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1 Potential impacts of climate and environmental change
2 on the stored water of Lake Victoria Basin and
3 economic implications

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11 **Abstract**

12 The changing climatic patterns and increasing human population within
13 the Lake Victoria Basin (LVB), together with overexploitation of water for
14 economic activities call for assessment of water management for the entire
15 basin. This study focused on the analysis of a combination of available
16 in-situ climate data, Gravity And Climate Experiment (GRACE), Tropical
17 Rainfall Measuring Mission (TRMM) observations, and high resolution Re-
18 gional Climate simulations during recent decade(s) to assess the water storage
19 changes within LVB that may be linked to recent climatic variability/changes
20 and anomalies. We employed trend analysis, principal component analysis
21 (PCA), and temporal/spatial correlations to explore the associations and
22 co-variability among LVB stored water, rainfall variability, and large scale
23 forcings associated with El-Niño/Southern Oscillation (ENSO) and Indian
24 Ocean Dipole (IOD). Potential economic impacts of human and climate-
25 induced changes in LVB stored water are also explored.

26 Overall observed in-situ rainfall from lake-shore stations showed a modest
27 increasing trend during the recent decades. The dominant patterns of rainfall
28 data from the TRMM satellite estimates suggest that the spatial and tem-
29 poral distribution of precipitation have not changed much during the period
30 of 1998-2012 over the basin consistent with in-situ observations. However,
31 GRACE-derived water storage changes over LVB indicate an average de-
32 cline of 38.2 mm/yr for 2003-2006, likely due to the extension of the Owen
33 Fall/Nalubale dam, and an increase of 4.5 mm/yr over 2007-2013, likely due
34 to two massive rainfalls in 2006-2007 and 2010-2011. The temporal correla-
35 tions between rainfall and ENSO/IOD indices during the study period, based
36 on TRMM and model simulations, suggest significant influence of large scale
37 forcing on LVB rainfall, and thus stored water. The contributions of ENSO
38 and IOD on the amplitude of TRMM-rainfall and GRACE-derived water
39 storage changes, for the period of 2003-2013, are estimated to be ~ 2.5 cm
40 and ~ 1.5 cm, respectively.

41 *Key words:* Lake Victoria Basin, surface and groundwater, climate change,
42 ENSO, GRACE, environmental change, economic impacts

43 **1. Introduction**

44 Freshwater, the most fundamental natural resource for human beings,
45 is required in abundance for drinking, agriculture and all forms of socio-
46 economic development. Its stored potential (surface, groundwater, soil mois-
47 ture, ice, etc) is increasingly facing challenges from climate change as well as
48 anthropogenic activities. That current and future climate change is expected
49 to significantly impact the fresh water systems including rivers, streams and

50 lakes, in terms of flow and direction, timing, volume, temperature and its
51 inhabitants has been documented in numerous publications (e.g., Bates et
52 al. , 2008; Palmer et al. , 2008). Changes in the freshwater system, both in
53 terms of quality and quantity, resulting from both natural climate variability
54 (e.g., rainfall patterns) and change, and other anthropogenic influences such
55 as excessive water withdrawals and construction of dams for hydropower gen-
56 eration in the upstream will have significant consequences on the ecosystem
57 and the people depending on them (e.g., Palmer et al. , 2008). The con-
58 ditions are expected to get worse for hugely populated basins such as Lake
59 Victoria Basin (LVB) (see, e.g., Hecky et al. , 2010).

60 Lake Victoria, the second largest freshwater body on Earth, is a source
61 of freshwater and livelihood for more than 30 million people living around it
62 (Awange and Ong'ang'a , 2006) and indirectly supports another 340 million
63 people along the Nile Basin (Sutcliffe and Parks , 1999) being the source of
64 the White Nile. Lake Victoria Basin (LVB, Figure 1) constitutes an area
65 of 193,000 km² and extends over Burundi (7.2%), Kenya (21.5%), Rwanda
66 (11.4%), Tanzania (44%) and Uganda (15.9%) (Awange and Ong'ang'a ,
67 2006). The basin acts as a constant source of water to the lake through
68 its massive catchment area and its ability to influence the regions' seasonal
69 rainfall. In the last decade, however, the stored waters within LVB have come
70 under immense pressure from climate change and anthropogenic factors that
71 resulted in significant fluctuations. However, the lake level remained above
72 average since the early 1960's (Nicholson , 1998, 1999) till the early 2000's.
73 Discharge estimates from the lake for the period 1950-2005 show that the
74 net balance between recharge and discharge remained relatively stable over

75 the estimation period (PPA , 2007). A decreasing trend in the lake's level in
76 the past decade as shown, e.g., by Kull (2006); Riebeek (2006); Swenson
77 and Wahr (2009); Awange et al. (2008a), however, is attributed equally
78 to over-abstraction and natural climate change such as evaporation (PPA
79 , 2007; Sutcliffe and Petersen , 2007; Awange et al. , 2008b; Swenson and
80 Wahr , 2009).

81 Lake Victoria Basin is characterized by modified equatorial type of cli-
82 mate with substantial rainfall occurring throughout the year, particularly
83 over the lake surface, to semiarid type characterized by intermittent droughts
84 over some near-shore regions (e.g., Anyah et al. , 2006). The seasonal rainfall
85 over the basin is further characterized by a bimodal cycle, just like most areas
86 of East Africa, and is controlled mainly by the north-south migration of Inter
87 Tropical Convergence Zone (ITCZ), a quasi-permanent trough that occurs
88 over Lake Victoria (e.g., Asnani , 1993) due to locally induced convection,
89 orographic influence and land-lake thermal contrast, which modulates rain-
90 fall pattern over the lake and hinterlands. The large-scale precipitation over
91 the lake is mainly initiated from the easterly/southeasterly (Indian Ocean)
92 monsoon flow that transports maritime moisture into the interior of East
93 Africa. The humid Congo air mass has also been linked to significant rain-
94 fall amounts received over the western and northwestern parts of the lake
95 (Asnani , 1993). Large-scale winds over the Lake Basin are mainly easterly
96 trades most of the year. Superimposed on this basic flow regime are the
97 south-easterly (SE) or north-easterly (NE) monsoons that are mostly driven
98 towards, and often converge over, the ITCZ location. The strength of the
99 monsoons also depends on the sub-tropical anticyclones over the Arabian Sea

100 (Arabian high pressure cell) and southwestern Indian Ocean (Macarene high
101 pressure cell).

102 In terms of inter-annual variability, Lake Victoria Basin climate is char-
103 acterized by periodic episodes of anomalously wet/dry conditions with some
104 of the memorable events including the 1961/62 and 1997/98 floods that left
105 behind a huge trail of damage to property and infrastructure. The 1961/62
106 floods were associated with a strong zonal SST gradient over the equato-
107 rial Indian Ocean and mid-troposphere westerly flow from Tropical Atlantic
108 (Anyamba , 1984; Anyah and Semazzi , 2006, 2007). It is noteworthy that
109 1997/98 floods coincided with one of the warmest ENSO episodes (strongest
110 El Niño) of the last century as well as very strong IOD mode. Hence, the
111 inter-annual variability of the Lake Basin is also closely linked to the SST
112 anomalies over the global ocean basins.

113 On the one hand, climate Change influences rainfall and temperature
114 patterns thereby affecting LVB's stored water. This is attributed to the
115 fact that more than 80% of LVB's water source is derived directly from
116 the seasonal precipitation (e.g., Awange and Ong'ang'a , 2006) and almost
117 an equivalent amount of the precipitation is lost to evaporation (Yin and
118 Nicholson , 1998; Sewagudde , 2009). The temperature in the LVB region is
119 projected to increase by 3 – 4° C by the end of this century without much
120 change in the rainfall regime, leading to a significant downward trend in the
121 Lake's net Basin supply as a result of enhanced evaporation (Sewagudde ,
122 2009) as well as increased water temperatures. Impacts of climate change on
123 LVB have been reported, e.g., in (PPA , 2007; Sutcliffe and Petersen , 2007;
124 Swenson and Wahr , 2009; Lejju , 2012).

125 On the other hand, on anthropogenic influence on LVB, Yin and Nichol-
126 son (1998) characterized most of the LVB's catchment areas as semi-arid
127 zones, with exception of areas close to the lake, and hence the catchments
128 ability to discharge water into Lake Victoria is expected to decrease as a
129 result of increased abstraction demand for agricultural and industrial activ-
130 ities. This, in addition to declining lake water quantity and quality due to
131 increasing population will thus have serious impacts on the regional water
132 requirement, domestic food supplies, and global food trade (e.g., Geheb and
133 Crean , 2003; Awange et al. , 2007; Johnson , 2009).

134 Combined, the impacts of both climate change and other anthropogenic
135 factors on LVB's total water storage (TWS) is having a toll on the economic
136 as well as the environment of the region. For instance, there are already
137 signs of declining fish trades (Geheb and Crean , 2003) and access to fresh
138 water in the LVB leading to environmental scarcity (e.g., Mwiturubani ,
139 2010; Canter and Ndegwa , 2002). Change of fish community and loss of
140 phytoplankton (e.g., Geheb and Crean , 2003; Hecky et al. , 2010) are some
141 impacts of climate change and anthropogenic influences on the lakes water
142 quality, questioning the quality and health of the food. Lake Victoria's out-
143 flow is determined by the "agreed curve" drawn between Egypt and Uganda,
144 which also determines the level of hydropower generation. The current and
145 more alarming anthropogenic stress is the increasing demand for power as
146 a result of increasing population in the basin area (Mutenyo , 2009; PPA ,
147 2007). The impact of hydropower plants along the Nile river are found to
148 be largest during the drought seasons (or years) and is therefore, expected
149 to put more pressure on the lake with increasing hydropower plants (e.g.,

150 Mutenyo , 2009; Hecky et al. , 2010). Recent studies on climate variabil-
151 ity and change over the LVB and fluctuations of Lake Victoria levels show
152 some worrying scene of drought patterns and receding lake levels, which are
153 both attributed to natural climate change and increasing human influence
154 (e.g., Yin and Nicholson , 1998; Awange et al. , 2008a,b, 2013; Swenson
155 and Wahr , 2009; Sewagudde , 2009). Thus, it is very important to monitor
156 the basin’s hydrological cycle using the up-to-date technology and methods
157 to inform the policy-makers and politicians, who plays the most important
158 role in managing the regional water resource. All these poses a significant
159 environment and economic challenge to the East African region as a whole,
160 leading to various levels of domestic and interstate conflicts, see e.g., (Canter
161 and Ndegwa , 2002).

162 This contribution examines the changes of total water storage (surface,
163 groundwater and soil moisture) caused by climate variability and extremes
164 over the recent decade (2003-2013) over LVB and the potential economic
165 impacts. To achieve this, we employ freely available global high resolution
166 satellite data sets of Tropical Rainfall Measuring Mission (TRMM) rainfall
167 estimates and Gravity Recovery and Climate Experiment (GRACE) time-
168 variable gravity fields (Tapley et al. , 2004a,b; Rummel et al. , 2002) coupled
169 with outputs from various regional climate models (RCMs) in addition to
170 analysis of observed in-situ rainfall data over specific stations within the
171 lake’s perimeter to study trends of climate over the basin.

172 The rest of the study is organised as follows. Section 2 presents a brief
173 overview of the various data sets used and discusses the methods employed
174 to investigate the impacts of climate variability and extremes on stored water

175 potential of LVB. The results are presented and discussed in Section 3 while
176 Section 4 concludes the report.

FIGURE 1

177 **2. Data sets and Methodology**

178 This section gives a brief overview of the various datasets employed in this
179 study. These include observed in-situ data, Gravity Recovery And Climate
180 Experiment (GRACE) and Tropical Rainfall Measuring Mission (TRMM).
181 The next subsection gives brief highlights on each dataset used.

182 *2.1. Rainfall data (1960-2012)*

183 Monthly observed in-situ precipitation data for stations along Lake Victo-
184 ria Basin (see, Figure 1) were employed in this analysis. There are a number
185 of other meteorological stations within the Lake Victoria basin, but only
186 those representatives of their climatological zones with homogeneous anoma-
187 lies were used. The annual rainfall total was computed through accumulation
188 of the monthly observed data. These data sets were first subjected to qual-
189 ity control and homogeneity tests, see e.g., (Peterson et al. , 1998; Omondi
190 et al. , 2012), before being analyzed. The slopes of linear trends from the
191 annual rainfall total for the common period 1921 to 2012 were computed
192 using least-squares regression analysis while statistical significance assessed
193 using Student's t-test (Awange et al. , 2008b). Linear regression model was
194 applied to the accumulated annual rainfall total for various stations used for
195 the study.

196 *2.2. Tropical Rainfall Measuring Mission (TRMM)*

197 The rainfall measurements employed in this work are a product derived
198 largely from observations made by the Tropical Rainfall Measuring Mission
199 or TRMM (Kummerow et al. , 2000). TRMM products have been employed
200 in a number of studies of African precipitation where they have been found to
201 be adequate when compared with ground truth observations (e.g., Nicholson
202 et al. , 2003; Owor et al. , 2009). The product employed in this work is re-
203 ferred to as the *TRMM and Other Precipitation Data Set* (denoted as 3B43),
204 and covers the period 1998 to 2013. 3B43 provides monthly rainfall (average
205 hourly rate) between latitudes 50°N/50°S over a $0.25^\circ \times 0.25^\circ$ grid. It is
206 derived not only from TRMM instruments, but also a number of other satel-
207 lites and ground-based rain-gauge data. Over time, the products produced
208 from the TRMM observations are updated as the processing techniques and
209 methods for integrating the different data sets are improved upon. In this
210 work we use the latest version, number 7, which has been found to be a signif-
211 icant improvement over the previous version 6 owing to such changes as the
212 use of additional satellites and a superior means of incorporating rain gauge
213 information from the Global Precipitation Climatological Centre (Huffmann
214 and Bolvin , 2012; Fleming and Awange , 2013).

215 *2.3. Gravity Recovery And Climate Experiment (GRACE)*

216 The Gravity Recovery And Climate Experiment (GRACE) is a United
217 States (National Aeronautics and Space Administration, NASA) and German
218 (Deutsche Zentrum für Luft- und Raumfahrt, DLR) space mission which has
219 been providing products that describe the temporal variation of the Earth’s
220 gravity field arising from mass movements within the Earth’s system. Level 2

221 time-variable gravity field products of GRACE have been frequently used to
222 study the Earth's water storage variations (see, e.g., Awange et al. , 2008a).
223 This study uses the latest release five (RL05) monthly GRACE solutions,
224 provided by the German Research Centre for Geosciences (GFZ) (Dahle et
225 al., (2012)), covering 2003 to 2013.

226 For computing monthly total water storage (TWS) fields over the LVB
227 basin, the following items are considered:

- 228 1. GRACE level-02 products contain correlated errors among higher order
229 spherical harmonics, known as the north-south striping pattern in spa-
230 tial domain (Kusche , 2007). In order to remove stripes, we applied the
231 de-correlation filter of DDK3 (Kusche et al. , 2009) to the GFZ-RL05
232 solutions. The filtered solutions can also be downloaded from [http://](http://icgem.gfz-potsdam.de/ICGEM/TimeSeries.html)
233 icgem.gfz-potsdam.de/ICGEM/TimeSeries.html. Evaluation of the
234 DDK filter for computing correct water storage variations is addressed
235 e.g., in Werth et al. (2009).
- 236 2. Residual gravity field solutions with respect to the temporal average of
237 2003 to 2013 were computed.
- 238 3. The residual coefficients were then convolved with a basin function,
239 while considering the basin boundary of Figure 1. For computing the
240 basin function, we assumed a uniform mass distribution with the value
241 of one inside the LVB basin and no mass outside the basin ($S_1 = 1$, is
242 a uniform mass in the basin). Then, we transformed the uniform mass
243 into spherical harmonics. The obtained coefficients are filtered with
244 the same DDK3 filter as was applied for GRACE products.
- 245 4. In order to account for leakages (see e.g., Fenoglio-Marc et al. (2006,

246 2012)), the total surface mass of the basin was calculated from the basin
247 function coefficients (S2, synthesized uniform mass in the LVB basin).
248 The ratio of S1/S2 reflects the effect of the truncation of the spherical
249 harmonics as well as signal attenuation due to filtering GRACE prod-
250 ucts over LVB. More discussion of the leakage problem can be found,
251 e.g., in Klees et al. (2007).

252 5. The derived ratio is multiplied by coefficients in item 2 and the re-
253 sults were transformed into $0.5^\circ \times 0.5^\circ$ TWS maps within LVB, following
254 Wahr et al. (1998).

255 *2.4. CRU Data*

256 The University of East Anglia Climate Research Unit (CRU) gridded ob-
257 servational data comprises of 1200 monthly observed climate from 1901 to
258 2000. CRU data are derived from gauge observations over land areas only
259 and are interpolated on a regular grid of $0.50^\circ \times 0.50^\circ$ (Mitchell et al. , 2003).
260 The data sets contain five climatic variables including precipitation, surface
261 temperature, diurnal temperature range (DTR), cloud cover and vapor pres-
262 sure. In the present study, we only utilize monthly mean surface temperature
263 and precipitation to complement the available station-based observations.

264 *2.5. Regional Climate Simulations*

265 In this study we present results of simulated rainfall climatology dur-
266 ing the recent decades from four state-of-the-art high resolution Regional
267 Climate Models [a random sample from the Coordinated Regional Down-
268 scaling Experiment (CORDEX)] a group of models being used in CORDEX
269 (<http://wcrp-cordex.ipsl.jussieu.fr/>). CORDEX Africa Project

270 (<http://start.org/cordex-africa/about/>) used different RCMs to sim-
271 ulate rainfall over the whole Africa domain. The four RCMs data from the
272 CORDEX archive used in constructing simulated climatology over the LVB
273 were WRF, MPI, CRCM5, and PRECIS. The data is from 1989 to 2008 (20
274 years). The spatial resolution for RCMs-CORDEX is 50 km and for our
275 study, data was extracted for the LVB domain stretching from 31°E to 36°E,
276 and 4°S to 2°N. Details on these RCMs are explained in Nikulin et al.
277 (2012).

278 Given the importance of rainfall in the water balance of the LVB, in the
279 present study we only concentrate in comparing the model vs observations
280 (TRMM 3B43-V7 and CRU). We also evaluate how the model simulates the
281 impact of large-scale forcings on the seasonal and interannual variability of
282 LVB rainfall (i.e., influence of IOD and ENSO during the years 2005 and
283 2006, respectively). In order to understand the IOD and ENSO influence,
284 we also computed spatial correlations between Nino3.4 and IOD indices for
285 both model and observed (TRMM) data. Knowing the temporal pattern
286 of ENSO and IOD from the indices, their contributions were co-estimated
287 considering linear trends as well as the annual and semi-annual components
288 in the TRMM-derived rainfall and GRACE-derived TWS changes from 2003
289 to 2013.

290 **3. Results and Discussions**

291 *Rainfall variability analysis*

292 The trend analysis results for precipitation over the basin are shown in
293 Figure 2. Stations located within the Lake Victoria Basin generally showed

294 modest increase in rainfall trends (e.g., see, Figures 2 a, b, c and d). The
295 increase in trends shown by these stations are, however, not significant at 95%
296 confidence level when Student t-test is applied. We further employed PCA
297 analysis of TRMM data to isolate the dominant spatial and temporal patterns
298 of rainfall variability over the LVB during the recent years. We preferred
299 using the TRMM rainfall estimates here given the more complete spatial
300 coverage, albeit over a relatively short period. To extract the period with
301 relatively more rainfall, we summed up the rainfall values of each monthly
302 grids and showed them with respect to their corresponding month in Figure 3.
303 Impacts of the EL-Niño Southern Oscillation phenomenon can be seen e.g.,
304 in 2006-2007 and 2011-2012.

305 Applying PCA on rainfall data of LVB, we found four dominant EOFs
306 and PCs that are shown in Figure 4. EOF1 and PC1 (representing 63% of
307 total variance of the rainfall) show a superposition of the annual and seasonal
308 variabilities. The amplitude of the signal in some years such as that of 2007
309 is amplified as a result of El-Niño. EOF2 and PC2 representing 13% of total
310 rainfall are also related to the annual variation with the same dipole structure
311 of the annual TWS changes in Figure 7. We found a lag of one-month
312 between PC2 of TRMM and PC2 of TWS changes. PC3 shows a summation
313 of inter-annual changes and a linear trend over the basin. Considering the
314 structure of EOF3, which is negative over the north west and positive over
315 the southeast, we estimate respectively a rainfall rate of -2.0 and 2.8 mm/yr
316 over them, for the period of 2003 to 2013. The derived trends, however, were
317 not statistically significant. We do not interpret the fourth mode of PCA on
318 rainfall changes (EOF4 and PC4) here, since the temporal pattern is quite

319 noisy and they represent only 3% of variance in rainfall.

FIGURE 2

FIGURE 3

FIGURE 4

320 *Simulated climatology of LVB (1989-2008)*

321 The observed bimodal rainfall pattern over the LVB (31.5°E - 34°E; 2.5°S
322 - 1°N) is well reproduced by three of the four CORDEX Regional Climate
323 Models (RCMs) as shown in Figure 5. However, the MPI RCM captures
324 the bimodal rainfall regime but underestimates the peaks during MAM and
325 OND seasons. This level of RCMs differences (uncertainties) in reproduc-
326 ing the LVB spatial and temporal mean patterns of precipitation presents
327 a challenge in using numerical (theoretical) modeling techniques to under-
328 stand climate-hydrology connections as well as water level/storage variabil-
329 ity over LVB. The RCMs inability to reproduce variability of some peculiar
330 rainfall features of the LVB climate has been linked to incomplete represen-
331 tation/parameterization of localized convective and boundary layer processes
332 that exert significant influence on the spatio-temporal distribution of LVB
333 rainfall (Song et al. , 2006; Sun et al. , 1999; Anyah et al. , 2006; Anyah
334 and Semazzi , 2009).

FIGURE 5

335 In Figure 6, the Canadian Regional Climate Model version 5 (CRCM5),
336 compared to TRMM estimates, overestimates over-lake seasonal rainfall amounts

337 for both MAM and OND seasons. On the other hand, the PRECIS model
338 as well as the other two models (not shown) consistently simulate drier con-
339 ditions over the LVB; in some places underestimating the rainfall totals by
340 nearly 100% of the observed (TRMM) seasonal total, especially during the
341 March-May (MAM). However, the CRCM5 captures the OND seasonal mean
342 rainfall pattern quite well compared to TRMM, and also consistent with the
343 dominant EOF loadings of TRMM in Figure 4. The PRECIS model also re-
344 produces the observed spatial distribution of rainfall during OND although
345 the simulated center of rainfall maximum is over the northeastern quadrant
346 of the Lake as opposed to southwestern and western quadrants as in TRMM
347 estimates and CRCM5 simulation.

FIGURE 6

348 *GRACE total water storage over LVB*

349 We then employed PCA analysis on TWS to examine whether the ob-
350 served and simulated patterns of climate variability discussed in the previous
351 section are consistent with the water storage variability derived from GRACE
352 data. As a result, its first two dominant EOFs and PCs are shown in Figure 7,
353 where EOF1 and PC1 represents 82% of total variance in TWS changes and
354 EOF2 and PC2 represents 14%. EOF1 shows a strong anomaly all over the
355 basin, while its corresponding PC1 shows the dominant trend of the basin.
356 Using a linear regression, we found an average mass decline of 38.2 and in-
357 crease of 4.5 mm/yr over the LVB, respectively for the periods of 2003 to
358 2007 and 2007 to 2013. EOF2 shows a spatial north-south dipole structure,
359 which as PC2 indicates, corresponds to the annual changes of TWS over the

360 basin. The TWS decline of 2003 to 2007 is attributed to the extension of
361 the Owen Falls (Nalubale) dam as stated e.g., in (Awange et al. , 2008a;
362 Swenson and Wahr , 2009). The positive rate of 2007 to 2013 is likely due
363 to the positive impact of El Niño in the years 2007 and 2013. This result is
364 supported by rainfall analysis of Section 3.

FIGURE 7

365 *Influence of ENSO and IOD on inter-annual variability of LVB rainfall*

366 Some previous studies over equatorial eastern Africa (including LVB) have
367 shown that local forcings modulate regional climate by either amplifying
368 or suppressing the anomalies triggered by perturbations in the large-scale
369 circulations that are propagated through global teleconnections such as El-
370 Niño/Southern Oscillation and east-west sea surface temperature (SST) gra-
371 dient over equatorial Indian Ocean [i.e IOD mode: Saji et al. (1999); Indeje
372 et al. (2000); Schreck and Semazzi (2004); Omondi et al. (2013), among
373 others]. ENSO and IOD have thus been indicated as significant triggers of
374 some of the past extreme LVB rainfall anomalies (floods and droughts).

375 In the present study, we show in Figure 8 the observed and simulated rain-
376 fall anomalies during 2005 and 2006, associated with fairly strong La Niña
377 and El Niño/IOD conditions respectively. Generally, the apparent ENSO
378 influence on the spatial variability of LVB rainfall is manifest, with more
379 widespread below normal rainfall amounts during the OND season (2005)
380 and the opposite during 2006 season (based on 1989-2008 average). Over-
381 lake rainfall is more depressed during La Niña (2005), but there is a modest
382 increase during El Niño years (2006 and 2010), although TRMM estimates

383 show significant increases over the western and northern quadrants of the
384 Lake. This feature is clearly reproduced by all the four CORDEX models,
385 compared to TRMM estimates. Given the recent improvements in ENSO
386 prediction, with lead times over 6 months, the apparent link between LVB
387 rainfall and ENSO can have very practical application for LVB water re-
388 sources availability and governance.

FIGURE 8

389 In Figure 9, we show the spatial correlations between ENSO (Nino3.4
390 index) and LVB TRMM on the one hand, and simulated monthly rainfall
391 totals on the other hand during the OND season. In October (Figure 9,top),
392 statistically significant correlation between Nino3.4 and TRMM (3B43-V7)
393 during 1998-2008 is observed over the western parts of the Lake as well as
394 the northeastern shores (Winam Gulf and surrounding areas). In contrast,
395 significant r-values between nino3.4 and simulated rainfall tend to be more
396 widespread, especially over the northern sector of the Lake. Similar correla-
397 tion patterns are derived from TRMM during November (Figure 9. middle),
398 but nino3.4 index correlation with the simulated rainfall show very weak
399 correlations ($r \sim 0$), especially over the lake surface. The spatial correla-
400 tion pattern in December (Figure 9, bottom) for both TRMM and model are
401 somehow similar to the pattern in October (Figure 9, top).

FIGURE 9

FIGURE 10

402 A conspicuous similarity in the monthly spatial correlation patterns be-
 403 tween IOD and rainfall (Figure 10), and those shown in Figure 9 is unmistak-
 404 able. This apparently implies that co-occurrence of IOD and ENSO events
 405 exert significant influence on LVB rainfall, and hence significantly influence
 406 climate-sensitive socio-economic activities (see, Section 3 over the lake and
 407 its hinterland).

408 In order to estimate the impact of ENSO and IOD on the variability of
 409 rainfall and thus stored water, we assumed the normalized temporal pat-
 410 terns of the nino3.4 and IOD indices as known. Then, we co-estimated
 411 their contributions, beside a linear trend as well as the annual and semi-
 412 annual components, in the variability of TRMM-rainfall and GRACE-TWS,
 413 over 2003-2013. Thus, we assumed that the dominant temporal behavior of
 414 the rainfall and TWS changes is represented by $[a, b.t, c.\sin(2\pi t), d.\cos(2\pi t),$
 415 $e.\sin(4\pi t), f.\cos(4\pi t), g.\bar{E}(t - \phi_{ENSO}), h.\bar{I}(t - \phi_{IOD})]$, where t is time in year
 416 (2003-2013), \bar{E} and \bar{I} respectively contain the normalized ENSO and IOD
 417 indices and ϕ_{ENSO} and ϕ_{IOD} are the phase lags in year between the indices
 418 and the rainfall/TWS time series. The contributions of the components
 419 a, b, c, d, e, f, g are co-estimated using a least squares procedure. We found
 420 the correlation between nino3.4 and IOD indices and rainfall time series to
 421 be maximum when the lag is zero. Therefore, the normalized ENSO \bar{E} and
 422 IOD \bar{I} indices without considering any time lags, i.e. $\phi_{ENSO} = \phi_{IOD} = 0$
 423 are considered for the rainfall. The estimated coefficients for g and h are
 424 summarized in Figure 11. The magnitude of ENSO and IOD over 2003-
 425 2013 reached 25 mm whereas the magnitude of the annual ($\sqrt{c^2 + d^2}$) and
 426 semi-annual components ($\sqrt{e^2 + f^2}$) were 70 and 50 mm, respectively. The

427 same procedure was repeated for TWS time series while considering a lag of
428 one month for both ENSO and IOD ($\phi_{ENSO}=\phi_{IOD}=1/12$). This selection
429 is due to the fact that a delay of around one to two months exists between
430 rainfall changes and TWS changes as was discussed under rainfall variability
431 analysis. The corresponding coefficients are summarized in Figure 12. The
432 magnitude of their contribution reached 15 mm, over the period of 2003 to
433 2013. This is relatively less than what we observed in TRMM-rainfall in
434 Figure 11. Considering the simple water balance equation, where TWS is
435 equal to precipitation minus evaporation minus runoff, when a phenomenon
436 like ENSO happens, the amplitude of precipitation increases. One should,
437 however, also consider that consequently, the amplitude of evaporation and
438 runoff will increase and to some extent cancel out a part of the extra input
439 water.

FIGURE 11

FIGURE 12

440 *Economic implications of observed and simulated co-variability of LVB cli-*
441 *mate and total water storage*

442 This section provides an overview assessment of the economic impact of
443 climate change linked to changes in stored water potential of Lake Victoria
444 Basin as discussed in Section 3. It is important to point out that impact of
445 climatic change on economic activities is systemic, thus quite complex and
446 cannot be reduced to only monetary metrics for a single time period. Invari-
447 ably, the economic impact of climatic change can be categorized as first-order

448 impact, and second order impact. The first order impact can be noticed right
449 after a major extreme climatic event occurs, such as drought or floods (e.g.,
450 the El Niño rains of 2007, Figure 3). The second-order impacts are linked to
451 climatic variations in the LVB that happens over protracted length of time
452 or erratic happenings such as unpredictable rainy and dry seasons, which
453 do not correspond to, or altogether disrupt planned-economic activities. In
454 addition, lingering economic effects often happen in an incremental patten
455 over protracted periods of time.

456 Equally important, is the need to understand the complex link between
457 economic and social variables, which when subjected to climatic change, then
458 engenders negative outcomes, both in the short and long term. At the center
459 of economic impact assessment overview is also the heavy dependence of
460 majority of the LVB population on certain economic activities, and therefore
461 negative impact on such activities due to climatic change must be perceived
462 within this reality. For instance, 80% of the LVB population is engaged
463 in small-scale agricultural production and livestock farming, while fishing
464 directly or indirectly support the livelihood of about 3 million people (East
465 African Community Secretariat , 2004; Ntiba et al. , 2001; LVBC , 2011).
466 The population of LVB depends on wood biomass for 90% of their energy
467 requirement (LVBC , 2007).

468 It is difficult to arrive at precise monetary figures when making assess-
469 ment of economic impact of climatic change in the LVB. This is because
470 costs extend well beyond non-economic sectors in the eco-system, but have
471 indirect negative bearing on economic activities in the LVB. Compounding
472 the difficulty of measuring precise economic impact is the sheer lack of accu-

473 rate statistical data of the gross domestic product (GDP) of the LVB. Lake
474 Victoria Basin Commission (LVBC) officials give conflicting GDP figures of
475 \$ 30 billion, and 40 billion for 2011 and 2012, respectively in various pre-
476 sentations (see, Mngube , 2011; Kanangire , 2012). Knowing the accurate
477 GDP can be helpful in estimating the economic impact of changes in stored
478 water potential of Lake Victoria due to climate change. We can then know
479 percentage decrease or increase in GDP that may have resulted from such
480 variability. Hence the overview assessment of economic impact given here is
481 restricted to giving the correlating economic impact to distinctive climatic
482 events drought, floods and erratic seasonal rainfall patterns within spatial
483 dimension.

484 The major economic sectors that are subjected to first-order impact of
485 climatic change are: water resources, ecosystems and fishery, agriculture, en-
486 ergy, transportation, infrastructure and communications, and public health
487 and labor productivity. The second-order economic impact of climatic change
488 are such as lingering food shortages, energy poverty, malnutrition and im-
489 paired learning ability, and gradual loss of ecosystems that previously sup-
490 ported economic and social life of inhabitants. The 1997/98 El Niño floods
491 (see, Figure 2) caused damage to buildings, roads, communications systems,
492 crops, and in addition to costs of treating diseases (Mogaka et al. , 2005).
493 This type of damage has immediate and lingering future costs. Taking the
494 costs of replacement of infrastructure, we can assess immediate costs for all
495 damaged structures, in addition to lost value due to impaired infrastructure,
496 cost of treating diseases, and lost productivity due to diseases and inability
497 to move and communicate freely.

498 Likewise, the drought spawned by La Niña between October 1998 to
499 2000 led to massive crop and livestock loss, decreased hydro-electric power
500 station outputs, water shortage and contamination-related diseases (Mogaka
501 et al. , 2005). Awange et al. (2007) found a link between highly variable
502 climate pattern in the LVB to the frequency and severity of droughts and
503 food insecurity in the region or parts of it. A commissioned research by
504 United States Agency for International Development (USAID) conducted by
505 International Resource Groups (Hecht et al. , 2011), gives some conservative
506 estimates of cost of climate change for LVB at about \$ 6.5 billion for the year
507 2005, in period in which LVB level dropped (see, Figure 7 and also Awange et
508 al. (2008a)). This study gives the GDP of the LVB at around \$ 31.4 billion,
509 thus the cost of climate change impact stands at almost 21% of the region's
510 GDP for the single year. Even more surprising result of this study is the
511 huge cost of public healthcare, which claims 4.4% of LVB GDP. Huge costs in
512 healthcare are related to the elevated incident of malaria, diarrheal diseases
513 and malnutrition, all of which have direct link either to drought or floods
514 (Wandiga , 2006). The economic impact overview assessment here depicts
515 great exposure of the LVB's economic activities to adverse impact of climate
516 change. However there is need for accurate data from which reliable monetary
517 cost of the impact of climate change can be measured and therefore allowing
518 for cost-effective adaptation mechanisms to be planned and implemented.

519 **4. Conclusions**

520 In this study, decadal water storage changes over the basin derived from
521 monthly GRACE, TRMM and RCM products are analyzed. The PCA results
522 from both GRACE and TRMM together with in-situ data analyzed showed
523 a general increase in rainfall and water volume over Lake Victoria Basin.

524 Overall our study confirm that there has been a modest increase in rainfall
525 and stored water over the basin during the last decade. This is captured by
526 in-situ-observed data obtained from lake-shore stations, TRMM and GRACE
527 satellite remote sensing. TRMM data suggest that rainfall conditions have
528 not changed much during the study period (1998-2013) over the basin while
529 GRACE-TWS indicates average mass decline of 38.2 mm/yr for the period
530 2003 to 2007 and increase of 4.5 mm/yr for 2007 to 2013 over the basin.
531 This decline has been attributed to expansion of the Owen Falls/Nalubale
532 Dam, at Jinja Uganda in earlier investigations by Awange et al., (2008) and
533 Swenson and Wahr (2009).

534 Futhermore, the four high-resolution regional climate model simulations
535 analysed clearly reproduced the broad spatial and temporal patterns of pre-
536 cipitation over the LVB, as well as El Nino and La Nina linked anomalous wet
537 and dry conditions during the recent decades. However, only two (CRCM5
538 and PRECIS) of the four RCMs capture the observed spatial distribution of
539 rainfall over the LVB, and this is likely to compromise their ability to depict
540 the correct (GRACE) water stored over the LVB.

541 The economic impact assessment of LVB depicts great exposure of the
542 LVB's economic activities to adverse impact of climate change, specifically
543 its impact on stored water.

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Figure 1: Lake Victoria Basin and in-situ rainfall stations (red) used in the study (Source: Kayombo and Jorgensen (2006))

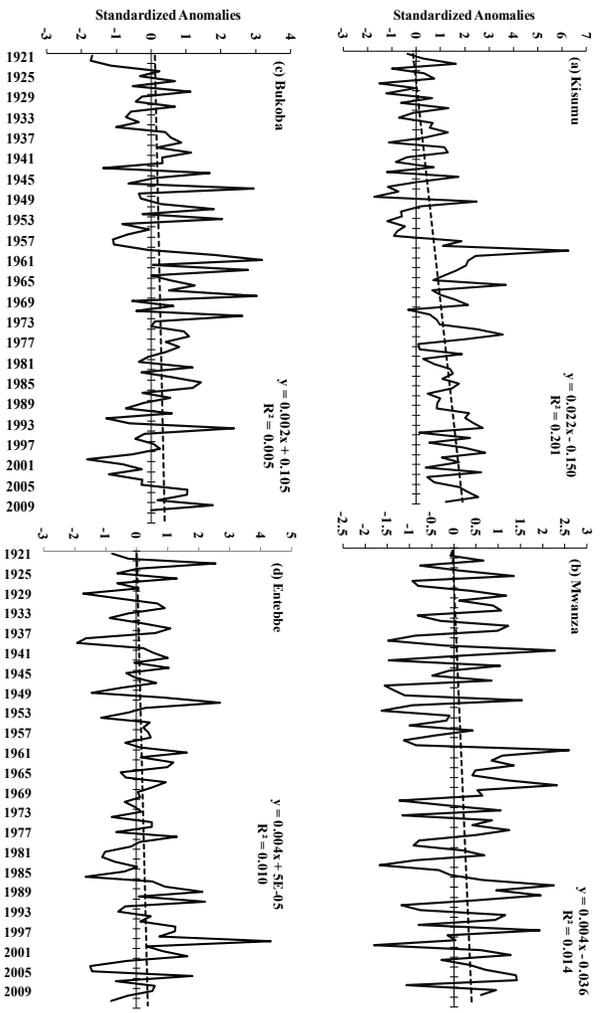


Figure 2: Rainfall trends for some stations in the Lake Victoria Basin

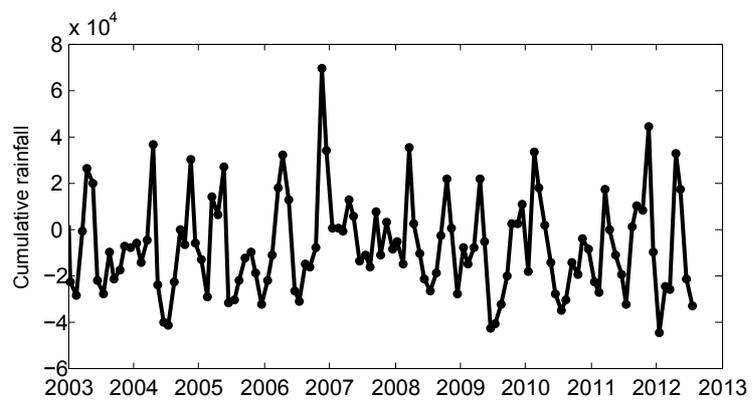


Figure 3: An overview of the cumulative rainfall, derived from each month of TRMM data over LVB, for the period of 2003 to 2013.

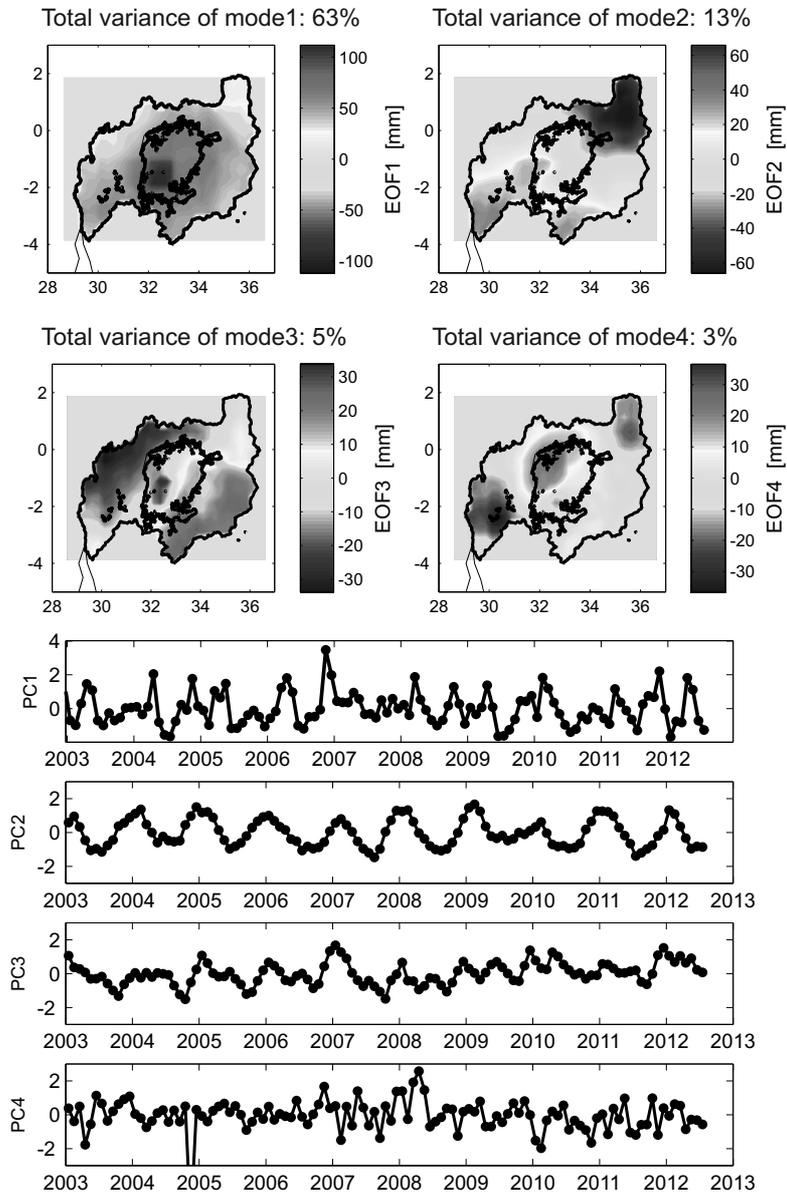


Figure 4: PCA decomposition of rainfall changes derived from TRMM, over LVB. EOFs are rainfall anomaly maps and PCs are their corresponding unit-less temporal patterns.

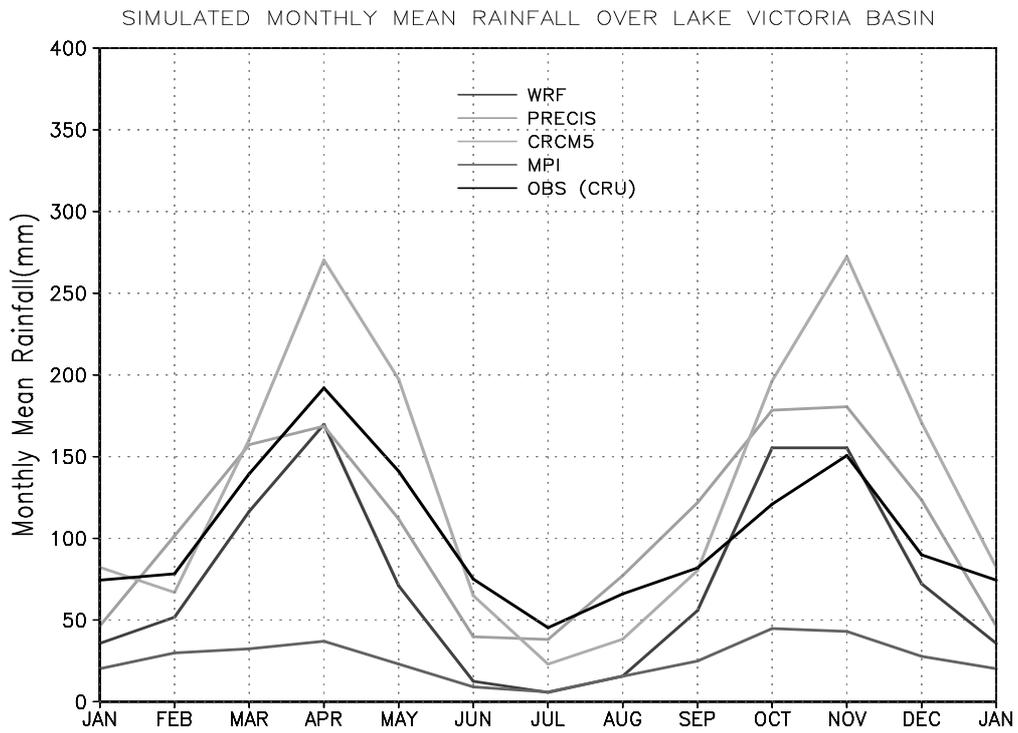


Figure 5: Mean annual cycle of precipitation (mm) over Lake Victoria Basin (31.5E-34E, -2.5S-0.5N).

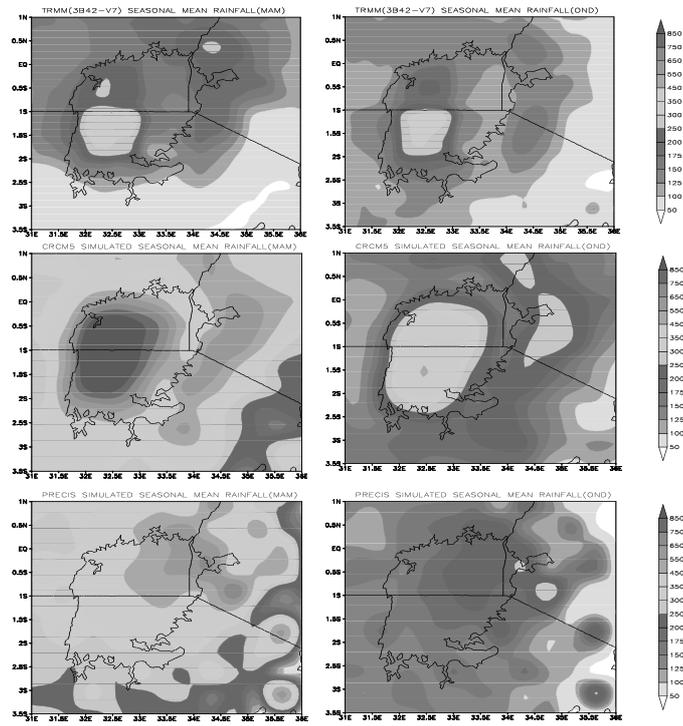


Figure 6: Spatial pattern of seasonal mean rainfall (mm) over LVB. Left panels (March-May season); Right panels (October-December season).

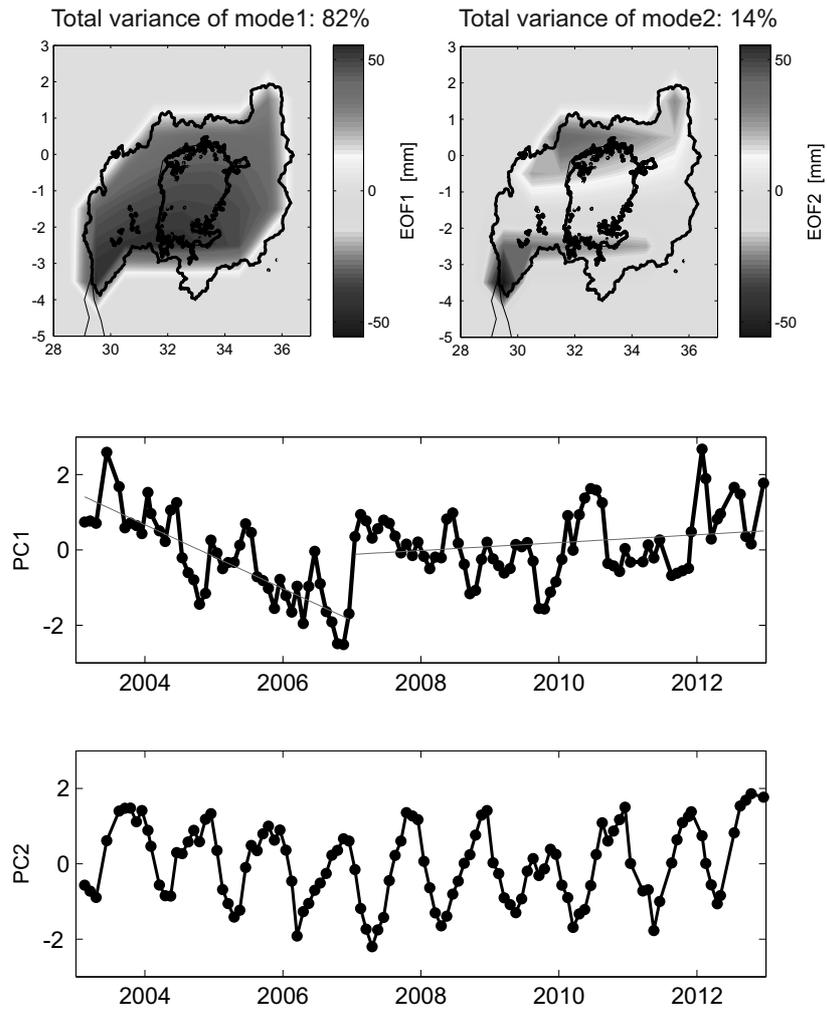


Figure 7: PCA decomposition of TWS changes over LVB. EOFs are counted as anomaly maps that show the spatial distribution of TWS changes within the basin. Corresponding PCs are temporal variations which are scaled with their standard deviations to be unit-less.

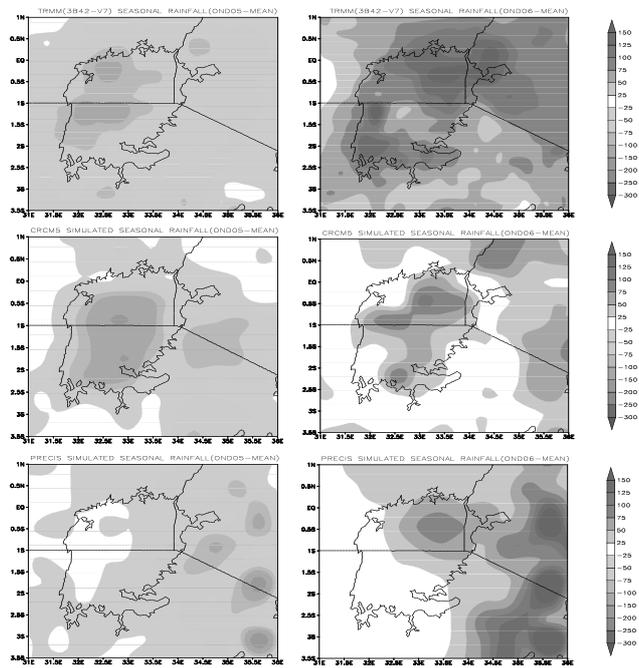


Figure 8: Left: Spatial pattern of 2005 (La Niña), and Right: 2006 (El Niño) seasonal rainfall anomalies(mm) from long term mean over LVB.

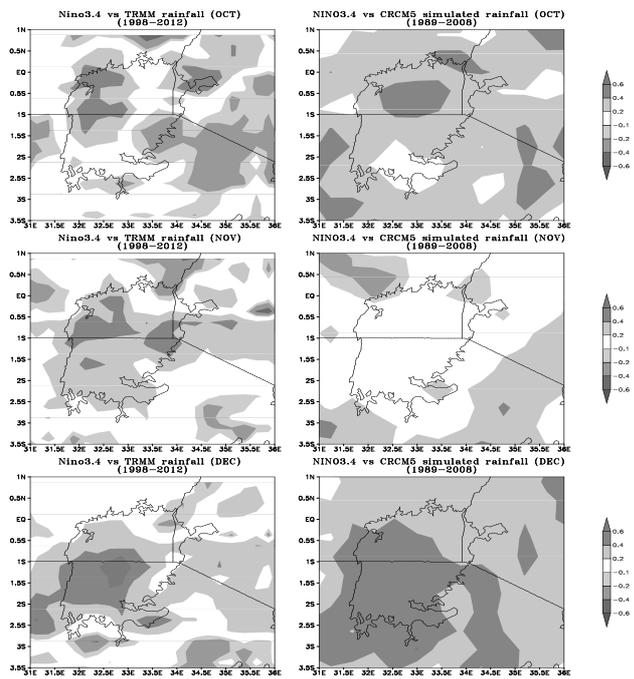


Figure 9: Spatial correlation between ENSO (nino3.4 index) and monthly rainfall over LVB ($r=0.44$ significant at 0.05 confidence level). Top (October), Middle (November) and bottom (December)

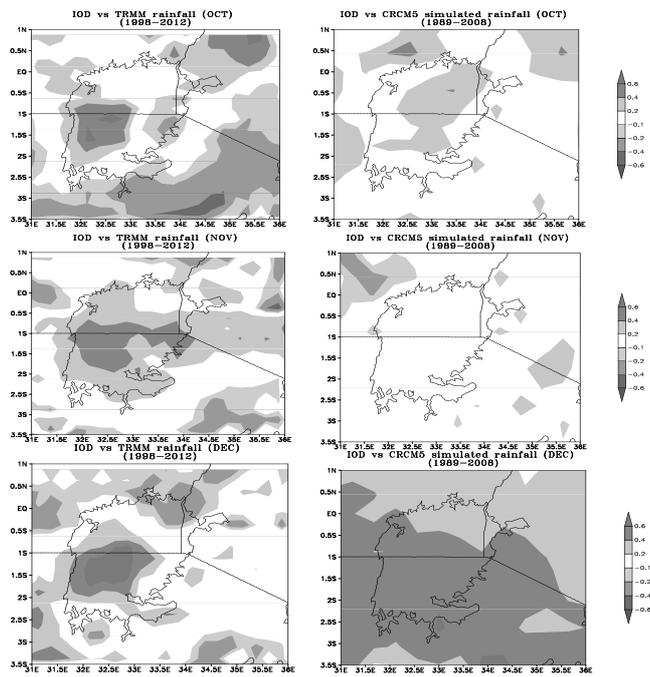


Figure 10: Spatial correlation between IOD (index) and monthly rainfall over LVB ($r=0.44$ significant at 0.05 confidence level). Top (October), Middle (November) and bottom (December)

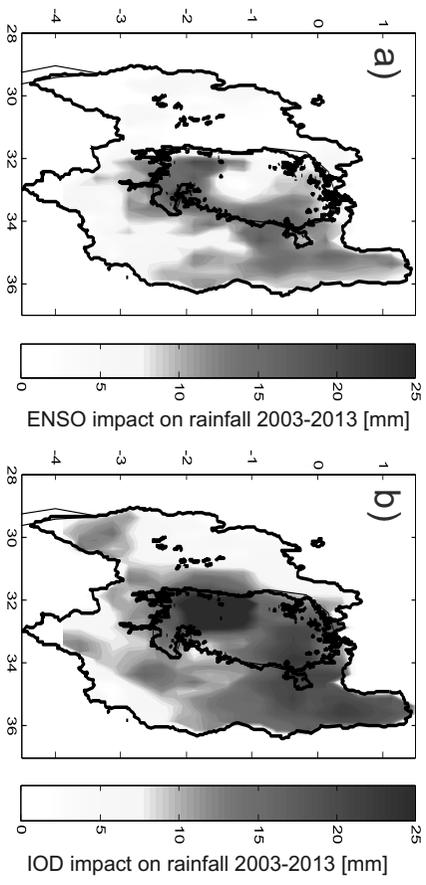


Figure 11: Contribution of ENSO (left) and IOD (right) on the TRMM-derived rainfall variability of LVB.

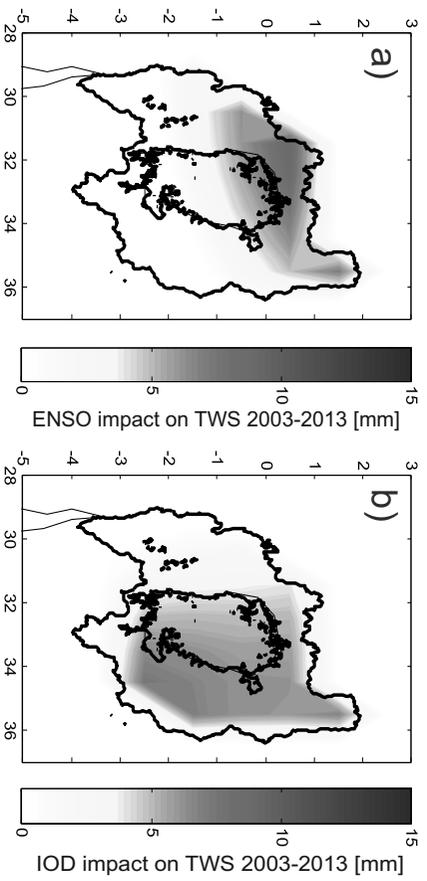


Figure 12: Contribution of ENSO (left) and IOD (right) on the GRACE-derived TWS variability of LVB.