lake rainfall. (from Tate et al., 2004)

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Regressions</th>
<th>Correlation, $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nzoia</td>
<td>$P_c = (0.685 \times P_l) + 154.5$</td>
<td>0.52</td>
</tr>
<tr>
<td>Yala</td>
<td>$P_c = (0.951 \times P_l) + 64.7$</td>
<td>0.61</td>
</tr>
<tr>
<td>Sondu</td>
<td>$P_c = (0.666 \times P_l) + 302.6$</td>
<td>0.39</td>
</tr>
<tr>
<td>Awach Kaboun</td>
<td>$P_c = (0.785 \times P) + 337.4$</td>
<td>0.29</td>
</tr>
<tr>
<td>Kagera</td>
<td>$P_c = (0.556 \times P_l) + 142.8$</td>
<td>0.60</td>
</tr>
</tbody>
</table>
Figure 3.1: Water balance model algorithm for Lake Victoria used by Tate et al. (2004). The dashed arrow is not followed in the modified algorithm used in this study.
3.5.1 Agreed Curve Outflow

There are four versions of the Agreed Curve. Koren (1995) created an agreed curve, \( Q_{outn} = 70.332(L_n - 8.058)^2 \) \( Sene (2000) \) developed a similar formula with slightly different coefficients, \( Q_{outn} = 66.3(L_n - 7.96)^2 \) by fitting a curve to observed levels and discharges over a long period of time. According to Sutcliffe and Petersen (2007), the actual equation used by the Directorate of Water Development is \( Q_{outn} = 132.9238(L_n - 8.486)^{1.686} \). These three formulations produce similar results. Figure 3.2 shows the Agreed Curve for discharge from the Owens Falls Dams based on Lake Victoria’s level. Power Planning Associates Ltd (2007) have suggested a constant Agreed Curve, or Agreed Curve by steps, where the release would be a constant 687 \( m^3/s \) during low hydrology scenarios and 1247 \( m^3/s \) during high hydrology scenarios. The low hydrology scenario is defined as annual variations around an average net basin supply (NBS) of 660 \( m^3/s \), which is consistent with the years 1900-1959. The high hydrology scenario is defined as the NBS averaging more than 1000 \( m^3/s \), which is consistent with the years 1960-1999. Annual NBS for 1900-2005 is shown in figure 3.3. They then suggest that in an optimized operation situation, the lake would not fall to the minimum acceptable value if the release had been reduced to a constant intermediate value, approximately 900 \( m^3/s \), as soon as the lake level decreases below approximately 1135 m above sea level. The curve developed by Sene (2000) will be used in this study.
Figure 3.2: The Agreed Curve for outflow from Lake Victoria based on lake levels.

Figure 3.3: Yearly net basin supply (blue) and outflow (red) for Lake Victoria (1900-2005) from Power Planning Associates (2007).
3.6 Bias Removal

We used a simple normalization technique to adjust the model systematic bias for FvGCM, RegCM3 and the IPCC ensemble. This is done using the equation:

\[(y_i - y_{avg}) = \frac{\sqrt{S_{lx}}}{\sqrt{S_{ly}}} + x_{avg}\]  

(3.14)

where \(y\) is the model precipitation; \(y_{avg}\) is the mean model precipitation; \(\sqrt{S_{lx}}\) is the observed standard deviation; \(\sqrt{S_{ly}}\) is the model standard deviation; and \(x_{avg}\) is the mean observed precipitation. For observed values we use CRU precipitation. The bias correction average and standard deviation values are calculated for each month for all grid points \(i\). The normalization technique preserved the variance but adjusts the values to the observed mean. We apply this method to the A2 scenario runs by removing the model mean for the reference period \((y_{avg})\) and adding the observed reference mean \((x_{avg})\). The difference between the observed mean and the observed A2 precipitation values will still have the mean climate change signal while preserving the variance of the A2 simulations.
Chapter 4

Results

4.1 Lake Victoria Levels

We use a water balance model developed by Tate et al. (2004) to investigate the role of the following factors in modulating the Lake Victoria levels: climate variability factors: the regional response to ENSO and IOZM and other interannual and decadal climate modes, anthropogenic causes: distorted outflow from dams and non-linear feedbacks due to changes in land cover, and non-climate geophysical changes: the time necessary for lake levels to adjust to equilibrium and changes in level due to accumulation of bottom sedimentation.

We first show that we can reproduce Lake Victoria levels using precipitation from six of the original eight stations in the water balance model. Unlike Tate et al. (2004) we start the model in 1960 so that we can use precipitation from stations in the East African region to obtain and analyze the significant modes of variability in Section 4.3 for the same years. We then show that CRU TS 3.0 precipitation in the model gives similar levels for the same time period. This is done in order to obtain confidence so we can use the longer and more current 1950-2005 CRU TS 3.1 data to investigate the role of climate factors on lake levels over the longer time
period.

Lake Victoria levels calculated using the water balance model are shown as a red line in figure 4.1. Our modeled levels do not capture the sudden increase in levels from 1961-64 as well as the levels modeled by Tate et al. (2004) (Fig. 4.2). This is most likely because the water balance model run by Tate et al. (2004) was initialized earlier than ours. Their model run predicts higher than actual levels, starting approximately twenty years before the jump in lake levels. These higher modeled levels give their lake levels a “boost” when it gets to the early 1960’s, where the model had already accumulated extra water in the lake that then was included in the 1961-64 levels. Our model starts before the jump and does not over predict lake levels before 1961; therefore it does not have this extra water to use towards the higher levels in 1963-64.

After the jump in levels, our model run does a good job of capturing the lake level, while the model run by Tate et al. (2004) under predicts lake levels by small amounts in the 1970’s and 1980’s followed by predicting higher than actual lake levels in the mid to late 1990’s. When CRU precipitation is used in the model (Fig. 4.3), the first two years of the 1961-64 jump are captured, while the modeled lake levels are a little low for 1963 and 1964. The model does well until the 1980’s when it under-predicts lake levels by up to 0.5 meters in 1983 and then predicts higher than actual levels in the late 1990’s through 2005, over-predicting by as much as 0.73 m in 2005 which is most likely related to the over-release from Nalubaale and Kiira dams found by Kull (2006(a) and expanded upon in Kull (2006(b). For the subsections 4.1.1 through 4.1.8 we will use the 1949-2005 CRU modeled levels as the true levels for comparison purposes only in order to focus on the influence of the potential sources of lake level variability being investigated and not model error.
Figure 4.1: Station precipitation in water balance model. Blue line is actual lake levels from satellite altimetry, red line is modeled level.

Figure 4.2: Modeled vs observed Lake Victoria levels and outflows, 1925-2000. Top two lines are observed and modeled levels, lower two lines are observed and modeled outflow. From Tate et al. (2004), their figure 4.
4.1.1 ENSO and other inter-annual modes of precipitation variability

In order to further verify that CRU is a reasonable alternative for station gauge precipitation we perform an EOF analysis on OND and annual precipitation for each dataset over the same time period (1961-90) for comparison. If the significant modes of OND and annual variability are comparable for both datasets, we can then use the time series from a longer EOF analysis on CRU to investigate the role of these annual modes of variability on Lake Victoria levels.

Station precipitation and CRU precipitation each have 2 significant modes of precipitation for the OND season accounting for 51.9 percent (first mode) and 6.3 percent (second mode) of the variability. The time series and first mode of variability for OND station precipitation is shown in figure 4.4. We describe the OND station modes further in section 4.3.1, however the first mode is ENSO while the second mode is a dipole mode described by Schreck and
Semazzi (2004). The first mode of CRU precipitation accounts for approximately 60 percent of the variability for that season, while the second mode accounts for just under 9 percent (Fig. 4.7). The time series of the first mode has a correlation of 0.991 with the corresponding mode for station variability, while the second mode has a correlation of 0.752 with its corresponding mode.

There are two significant modes of variability for annual station precipitation (Fig. 4.10). The time series and first mode of variability for annual station precipitation is shown in figure 4.11. The first annual EOF mode accounts for 33 percent of the variability in station precipitation (Fig. 4.10). The loading is mostly positive with the time series showing a high amount of variability but a general drying trend after 1961 (Fig. 4.11). The first mode CRU accounts for 39 percent of variability (Fig. 4.13). The time series and loadings are shown in figure 4.14. The loading is very similar to the loading for the stations with a mostly positive loading. The time series has a 0.983 correlation with the time series of the first mode from the station data. The time series of this mode has a 0.814 correlation with that of the first mode of OND precipitation. This mode is most likely ENSO as in the first mode from OND precipitation, complicated by influences from the other seasons. We will go into the identification of the modes further in section 4.3.

The second annual EOF mode for the station gauge precipitation accounts for almost 10 percent variance. The loading is negative surrounding the lake, north into Uganda and halfway into Kenya, while it in extreme southern Kenya and southwestern Tanzania there is a positive pattern (Fig. 4.12). The corresponding CRU mode has a similar pattern with a negative loading surrounding the lake and to the north into Uganda and Kenya and a positive loading to the south (Fig. 4.15). The time series has a 0.868 correlation with the time series of the corresponding mode from the station data. The time series shows a decadal oscillation similar to the OND second mode, however there is only a 0.532 correlation between the two once the data is filtered.
using a ten year running mean.

Even though the third mode is not significant for station precipitation, it is significant for CRU and has just over 9 percent of the variability. The third mode of CRU precipitation has a negative pattern to the north and south of the lake basin with a positive loading to the east (Fig. 4.16). Over the lake there is a more neutral loading with areas of positive and negative loadings. The time series has a correlation of 0.744 with the time series for the third mode of station precipitation (not shown).

Figure 4.17 shows lake levels obtained using precipitation reconstructed from individual annual modes of station precipitation variability found above compared to the level obtained using the complete station precipitation dataset. Reconstructing the precipitation accounted for by the first mode of annual station variability shows that it accounts for most of the variability in Lake Victoria levels, while the effects of the second and third modes on the variability of lake levels is negligible. While the remaining modes account for 68 percent of the variability, when precipitation is reconstructed using individual modes, only the first mode has an effect on lake levels.

There is a record IOZM in 1961 when lake levels suddenly started increasing. This record IOZM shows up in the time series of annual precipitation over the lake as a high peak in 1961 (Fig. 4.18). It is followed by 3 years of above average precipitation. We investigate the sensitivity of the lake to this type of occurrence by adjusting the precipitation in the water balance model from only 1961 (Fig. 4.19) and 1961-64 (Fig. 4.20) to the pre-jump average. The record IOZM in 1961 does not fully explain the jump in lake levels. Without the extreme, amount of rainfall in 1961, the lake level persists near the 1958-60 levels during 1961 and then there are large increases in 1962-64, followed by slightly lower levels until the levels increase again in 1967-68. It is interesting to note that changing the precipitation in that one year causes a change in modeled lake levels for several years. It takes 20 years for the lake to
return to within 0.01 meters of what the levels would have been without this change. This will be explained further in section 4.1.3. When the extreme rainfall event in 1961-64 is removed in the same manner, there is still a smaller, close to 1 meter, increase in levels from 1966-68. The modeled lake levels for both scenarios do not reach the same height as the non-modified lake for approximately 20 years in each scenario because the water balance model does not have the higher levels from the years with modified precipitation to build upon. After the hydrologic adjustment time, the precipitation from those years is not a factor in the lake levels.

![Scree Plot OND Station EOF](image)

Figure 4.4: Scree Plot OND Station EOF
Figure 4.5: Station OND EOF1 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral. Stations used in the WBM are starred.
Figure 4.6: Station OND EOF2 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are starred.
Figure 4.7: Scree Plot OND CRU 3.0 EOF
Figure 4.8: CRU 3.0 OND EOF1 time series (top) and loading (bottom). Stations used in the WBM are starred.
Figure 4.9: CRU 3.0 OND EOF2 time series (top) and loading (bottom)
Figure 4.10: Scree Plot annual Station EOF
Figure 4.11: Station annual EOF1 time series (top) and loading (bottom)
Figure 4.12: Station annual EOF2 time series (top) and loading (bottom)
Figure 4.13: Scree Plot annual CRU EOF
Figure 4.14: CRU 3.0 annual EOF1 time series (top) and loading (bottom). Stations used in the WBM are marked with a star.
Figure 4.15: CRU 3.0 annual EOF2 time series (top) and loading (bottom). Stations used in the WBM are marked with a star.
Figure 4.16: CRU 3.0 annual EOF3 time series (top) and loading (bottom). Stations used in the WBM are marked with a star.
Figure 4.17: Lake Victoria levels modeled using significant modes of annual precipitation variability for stations in Eastern Africa. Modeled using total station precipitation (black line with circles), first EOF mode of annual precipitation variability (blue line with asterisks); second EOF mode of annual precipitation variability (red line with triangles), and third EOF mode of annual precipitation variability (green line with squares).
Figure 4.18: Precipitation over Lake Victoria estimated from CRU gridded precipitation.
Figure 4.19: Lake Victoria levels modeled setting 1961 to pre-jump climatology (black) compared to modeled with all years (blue).
Figure 4.20: Lake Victoria levels modeled setting 1961 through 1964 to pre-jump climatology (black) compared to modeled with all years (blue).

4.1.2 Decadal precipitation variability

Examining the values for precipitation over the lake (Fig. 4.18), there is a decadal oscillation. We filtered the precipitation over Lake Victoria calculated from the interpolation of CRU gridded precipitation, with no EOF filtering, to the six stations (section 3.5) using a 10 year running mean and fft analysis, where we then reconstructed the precipitation using frequencies below 11 years, 15 years and 19 years (Fig. 4.21). Since the 10 year running mean causes data loss at both ends of the time series, only the reconstructed fft time series were used as input to the water balance model in order to start the water balance model using 1949 levels for
comparison in sections 4.1.7 and 4.1.8. The resulting levels are shown in figure 4.22. The levels modeled using low frequency precipitation are similar and approximate the low frequency oscillation in lake levels. with the 19 year fft levels peaking slightly later than the other two in the late 1960’s and reaching its lowest point in 1986, a couple of years before the other two. The peak in lake level shifts depending on which frequencies are kept. This is an artifact of the fft smoothing in both directions.

Figure 4.21: Low frequency precipitation over Lake Victoria. 10 year running mean of precipitation (blue circles), 19 year fft (red triangles), 15 year fft (green circles) and 11 year fft (gray squares).
Figure 4.22: Lake Victoria levels modeled using low frequency precipitation over Lake Victoria: 10 year running mean of precipitation (blue circles), 19 year fft (red triangles), 15 year fft (green circles) and 11 year fft (gray squares).

4.1.3 Lake hydrologic adjustment to equilibrium

Since the Agreed Curve approximates the amount of water that would naturally flow out of Lake Victoria if there were no dams, the lake can be treated like an open lake and a time for hydrologic adjustment to equilibrium can be found. The adjustment time is different for individual lakes based on their size (Sene, 1998). This hydrologic adjustment time and resulting equilibrium level do not depend on starting level. Salas et al. (1982) found an adjustment time of approximately 10 years. Sene and Plinston (1994) found the adjustment time to be 19 years for levels to reach 1 cm from equilibrium for an initial departure from equilibrium of one meter.
While their calculations give different results, it is clear that the hydrologic adjustment time is on a decadal time scale. The changes in equilibrium levels are considered in this study to be a result of changes in the long term mean in precipitation over the lake basin and deviation from the Agreed Curve. However, it should be taken into account when interpreting lake levels. Comparing the water balance model run with the average precipitation over the lake before the 1961 jump, to the model run with average precipitation from 1965-2005, after the jump (Fig. 4.23) there is a new regime in precipitation with a higher average after 1965, even without the four years of consistent, above average precipitation. Starting the water balance model in 1964 and using the mean 1964-1990 precipitation shows a decrease in levels about equal to the average decrease in actual levels during this time as the lake levels reach a new equilibrium consistent with the new mean precipitation after the peak in rainfall and level (Fig. 4.24).

Figure 4.23: Lake Victoria levels modeled using pre-jump (1950-1960) (green) and post jump (1965-2005) (black) average precipitation over Lake Victoria compared to levels modeled using CRU precipitation (blue).
4.1.4 Outflow from dams violating the Agreed Curve

While several studies have investigated the possibility of the violation of the agreed curve by the outflow from Owen’s Falls Dam, as one of the explanations for the 1961-64 increase in Lake Victoria Levels [Kite (1981)] showed using published excesses and shortages of released water on an annual basis for 1957-1979, that dam usage has caused a cumulative rise in lake level of just under 3 cm (Table 4.1). From 1961-1979, the table shows an excess release which would decrease Lake Victoria levels during this time. [Sene and Plinston (1994)] examined recorded releases from the Owen Falls dam site and compared those to expected releases from the extended Agreed Curve (Fig. 4.25). They found that since operations started at the Owen Falls dam, releases have followed the Agreed Curve for the most part and compensatory releases have usually been made at a later date when departures have occurred. They found that
the effects of the departures from the Agreed Curve were small up to 1994. More recently, Kull (2006(a) investigated the drop in Lake Victoria levels from 2002-2005, using a water balance simulation for 2004 and 2005. He found that the severe drops in levels from 2004-2005 were approximately 45% due to drought and 55% due to over-releases from Nalubaale and Kiira dams. Kull (2006(a) extended these results by sampling technical reports and interviews from 2005 to compare reported dam releases to estimated lake levels from USDA (2005).

Table 4.1: Possible effect of Owen Falls Dam on Lake Victoria levels adapted from (Kite, 1981), his Table 2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Excess (+) or shortage (-) in River Nile flows ((10^6 \text{m}^3))</th>
<th>Possible increase (+) or decrease (-) in natural level of Lake Victoria (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>+6.37</td>
<td>-0.01</td>
</tr>
<tr>
<td>1958</td>
<td>+30.44</td>
<td>-0.05</td>
</tr>
<tr>
<td>1959</td>
<td>+17.73</td>
<td>-0.03</td>
</tr>
<tr>
<td>1960</td>
<td>+1.15</td>
<td>0</td>
</tr>
<tr>
<td>1961</td>
<td>+61.75</td>
<td>-0.09</td>
</tr>
<tr>
<td>1962</td>
<td>+66.24</td>
<td>-0.10</td>
</tr>
<tr>
<td>1963</td>
<td>+60.73</td>
<td>-0.09</td>
</tr>
<tr>
<td>1964</td>
<td>+468.70</td>
<td>-0.69</td>
</tr>
<tr>
<td>1965</td>
<td>+3183.20</td>
<td>-4.68</td>
</tr>
<tr>
<td>1966</td>
<td>+896.08</td>
<td>-1.32</td>
</tr>
<tr>
<td>1967</td>
<td>+40.92</td>
<td>-0.06</td>
</tr>
<tr>
<td>1968</td>
<td>+20.27</td>
<td>+0.03</td>
</tr>
<tr>
<td>1969</td>
<td>+571.05</td>
<td>-0.84</td>
</tr>
<tr>
<td>1970</td>
<td>-503.99</td>
<td>+0.74</td>
</tr>
<tr>
<td>1971</td>
<td>+30.71</td>
<td>-0.05</td>
</tr>
<tr>
<td>1972</td>
<td>+16.30</td>
<td>-0.02</td>
</tr>
<tr>
<td>1973</td>
<td>-150.40</td>
<td>+0.22</td>
</tr>
<tr>
<td>1974</td>
<td>-1188.65</td>
<td>+1.76</td>
</tr>
<tr>
<td>1975</td>
<td>-1585.68</td>
<td>+2.34</td>
</tr>
<tr>
<td>1976</td>
<td>+209.10</td>
<td>-0.31</td>
</tr>
<tr>
<td>1977</td>
<td>+289.07</td>
<td>-0.43</td>
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<tr>
<td>1978</td>
<td>-1161.51</td>
<td>+1.71</td>
</tr>
<tr>
<td>1979</td>
<td>-3316.21</td>
<td>+4.84</td>
</tr>
<tr>
<td></td>
<td>-2569.08</td>
<td>+2.89</td>
</tr>
</tbody>
</table>
4.1.5 Modulation due to changes in land and water use

The water balance model estimates tributary inflow using a linear regression between the runoff coefficient and subcatchment rainfall which are estimated from rainfall directly over the lake. Changes in land and water use in the catchments could change these relationships in the future. For example, more water could be used from the tributaries for irrigation before it reaches the lake or deforestation could change the runoff coefficient and alter the climate of the basin. In retrospect, based on our results, the contribution of this factor is relatively minor. Moreover, further investigation of this factor is beyond the scope of this study.

4.1.6 Bottom sedimentation, thermal expansion, and changes in groundwater

Several factors have not been studied fully in estimating Lake Victoria levels. Among these are sedimentation accumulation at the bottom of the lake, changes in groundwater, and thermal expansion from warming lake water.
Kayombo and Jorgensen (2007) found a rate of sediment accretion of 1 mm/yr. Swallow et al. (2001) showed the sedimentation rate at the river inlets in the catchment area was 1 cm/yr, suggesting that sediment accumulates at the lake shore. The effect of groundwater is assumed to be negligible due to the absence of data (Krishnamurthy and Ibrahim; Piper et al., 1986).

In retrospect, based on our results, the contribution of these factors are relatively minor. Moreover, further investigation of these factors is also beyond the scope of this study.

4.1.7 Relative contribution of different factors to Lake Victoria level jump 1960-64

The percentage of ΔL was calculated by dividing the change in level from 1960-64 using the time series of the mode under investigation by the change in level for the same years in the water balance model using CRU. All water balance model runs were started in 1949 and run through 2005. Since the decadal harmonic was performed on the full precipitation data set instead of individual EOF modes, the decadal harmonic is subtracted from the EOF mode time series in order to separate the two factors before running the water balance model. The change in levels for release, construction and sediment were estimated using the references in table 1. We estimated the effect of over- and under-release by adding the possible increase or decrease in the level of Lake Victoria from 1961 through 1964 found in table 2 of Kite (1981). The possible changes in level found by Kite (1981) for each year equal are assumed to be small enough that they do not affect Agreed Curve outflow.

Table 4.3 shows that the first mode of variability from the EOF analysis on CRU annual precipitation accounts for between 28% and 43.7% of the jump from 1961-64 once the decadal mode is removed, while the decadal mode accounts for between 18.4 and 34.2% of the jump. These two modes account for 62% of the jump, no matter what wavelengths were kept in the
fft analysis. The remaining modes each account for less than 10% of the jump, with release from the Nalubaale dam reducing the jump by half of a percent.

4.1.8 Relative contribution of factors to Lake Victoria level decline 1965-2005

We focus on the drop in levels from 1965-2005 using the same technique described in section 4.1.7. Using CRU in the water balance model, the level drops by 0.86 meters during this time, while the satellite altimetry derived levels show a drop of 1.7 meters. There is a large discrepancy between modeled levels and actual lake levels from 1997 to 2005, with the model predicting higher than actual levels during these years. Without further information on releases from Nalubaale and Kiira dams, we are unable to determine the cause of this discrepancy. The main cause of the decrease in levels is the lake reaching a new equilibrium in response to mean precipitation from 1965-2005 being lower than the four years of extreme precipitation which caused the jump in levels investigated in section 4.1.7. This accounts for approximately 73% of the decline in levels from 1965-2005.

The remaining factors each account for less than 10% of the decline. Even though ENSO/IOZM account for a majority of the interannual variability in lake levels, the decadal oscillation accounts for more of the decline than ENSO/IOZM.

Table 4.2: Calculations to determine contribution of factors mentioned in section 4.1 to changes in Lake Victoria levels from 1949-64 and 1965-96.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Data/Source</th>
<th>Method</th>
<th>output</th>
<th>uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decadal</td>
<td>CRU (1950-2005)</td>
<td>decadal filter (19 year fft filter)</td>
<td>% of total ΔL</td>
<td>changing window of filter (eg 10,15, 20 y cycle)</td>
</tr>
<tr>
<td>ENSO/IOZM</td>
<td>CRU</td>
<td>annual EOF 1 time series in WBM-decadal harmonic</td>
<td>% of total ΔL</td>
<td>subtraction of decadal mode</td>
</tr>
<tr>
<td>Adjustment</td>
<td>CRU</td>
<td>result of previous lake level and precipitation over lake basin</td>
<td>% of total ΔL</td>
<td></td>
</tr>
<tr>
<td>Trend</td>
<td>CRU</td>
<td>linear regression in R</td>
<td>% of total ΔL</td>
<td></td>
</tr>
<tr>
<td>Over/under release</td>
<td>citation</td>
<td>Kite (1981), Sene and Hinton (1991), Kull (2006)</td>
<td>% of total ΔL</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>citation</td>
<td>Kite (1981), Sene and Hinton (1991)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land/water cover area, deforestation</td>
<td>citation</td>
<td>Kayombo and Jorgensen (2000)</td>
<td>believed to be small</td>
<td></td>
</tr>
<tr>
<td>ΔL due to bottom sedimented erosion</td>
<td>citation</td>
<td>Kayombo and Jorgensen (2000)</td>
<td>believed to be small</td>
<td></td>
</tr>
<tr>
<td>ΔV due to thermal expansion</td>
<td>citation</td>
<td>Krishnamurthy and Briefle (1984)</td>
<td>-1 meter</td>
<td>believed to be small</td>
</tr>
<tr>
<td>Δgroundwater</td>
<td>citation</td>
<td>Krishnamurthy and Briefle (1984)</td>
<td>believed to be small</td>
<td></td>
</tr>
</tbody>
</table>

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Figure 4.26: Effects of various modes of variability in Lake Victoria levels. Blue circles: CRU in the water balance model, Purple +’s: EOF first mode precipitation. minus decadal precipitation. in water balance model, Red triangles: decadal, Black asterisks: trend from 1950-2005 CRU in water balance model (similar to average over same time period), Green triangles: 1950-1960 average precipitation. in water balance model.

Table 4.3: Estimation of amount of change in level, 1949-1964, covered by each factor mentioned in section 4.1 and confidence.

<table>
<thead>
<tr>
<th>mode</th>
<th>% of total ΔL</th>
<th>confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decadal</td>
<td>18.4</td>
<td>between 18.4% and 34.2%</td>
</tr>
<tr>
<td>ENSO/IOD/ZM (EOF1)</td>
<td>43.5 (When 19 year fft is subtracted out)</td>
<td>58.1% w/ decadal included, between 28% and 43.7% w/ fft removed</td>
</tr>
<tr>
<td>Decadal + (EOF1 - Decadal)</td>
<td>62</td>
<td>±0.1%</td>
</tr>
<tr>
<td>Adjustment</td>
<td>7.8 (WBM reaching equilibrium using 1950-60 pre-jump mean)</td>
<td>high</td>
</tr>
<tr>
<td>Trend</td>
<td>4.1 (1950-2005 trend)</td>
<td>depends on when trend was taken</td>
</tr>
<tr>
<td>Over/under release</td>
<td>7.5 (WBM reaching equilibrium using 1950-60 pre-jump mean)</td>
<td>high</td>
</tr>
<tr>
<td>Construction</td>
<td>included with Over/under release</td>
<td>N/A</td>
</tr>
<tr>
<td>Land/water cover area, deforestation</td>
<td>considered small</td>
<td>low, needs more study</td>
</tr>
<tr>
<td>ΔL due to bottom sediment/sediment erosion</td>
<td>0.2</td>
<td>high</td>
</tr>
<tr>
<td>ΔV due to thermal expansion</td>
<td>0 (very small)</td>
<td>low, beyond scope of study</td>
</tr>
<tr>
<td>Δgroundwater</td>
<td>0 (very small)</td>
<td>low, beyond scope of study</td>
</tr>
</tbody>
</table>

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Table 4.4: Estimation of amount of change in level, 1965-2005, covered by each factor mentioned in section 4.1 and confidence.

<table>
<thead>
<tr>
<th>mode</th>
<th>% of total $\Delta L$</th>
<th>confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decadal</td>
<td>3.3%</td>
<td>between -4 and 6.8%</td>
</tr>
<tr>
<td>ENSO/IOZM (EOF1)</td>
<td>0 (When 19 year fft is subtracted out)</td>
<td>13.4 w/ decadal included, between 2% and 0% w/ fft removed</td>
</tr>
<tr>
<td>Decadal + (EOF1 - Decadal)</td>
<td>4</td>
<td>+/- 2.8%</td>
</tr>
<tr>
<td>Adjustment</td>
<td>73.1 (WBM reaching equilibrium using 1965-2005 post-jump mean)</td>
<td>high</td>
</tr>
<tr>
<td>Trend</td>
<td>-3.6 (1950-2005 trend)</td>
<td>depends on when trend was taken</td>
</tr>
<tr>
<td>Over/under release</td>
<td>unable to determine</td>
<td>low</td>
</tr>
<tr>
<td>Construction</td>
<td>included with Over/Under release</td>
<td>N/A</td>
</tr>
<tr>
<td>land/water cover area, deforestation</td>
<td>considered small</td>
<td>low, needs more study</td>
</tr>
<tr>
<td>$\Delta L$ due to bottom sediment/soil erosion</td>
<td>0.2</td>
<td>high</td>
</tr>
<tr>
<td>$\Delta V$ due to thermal expansion</td>
<td>0 (very small)</td>
<td>low, beyond scope of study</td>
</tr>
<tr>
<td>$\Delta L_{groundwater}$</td>
<td>0 (very small)</td>
<td>low, beyond scope of study</td>
</tr>
</tbody>
</table>

4.2 21st Century projection of Lake Victoria Levels

To estimate the projected changes in the levels of Lake Victoria in response to climate change, we used the projected rainfall from two primary sources. One source is the downscaled FvGCM rainfall using the RegCM3 model (Bowden, 2008). As explained in section 3.5 for CRU data, the gridded rainfall is interpolated to six stations to provide input to the Water Balance Model. The second source are the IPCC ensemble projections described in section 2.6.

Figure 4.27 shows the preliminary results based on downscaling of the FvGCM global model projection simulations using RegCM3. The regional model projections reveal details which are not in the FvGCM and the average of 9 AR4 global model projections where all the IPCC models exhibit wetter conditions throughout the region. Based on these preliminary results, it is clear that the largest projected climate change signal in the interior of East Africa is located over the Lake Victoria basin for all the three types of climate change projections. The regional climate model (RegCM3), the FvGCM (1 degree resolution) and the coarser resolution 9 member IPCC GCM ensemble average agree on this outcome. However, the intensity of the signal gets larger with increasing resolution and it is weakest with the IPCC AR4 ensemble.
average. Since all three models show similar features, specifically around the lake basin, we feel confident using their output in the water balance model.

Since the lake level in 2070 is unknown, several initial conditions are used in modeling Lake Victoria levels from 2071-2100. Figure 4.27 shows the resulting lake levels for RegCM3 and the IPCC ensemble projections. FvGCM is not shown due to similarity to RegCM3 results. The future levels from all three models give projected lake levels of 14 to 16 meters. The higher resolution RegCM3 gives higher lake levels due to the larger amount of intensity in the signal over the lake. There is also more variability in the regional climate model (RegCM3) due to the fact that it is one model run, while the IPCC AR4 ensemble is an ensemble of 9 model ensembles which filters out any variability in the time series of precipitation over the lake. While these levels are almost 2 meters higher than the current lake levels and over a meter higher than the 12.91 maximum lake level in December 1963, the lake level has reached an average level of approximately 14 meters during 1876 to 1880, as reported by missionaries at Buganda and shown in figure 4.2 [Nicholson, 1998].

We take the more conservative 14 meter increase from the IPCC AR4 ensemble and map the flooding that increase would cause in ESRI ArcMap. This is done by first mapping a SRTM 90 m resolution digital elevation model of the area downloaded from http://edcns17.cr.usgs.gov/EarthExplorer/. The current levels are 11.9 m (1,134 meters above sea level) at Jinja gauge, which is the level Riebeek (2006) states the lake stayed above this level until December 2005 when the levels dropped rapidly. The current (11.9 m) and future (14 m) lake levels are then converted from heights at Jinja gauge to heights above sea level, considering the Jinja gauge to be 1122.1 m above sea level. The values from the DEM are then subtracted from the current and future lake heights using the raster calculator tool in the Spatial Analyst toolbox. Positive values are considered to be under water and negative values are not. Figure 4.30 shows the result of this analysis for the entire lake. There will be more flooding in NW
sector of lake, so we will focus on this region. Figure 4.31 shows projected flooding on the northwest side of Lake Victoria if levels reach 14 meters. The flooding focuses on the area around Masaka. Figure 4.32 shows flooding near Kampala in Nakivubo wetland. While these areas are mostly swamp, there has been encroachment on this flood land by people who build houses and businesses in these locations. Nakivubo wetland is also used for sewage control (Kyambadde et al., 2004). A railroad track near Fort Bell, Uganda is among the areas that would be flooded.

The modeled A2 scenario levels can be used when planning for future use of hydroelectric dams. Power Planning Associates (2007) recommended a new “constant release” or “Agreed Curve by steps” rule for releasing water from Kiira and Nalubaale dams while working on Bujagali II dam proposals. This rule was suggested in order to follow the Agreed Curve but allowing for a constant release to be applied when the lake fluctuates within a certain range. They recommend a “low hydrology” scenario where the mean release from Lake Victoria should be kept around a value of $687 \text{ m}^3/\text{s}$ when the lake level is between 1133.5 and 1135.0 meters above sea level (between 10.64 and 12.14 m at Jinja gauge) and an “high hydrology” scenario where the mean release is kept near $1247 \text{ m}^3/\text{s}$ when the lake level is sustained above 1135 meters above sea level (12.14 m at Jinja gauge). Power Planning Associates base the “high hydrology” scenario on the 1961-64 levels, followed by approximately 35 years with an average net inflow of $1200 \text{ m}^3/\text{s}$ during the entire period. The current Agreed Curve rule release is between $1300 \text{ m}^3/\text{s}$ and $1400 \text{ m}^3/\text{s}$ in the water balance model for the projected lake levels of around 14 meters. A new higher release scenario should be created for this scenario as a release of less than that amount would cause lake levels to increase even further. This scenario should be taken into account while a new Nile Basin treaty is being formed to share Nile River water between Egypt, Sudan, Ethiopia, the Democratic Republic of Congo, Uganda, Tanzania, Kenya, Burundi and Rwanda.
This information is potentially highly valuable over the River Nile basin in predicting future outflow from Lake Victoria which could be used to assess future use of hydroelectric dams and other applications such as land use and infrastructure planning over Lake Victoria basin.

Figure 4.27: Rainfall projections (A2: 2071-2100 average) minus (RF: 1961-1990 average) for the Oct-Dec short rains: (left) RegCM3 (40 km grid); (center) 2-member FvGCM ensemble average); (right) IPCC GCM super ensemble average. Units (mm).

Figure 4.28: From Nicholson (1998). Fluctuations of Lake Victoria from 1780. Years with levels determined from specific references have dots above them. Levels since 1896 are based on modern measurements.
Figure 4.29: 2070-2099 Lake Victoria levels modeled using A2 scenario IPCC ensemble precipitation.

Figure 4.30: Projected flooding of Lake Victoria shores if lake level rises to 14 meters.
Flooding around northwest side of Lake Victoria

Figure 4.31: Projected flooding on Northwest side of Lake Victoria if lake level rises to 14 meters.
Figure 4.32: Projected flooding near Kampala, Uganda if lake level rises to 14 meters.
4.3 Seasonal Variability of Station Precipitation

In this section we (i) reproduce the EOF modes of Schreck and Semazzi (2004) using station precipitation over Eastern Africa and then (ii) investigate the significant modes of variability of precipitation from January-February, March-May, and June-September in terms of the findings of Schreck and Semazzi (2004) and other studies. We relate these seasonal modes to the annual modes used in section 4.1.1.

4.3.1 Confirmation of Schreck and Semazzi (2004)

The percentage of variability covered by each EOF mode of station precipitation for the OND season is shown in figure 4.33. The first two modes are significant and account for just under 58% of the variability. We will be examined these modes in detail.

The first mode of OND station precipitation variability has a loading which is mostly one sign except for a couple of stations to the south of the lake (Fig. 4.34). The time series we obtain for the first mode of variability of OND station precipitation reproduces the time series found by Schreck and Semazzi (2004) (Fig. 4.38). Schreck and Semazzi (2004) mention that for a larger region using CMAP gridded precipitation, the first mode explained 29% of variability, while a study by Nyenzi (1992) based on a smaller region covering only Uganda, Kenya and Tanzania had a corresponding mode which had a variance of 50%. They believed the difference in variability could be attributed to the larger region they used for the analysis of CMAP precipitation. Our first mode explains 51.7% of the variability, which supports this finding. Schreck and Semazzi (2004) relate their EOF1 to ENSO by correlating their time series with the first significant EOF mode from global CMAP precipitation. They find that the first mode from the EOF analysis on regional precipitation corresponds to a combination of the first global EOF mode representing ENSO and the second global mode (IOZM). The major
warm ENSO events for the period covered by the station data correspond to the low valleys of
the time series. In particular the ENSO of 1982 is distinctly conspicuous. When the first mode
from OND precipitation is correlated with SSTs for 1961-1990, an Indian Ocean Dipole mode
pattern emerges (Fig 4.35). However, when they are correlated without 1961, an ENSO pattern
emerges (Fig. 4.36). This implies that the strong IOZM event that happened in 1961 was so
anomalous that it influenced the EOF analysis. This mode has a high correlation (0.82) with
the first annual mode from station precipitation from section 4.1.1. The first annual mode is
ENSO with some influence from IOZM, particularly in 1961.

Similar to Schreck and Semazzi (2004), the second mode of variability for station precip-
itation is significant. The second mode is a dipole mode with negative loading to the north
and positive loading to the south, which split the stations used in the water balance model in
section 4.1.1 with the stations to the east of the lake having negative loadings and those on the
western coast of the lake having positive loadings. The corresponding time series exhibits both
strong interannual variability and low-frequency background variability (Fig. 4.39). Overall,
there is an increasing trend during the entire time period. To explore possible associations with
global warming, Schreck and Semazzi (2004) plotted their Gauge EOF2 time series with the
global warming index (GWI). A 5 year running mean was applied to each of the time series
to filter out high frequencies and focus on low frequency variability (Fig. 4.40). Applying a
5 year running mean to our second mode time series gives the same time series (Fig. 4.41).
Combined interpretation of the distribution of loadings and the corresponding time series sug-
gests that the southern sector of eastern Africa has been getting wetter for the period 1961 to
1990 while the northern section has been drying up. This is opposite to the dipole described by
Schreck and Semazzi (2004) who claim that the northern sector has been getting wetter while
the southern sector has been drying up. While our time series is the same as the time series
in Schreck and Semazzi (2004), our loadings are the inverse of theirs. To determine if there
is a problem with our EOF analysis we proceed to do an EOF analysis of CRU precipitation
over Eastern Africa for the OND season 1979-2001 similar to that done for the Regional-EOF
analysis using CMAP in [Schreck and Semazzi (2004)]. Examining the second EOF mode of
this analysis and comparing it to Regional-EOF2 in their paper (not shown), we obtain simi-
lar results to the Regional-EOF2 dipole with moistening to the north and drying to the south
(Fig. 4.42). This proves that there are no errors in our EOF calculations, at least for gridded
CRU precipitation. Comparing the second EOF modes for CRU precipitation data for the OND
season from 1961-90 (Fig. 4.44), to those from station gauge precipitation (Fig. 4.39), the load-
ings are similar, with negative loadings to the north and positive loadings to the south. There is
a 0.75 correlation between the time series from the EOF analysis of CRU and the EOF analysis
of station gauge precipitation for the OND season 1961-90. We find that [Schreck and Semazzi
(2004)] must have inverted their Gauge-EOF2 loading. In order to determine source of vari-
ability associated with the second mode, we correlated it with SST anomalies (Fig. 4.45). The
areas of significant correlation focus towards the Bering Strait. We do not see any connection
between the SSTs in this area and East African rainfall. It could be a spurious correlation, but
should be investigated in the future. This mode has a 0.53 correlation with the second annual
mode from section 4.1.1 which suggests that it might be related to the second annual mode, but
other seasons might have more influence on this mode.
Figure 4.33: Scree Plot OND Station EOF
Figure 4.34: Station OND EOF1 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral. Stations used in the WBM are marked with a star.
Figure 4.35: First mode from OND EOF analysis on station precipitation correlated with ERSST from 1961-90.

Figure 4.36: First mode from OND EOF analysis on station precipitation correlated with ERSST from 1962-90.
Figure 4.37: Stations used in Schreck and Semazzi (2004).

Figure 4.38: Station OND EOF1 time series (left) and Gauge OND EOF1 time series from Schreck and Semazzi (2004) their figure 8 (right)
Figure 4.39: Station OND EOF2 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are marked with a star.
Figure 4.40: From Schreck and Semazzi (2004), Gauge-EOF 2 time series and loading. Their figures 12(b) and 13.

Figure 4.41: 5 year running mean of time series from OND EOF2.
Figure 4.42: Second EOF mode from CRU OND 1979-2001 time series (top) and loading (bottom).
Figure 4.43: Second EOF mode from CMAP OND 1979-2001 time series (top) and loading (bottom) from Schreck and Semazzi (2004). Their figure 5(b) and 6(b). For the loading dark/light gray represents positive/negative values.
Figure 4.44: CRU 3.0 OND EOF2 time series (top) and loading (bottom)
4.3.2 Extension of Schreck and Semazzi (2004) to other seasons

In order to examine the effects of each season on the annual EOF analysis performed in section 4.1.1 and to Lake Victoria levels, we extend the analysis of Schreck and Semazzi (2004) to the long rains of March through May and the dry seasons of January through February and June through September.

4.3.2.1 March-May (MAM)

According to Indeje et al. (2000), about 42 percent of the total east African rainfall is observed during the MAM season. The highest intensity is observed near the Indian Ocean, Lake Victoria, and the East African Highlands. In MAM season, there are two significant modes of variability for station precipitation (Fig. 4.46) the first mode accounts for 23.6% of
variability for station precipitation. The loading is negative in southern Tanzania and is split across the lake with negative loadings on the western coast of Lake Victoria and positive on the eastern coast of the lake and into the Kenya highlands (Fig. 4.47). The stations used in the water balance model have mostly small near-zero to larger positive loadings. Combined analysis of the time series and corresponding loadings for the stations used in the water balance model indicate that this mode would contribute to the interannual variability of the lake, but there is no definite trend. The time series has no correlation with the OND first mode time series (0.056 correlation) or the second mode (0.205). However it does have a 0.526 correlation with the first mode of annual station precipitation from section 4.1.1. We investigate the source of variability for the mode by correlating it with SST over the globe and find that there are high correlations in the area off the pacific coast of Central America and northern South America (Columbia, Ecuador, Peru). There is a small horseshoe pattern in the Pacific Ocean similar to an ENSO pattern (Fig. 4.48). The second mode for this season accounts for 10.9% variability. It is positive to the north and east coasts of the lake, and in northern Uganda and western Kenya with a negative loading in southern Kenya and eastern Tanzania (Fig. 4.49). The loading is similar to the loading for the first mode, but with a shift in negative loadings northward. This mode is not well correlated with either the first or second modes from OND precipitation (-0.10 and -0.37 correlations respectively). However it is highly correlated (-0.74) with the second mode of variability of annual precipitation from section 4.1.1. Correlating the time series with SST anomalies shows a negative correlation with temperatures in the Arabian Sea and off the coast of Taiwan and the Philippines in the Pacific Ocean.
Figure 4.46: Scree Plot MAM Station EOF
Figure 4.47: Station MAM EOF1 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are marked with a star.
Figure 4.48: First mode from MAM EOF analysis on station precipitation correlated with ERSST from 1961-90.
Figure 4.49: Station MAM EOF2 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are marked with a star.
There is only one significant mode of variability during the January-February season which accounts for 27% variability. The loading is positive over the entire East African region as seen in figure 4.52. The time series has low frequency variability with a high amount of interannual variability for the first half of the period, but less variability after 1980. Combined interpretation of the distribution of loadings and the corresponding time series suggests that during the JF season, the entire area was wetter in the 1960’s and early 1970’s, with a dry period from 1973-76, a very wet period from 1977-79, and from 1980 has been recovering from a dry period. Correlation with SST anomalies shows that this mode is related to SST anomalies in the Indian Ocean, where warmer temperatures in the western Indian Ocean cause this season to become wetter. This mode is not correlated with either of the OND modes of variability, and only has a 0.30 correlation with the first mode of variability for annual precipitation discussed.
in section 4.1.1.

Figure 4.51: Scree Plot JF Station EOF
Figure 4.52: Station JF EOF1 time series (top) and loading (bottom). Yellow circles are neutral, blue circles are positive. Stations used in the WBM are marked with a star.
4.3.2.3 June-September (JJAS)

The JJAS rainfall season accounts for about 15% of the total regional annual rainfall (Indeje et al., 2000). There are two significant modes of variability during this season. The first mode accounts for 20 percent of the variability during this season (Fig. 4.54). The loading for this mode is mostly negative, except for a few positive stations to the south of the lake (Fig. 4.55). The time series has very large negative peaks in 1961 and 1967, with otherwise smaller interannual variability until the 1980’s. Correlation with SST anomalies does not give much insight into the source of variability of this mode as shown in figure 4.56. The source of variability of this mode is not related to SST. However, the correlation between the time series of this mode and that of the first mode of the OND season is -0.433. This mode has a -0.40 correlation with the first mode of variability for annual precipitation mentioned in section 4.1.1.

The second mode accounts for 15.8 percent of the variability of precipitation during this
season. The loading for this mode is negative surrounding the lake and to the north into Uganda and east halfway into Kenya while most of Tanzania and the southeastern portion of Kenya has positive loadings (Fig. 4.57). The corresponding time series has large interannual variability and a low frequency variability with a dip throughout the 1970’s reaching a minimum in 1975. Combined analysis of the time series and corresponding loadings from the stations used in the water balance model in section 4.1.1 show dry conditions over the lake in the 1960’s, followed by moist conditions in the 1970’s and a return to drier conditions in the 1980’s. Correlation with SST anomalies shows high correlation with a warm tongue in the Pacific ocean and cooler SSTs off the coast of Australia. This mode has a negative correlation with the first mode from the OND season (0.407). While the time series of this mode has a negative correlation with the time series from the first mode of annual precipitation from section 4.1.1 (0.30). It has a higher, 0.64 correlation with the second mode of annual precipitation.

Figure 4.54: Scree Plot JJAS Station EOF
Figure 4.55: Station JJAS EOF1 time series (top) and loading (bottom). Blue circles are negative, yellow circles are neutral, red circles are positive. Stations used in the WBM are marked with a star.
Figure 4.56: First mode from JJAS EOF analysis on station precipitation correlated with ERSST from 1961-90.
Figure 4.57: Station JJAS EOF2 time series (top) and loading (bottom). Blue circles are negative, yellow circles are neutral, red circles are positive. Stations used in the WBM are marked with a star.
4.4 Decadal variability

In a new study by [Clement et al., Submitted], atmospheric models coupled to a mixed layer ocean (with no coupled ocean dynamics) simulate what they refer to as an “Atmospheric Walker Mode” which strongly resembles observed patterns associated with the SO. Their results suggest that there is power in the SO at decadal timescale, which can be thought of as the combination of multiple processes: mixed-layer integration of trade wind variability, damping by ocean dynamics, and a possible rectification of strong, non-linear interannual variability. [Clement et al., Submitted] claim that Pacific climate anomalies that have an ’ENSO-like’ spatial structure with warming in the eastern Pacific, eastward shift in convection, and a weaker Walker circulation can develop on decadal timescales without dynamical coupling to the ocean. In order to confirm the decadal Southern Oscillation recently found by [Clement et al., Submitted]...
and investigate its impact on Eastern Africa, we perform an EOF analysis on OND season 1961-90 station gauge precipitation data filtered using a 10 year running mean analysis and compared the results. We then examine the significant modes of variability for the filtered precipitation as we did for the non-filtered precipitation.

There are three significant modes of variability for the low frequency OND season (Fig. 4.59) accounting for a total of 83.9 percent of the variability. The first mode of low frequency OND precipitation accounts for 45.7 percent of the variability. The loading is mostly negative except for two stations towards the northeast corner of the lake, one station near the border of Uganda and Rwanda and two stations to the south of the lake with positive loadings (Fig. 4.60). The time series shows a very long term trend which increases from 1965-1972 and then decreases until 1981. Combined interpretation of the distribution of the loadings and the corresponding time series for this mode indicates that most of eastern Africa has gone from being wet in the 10 years centered on 1965 followed by a drying trend which peaked in the 10 years centered on 1972, followed by increased wetness. Correlating the time series from this mode with SST anomalies (Fig. 4.61) shows the 'ENSO-like' signal described by Clement et al. (Submitted) as seen in figure 4.62. In their analysis figure, three datasets are used here: HadISST (Rayner et al. 2003), ERSSTv2, and ERSSTv3(Smith et al. 2008). They averaged the three datasets in order to emphasize the patterns that are present in all datasets, but overall the patterns do not change significantly from dataset to dataset. In parts c and d of the figure, the stippling indicates areas that are not robust defined as where (1) the datasets do not agree in sign and (2) where the regression values are not significant at the 1-sigma level (67%) based on a t-test with reduced degrees of freedom to account for the auto-correlation in the filtered SO index. All data are detrended and regressions computed for the 1880-2004 period. This mode shows a 0.79 correlation with a 10 year running mean taken of the Southern Oscillation Index (SOI). This mode is the decadal Southern Oscillation found by Clement et al. (Submitted).
The second mode accounts for approximately 30 percent of the variability. The time series for this loading is very linear, going from a low in 1965 to a peak in 1983 before decreasing slightly (Fig. 4.63). While the stations used in the water balance model in section 4.1.1 all have very small neutral to larger negative loadings, the pattern of the loadings splits the lake with positive loadings on the western coast and negative loadings on the northern and eastern coasts. Outside of the coast, there is a general pattern of negative loadings to the north and more positive loadings to the south, similar to the loading for the second mode of annual OND precipitation (Fig. 4.39). Combined interpretation of the distribution of the loadings and the corresponding time series of this mode indicates that the areas on the north and east sides of the lake are getting dryer while areas to the south of the lake are becoming moister. Correlating the corresponding time series with SST anomalies in figure 4.64 shows very high correlations with warm temperatures in the Indian Ocean and towards Antarctica and negative correlations in the Pacific Ocean. There is an area of negative correlations between North America and Europe which look like the gulf stream. The time series and correlation with SST anomalies might be due to climate change, more research is needed to determine this. The strong correlations are due to the EOF time series trend correlating highly with trends in SST anomalies. Correlating two trends is risky and one has to be cautious that these two trends could be physically unrelated.

The third mode, accounting for 8.3 percent of the variability, has low frequency variability with a dip from 1965-1970, followed by a peak in the mid to late 1970’s and a decrease to 1983 (Fig. 4.66). The distribution of the loadings is noisier than the previous modes. There are both positive and negative loadings around the coast of Lake Victoria. Overall the loading is very noisy with positive and negative loadings scattered throughout the domain. The correlation of the time series with SST anomalies does not give a distinctive pattern. Combined analysis of the EOF loadings and the correlation of the time series with SST anomalies suggests that this...
mode is not affected by SSTs and could be related to land use near the different stations in the domain.

[Bowden (2008)] did a similar EOF analysis on a 10-year running mean of CRU for a larger domain focusing on the Greater Horn of Africa (Fig. 4.65). He found that for the majority of the Greater Horn of Africa, excluding portions of Tanzania and northern Sudan, the most significant mode was a drying trend from the wetter 1960’s to near normal conditions during the 1970’s, followed by a trend towards drier conditions in the early 1980’s. Since his domain is much larger, it is hard to compare his mode to ours. However, his mode is similar to our second mode which shows areas to the north of the lake becoming drier from 1960’s through 1980’s. It is possible that there was a different variability over the Greater Horn of Africa than there was in the smaller Eastern Africa domain and the modes were ordered differently between the two domains.

Figure 4.59: Scree Plot decadal OND Station EOF
Figure 4.60: Station OND 10 year running mean EOF1 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are marked with a star.
Figure 4.61: First mode from OND 10 year running mean EOF analysis on station precipitation correlated with 10 year running mean of OND ERSST from 1961-90.

Figure 4.62: Regression of observed SLP on monthly observed (a) high and (b) low pass filtered (Butterworth filter, 10-yr cutoff) SO index using the HadSLP reconstruction version 2 (Allen and Ansell, 2006). Multidataset ensemble-mean regression on monthly observed (c) high and (d) low pass filtered SO index (Butterworth filter, 10-yr cutoff) index. All regressions were performed on the normalized SO, so units are hPa (for SLP) and K (for SST). From Clement et al., (Submitted) (their Figure 2)
Figure 4.63: Station OND 10 year running mean EOF2 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are marked with a star.
Figure 4.64: Second mode from OND 10 year running mean EOF analysis on station precipitation correlated with 10 year running mean of ERSST from 1961-90.
Figure 4.65: Time series for the dominant EOF mode of variability for the 10-year running mean analysis for 1961-90 time series (top) and loading (bottom) from Bowden (2008).
Figure 4.66: Station OND 10 year running mean EOF3 time series (top) and loading (bottom). Blue circles are positive, yellow circles are neutral, red circles are negative. Stations used in the WBM are marked with a star.
Figure 4.67: Third mode from OND 10 year running mean EOF analysis on station precipitation correlated with 10 year running mean of ERSST from 1961-90.
Chapter 5

Conclusions and recommendations

5.1 Conclusions

We show that the jump in level from 1961-64 is due to 4 years of consistently above normal precipitation associated with the first mode of annual EOF variability, while the slow decline from 1964-90 is primarily due to the adjustment of the lake levels to ‘drier’ climatological conditions contrary to conventional wisdom that climate change may have had a primary role in determining this trend.

We find that the first EOF mode of annual precipitation variability (ENSO) has the highest impact on the annual variability of Lake Victoria level. It has high correlation with the first modes of variability during the OND and MAM seasons. While the second EOF mode of annual variability accounts for approximately 10 percent of the variability, its effect on the variability in lake levels is negligible. We further show that there was an error in the gauge-2 EOF from [Schreck and Semazzi (2004)] and that contrary to their results for 1961-90, the southern sector of eastern Africa was getting wetter for the period 1961 to 1990 while the northern section was drying up. The corresponding time series for the dipole mode has a
0.532 correlation with the time series for the second EOF mode of annual precipitation for the region. The annual dipole mode from CRU precipitation was contributing to a small overall increase in Lake Victoria levels from 1961-90. This does not affect lake levels considerably during that time period, as the lake is adjusting downwards toward a new equilibrium level from the levels associated with the four years of consistently high precipitation from 1961-64 and the slight drying trend in the first mode of annual precipitation. The EOF analysis of annual precipitation for 1961-90 has one sign of loading covering the lake for both CRU and station gauge precipitation. The second EOF mode of annual precipitation variability has is significantly correlated with the second EOF modes of variability from the OND, MAM, and JJAS seasons. Based on the EOF analysis of OND season rainfall for the years 1961-1990 and 1979-2001 performed in section 4.3.1, the dipole is split with very small values over the lake from 1961-1990 and 1979-2001. The dipole also splits with small values over the lake in the MAM season, while in JJAS there are negative loadings surrounding the lake but the lake is close to where the loadings switch to being positive, suggesting that they are smaller negative loadings surrounding the lake. This suggests that another reason the dipole may have negligible effect on Lake Victoria levels is that the loadings for the annual dipole are overall small since in the OND and MAM seasons there are a combination of positive and negative loadings over the lake that come close to cancelling out.

We reproduce the decadal SO studied by [Clement et al. (Submitted)] by correlating the first mode of variance of the running mean of station gauge OND precipitation over Eastern Africa to SST anomalies. The second mode has an increasing trend-like time series and negative loadings around the lake. Combined analysis of the time series and loadings indicate a drying trend around Lake Victoria.
5.2 Framework for use of climate change projections in applications

In section 4.2 we implement a framework for the use of climate change projections in the application of hydrology. The framework is to first show that the water balance model gives acceptable lake levels using observations. Next, climate model output is validated and then used in the water balance model. Following this, the A2 scenario levels are converted to height above sea level and ArcGIS software is used to map potential impacts of those levels. Our GIS-based visualizations highlight the high threat of flooding of the wetlands in the coastal regions of the lake which we believe would be a valuable tool for planners for climate adaptation and mitigation.

5.3 Recommendations:

While the water balance model used in this study was designed to predict annual lake levels, it would be useful for water resources and hydroelectric planning to have a corresponding monthly analysis. This would require high quality monthly observations for all factors in the water balance model including precipitation over the lake and in the lake basins, rates of flow for all the tributaries into the lake, evaporation from the lake and the tributaries, and groundwater flow. There is a definite need for sustained and improved monitoring of Lake Victoria and its basin. While current lake levels can be estimated using satellite altimetry, quality high resolution data for factors such as tributary inflow and groundwater is not available for the Lake Victoria basin. There also needs to be an accounting of water taken from the lake and its tributaries for human use in order to get a more accurate water balance.

It would be better to use dynamical water balance model which is could be run off of climate
model output for predicting lake levels under future climate change scenarios. The model used by Tate et al. (2004) would be less reliable outside the regimes under which it was calibrated. The regressions for runoff and tributary inflow into Lake Victoria could change with different land use scenarios and climate regimes. These changes could be incorporated into a dynamical model after it is calibrated using current conditions.

It would also be informative to calculate uncertainty over the entire chain of steps involved in this study from uncertainty in the data used to uncertainty in the water balance model and how this estimation of uncertainty cascades from data to impact. There is uncertainty from choice of data sets used, the statistical analysis through the choices of spatial and temporal domain for the EOF analysis and choice of filtering for the decadal analysis and the water balance model itself. These uncertainties are filtered through into the predicted lake levels and related impacts. This uncertainty could then be taken into account when planning for mitigation of the potential impacts.
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