P6.10 PHYSICAL MECHANISMS ASSOCIATED WITH THE VARIABILITY OF LAKE VICTORIA BASIN CLIMATE

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1 Introduction

The primary objective of the present study is to characterize and understand the relative roles of key physical mechanisms influencing the coupled lake-atmosphere climate variability over Lake Victoria Basin and contiguous areas on diurnal to inter-annual time scales. Lake Victoria is located within a geographical setting replete with complex terrain and land surface heterogeneities. Consequently, the Lake Basin constitutes a unique environmental setting in which a myriad of local and large-scale circulation systems combine in the modulation of the regional climate. These factors include topographic and lake-induced circulations, widespread variations in land cover/land use characteristics, monsoonal circulations associated with the thermal contrast between land and the nearby oceans (in particular Indian Ocean), and the influence of Congo air-mass emanating from the tropical (Congo) rainforest (Okeyo, 1982; Anyamba, 1984; Mukabana and Peilke, 1996; Sun et al., 1999; Song et al., 2004; Anyah and Semazzi, 2004).

However, the complex interactions among these processes and their associated modulating influence on the regional climate are not yet well investigated quantitatively. Furthermore, the empirical methods that have been employed in many previous studies do not offer adequate scope to sufficiently unveil the cause-effect relationships between regional climate variability and an individual process or combination of processes. Such cause-effect relationships may only be clarified through a numerical simulation approach that explicitly includes lake-atmosphere coupling. A coupled modeling system provides a rich test-bed for examining the response of the Lake Basin (and regional climate) to an individual process or a combination of processes through a suite of systematic and sensitivity simulations.

In this study a fully coupled numerical model, involving a regional climate model and a three dimensional hydrodynamical lake model (RegCM3-POM: Song et al., 2002, 2004; Mellor and Yamada, 1987) is used to investigate the physical mechanisms associated with Lake Victoria Basin and regional climate variability on diurnal to inter-annual time scales. In particular, we investigate the role of complex topography (steep terrain on both sides of the Lake) and whether they help to organize, enhance and/or suppress development of convective activity over the Lake Basin and surrounding areas. In addition, experiments are performed to investigate the extent to which steep topography modifies the transport of moisture originating oustide the Lake Basin.

The development of mesoscale circulations is often associated with spatial heterogeneities in surface heat fluxes (Laird et al., 2003). These surface heterogeneities can result from land-water boundaries; surface vegetation and land use differences and sea surface temperature gradients. The most obvious examples of the development of mesoscale circulations in response to variations in surface heat fluxes are lake-effect winter storms in the higher latitudes and afternoon and early morning thunderstorms in the tropics. The latter phenomenon is often observed over Lake Victoria Basin in East Africa. Previous studies have shown that the highest number of recorded thunderstorms in tropical Africa (and over the globe) occurs around Lake

Victoria Basin, with approximately 300 thunderstorm active days in a year (Asnani, 1993). The lake-induced mesocale systems and thunderstorm activities associated with them are closely coupled to their surface heat and moisture source (i.e Lake). This often results in substantial localized precipitation over the lake and its immediate surroundings compared to land areas farther away from the lake perimeter.

Mesoscale lake-effect circulations have been shown to develop through complex interactions of an array of environmental and geographic variables such as lake-air temperature differences, wind speed, lower tropospheric stability, lake shape or bathymetry (Laird et al., 2003). Mc Pherson(1970) established that the distribution of the thermal surface gradient (i.e caused by shoreline configuration) and interaction with the ambient wind may enhance or diminish the low-level convergence and vertical circulation within the Lake Basins. This is consistent with the study by Hostetler and Giorgi(1992) who notted that increased simulated precipitation in the presence of large inland lakes is due to two main reasons; (i) increased over-lake evaporation that adds moisture/water vapor to the prevailing flow systems and thus enhances convective instability and precipitation associated with such systems, and (ii) relatively warm lake surfaces instigate instabilities in the enveloping atmosphere, thereby increasing convective precipitation.

Fraedrich(1972) made significant contribution in understanding of this problem by investigating the dynamics of nocturnal circulations and frequent development of thunderstorms over the northwestern/western quadrant(s) of Lake Victoria. The dynamical processes linked to this phenomenon involve the three-way interactions among the diurnal lake-land breeze circulations, the upslope/downslope mountain/valley winds and large-scale winds. The resultant non-linear interactions favor strong convergence over the western half of the lake at night, but over the eastern borders during the day (Okeyo, 1982). The diurnal and monthly rainfall variability is also closely linked with this flow pattern (Mukabana and Pielke, 1996). Asnani (1993) also showed that rainfall over the lake is about 30-35% more than the surrounding land areas. Ba and Nicholson (1998) also used satellite data and showed that the frequency of cold cloud duration over the lake is about 25-30% greater than over the surrounding land, although the estimated over-lake rainfall was highly correlated with basin-wide rainfall. Thus, we hypothesize it is unlikely that much of the unexplained lake level variability originates from over-lake rainfall alone due to the strong coupling between over-lake and large-scale rainfall variability. Furthermore, the bimodal rainfall pattern associated with the passage of the ITCZ across eastern Africa is also well marked in the over-lake rainfall variability (Mistry and Conway, 2003).

Recently, Song et al.(2002,2004) developed a fully coupled regional climatee-3D lake climate modeling system (RegCM2-3D) to simulate the coupled lake-atmosphere climate variability over Lake Victoria Basin. They demonstrated that adopting the traditional modeling approach in which the lake hydrodynamics are neglected (as in 1D-lake formulation) is not entirely satisfactory for Lake Victoria basin and regional climate simulations. Their results further demonstrated that the fully coupled RegCM2-3D model simulated more realistic climate conditions over eastern Africa and the Lake Victoria Basin compared to observations and results of the standard RegCM2-1D model adopted in Sun et al.(1999).

In the present study the response of Lake Basin and regional climate to non-linear interactions among mountain/valley winds, lake-land breezes and large scale (prevailing) monsoonal flow are investigated. Besides, impacts of changes in the physical characteristics of the lake surface on the Lake Basin and regional climate are examined. The design and suite of experiments performed as well as the description of the coupled modeling system is given in section 2. Results and discussions are presented in section 3, while summary and conclusions are given in section 4.

2 RegCM3-POM coupled model

RegCM3 is a three-dimensional primitive equation atmospheric model (Pal et al., 2005). It is an improved and augmented version of the NCAR-RegCM2 (Giorgi et al., 1993 b,c). The model uses a terrain-following (sigma-pressure) vertical coordinate system. The radiation physics calculations are based on the latest version of NCAR-CCM3 scheme (Kiehl et al., 1996) that includes a component for computing the effects of greenhouse gases, aerosols and cloud ice. The land surface physics parameterizations are based on Biosphere-Atmosphere-Transfer Scheme (BATS1e: Dickinson et al., 1993) in which a standard surface drag coefficient based on surface-layer similarity theory is applied to calculate sensible, water vapor and momentum fluxes.

Further modifications and customization of RegCM3 and its earlier versions have been successfully customized for simulation of equatorial eastern Africa climate at North Carolina State University, Climate Simulation Laboratory (Sun et al.,1999a,b; Song et al., 2002; Anyah et al., 2005). Song et al.(2002) developed the coupled RegCM2-POM modeling system for Lake Victoria Basin, which has been further enhanced n the present study.

The three dimensional lake model is based on Ocean Model (Blumberg and Mellor, 1987) which is a three-dimensional, nonlinear primitive equation, finite difference ocean model. The model uses a mode splitting technique to solve for the 2D barotropic mode of the free surface currents and the 3D baroclinic mode associated with the full three dimensional temperature, turbulence and current structure. The barotropic mode uses a shorter time step, while the baroclinic mode uses relatively longer time step. Both modes are constrained by the CFL computational stability criteria. The model is based on a split-explicit Eulerian scheme in which the internal and external modes are integrated separately to optimize computational efficiency. The model includes a 2.5 turbulence closure sub-model (Mellor and Yamada, 1974) with an implicit time scheme for vertical mixing. The equation of state (Mellor, 1991) is used to calculate density as a function of temperature, pressure and salinity. POM is currently one of the most widely used ocean models and has also been extensively used for studying coastal estuaries and inland lake basins. Detailed description of POM model can be found in Mellor and Yamada (1987). Modifications made to POM model for freshwater Lake Victoria can be found in Song et al.,2002 and Anyah, 2005.

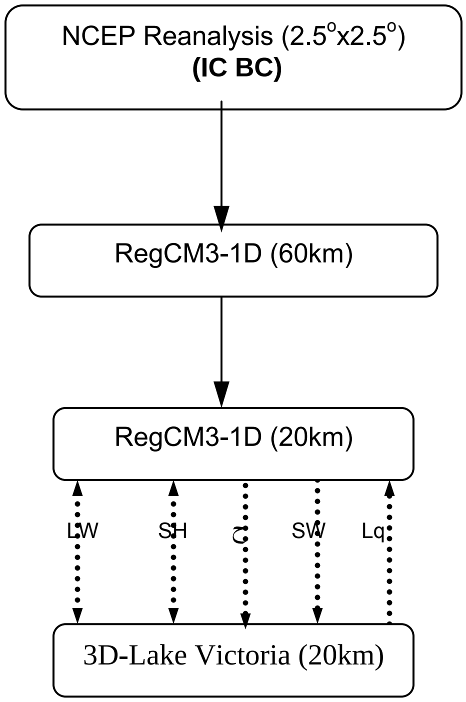


Figure 1: Schematic of the coupled atmosphere-lake system (modified from Song et al, 2004)

Surface boundary conditions used in the coupling between the atmosphere and lake models are expressed as follows:

ω = 0 at σ = 0, $\frac{K_M}{D}\left(\frac{\partial U}{\partial \sigma}, \frac{\partial V}{\partial \sigma}\right)$ = - $\omega u(0), \omega v(0)$

at σ = 0 ; (1)

where, ωu(0) and ωv(0) are the x and y components, respectively, of surface momentum fluxes required in the horizontal model equations; K_M is the vertical mixing coefficient for momentum; D is depth.

The upper boundary condition for temperature:

$$\frac{K_H}{D}\left(\frac{\partial \theta}{\partial \sigma}\right) = -(\omega\theta) \text{ at } \sigma = 0; \quad (2)$$

where ω θ is the input value of surface turbulence heat flux; K_H vertical mixing coefficient for heat; D is the depth

The other upper boundary conditions for the coupled RegCM3-3D lake model are mathematically summarized below:

Lake surface momentum flux exchange: -

$$-\rho_o[\omega u(0)] = -\bar{\rho} C_{dm} V_a u_a \quad (3a)$$

$$-\rho_o[\omega v(0)] = -\bar{\rho} C_{dm} V_a v_a \quad (4b)$$

Upper boundary conditions for temperature (at the lake surface):

$$-\rho_0[\omega\theta] = F_s + F_l + F_{LW} + F_{SW}; \quad (5)$$

where F_s and F_l are sensible and latent heat fluxes, respectively. F_{LW} and F_{SW} are net longwave and shortwave radiation , respectively. F_{SW} is calculated from the atmosphere while F_{LW} is calculated from the relation,

$$F_{LW} = \gamma\sigma T_l^4 + F_{latent}, \quad (6)$$

where γ is the index of reflection (0.97), σ is the Stefan-Boltzman constant, T_l is lake surface temperature and F_{latent} is net longwave radiation from the atmosphere (calculated from RegCM3 model). F_l is calculated from,

$$F_l = \frac{L_v}{C_p} F_q; \quad (7)$$

F_q is evaporation (moisture flux) from the lake surface.

Sensible Heat flux (F_s):

$$F_s = \bar{\rho}_a C_{dh} V_a (\theta_a - \theta_0) \quad (8)$$

$$F_q = \bar{\rho}_a C_{dq} V_a (q_{va} - q_{v0}) \quad (9)$$

where, u_a and v_a are the surface wind components in the zonal and meridional directions, respectively. $V_a = \sqrt{u_a^2 + v_a^2}$ is the resultant wind speed, subscripts ‘a’ and ‘o’ refers to quantities at the lowest model level and the uppermost surface of the lake, respectively.

C_{dm}, C_{dh} and C_{dq} are the drag coefficients for momentum, sensible heat and latent heat fluxes, respectively and depends on surface roughness, temperature and wind speed. C_{dm} is set to 0.0015.

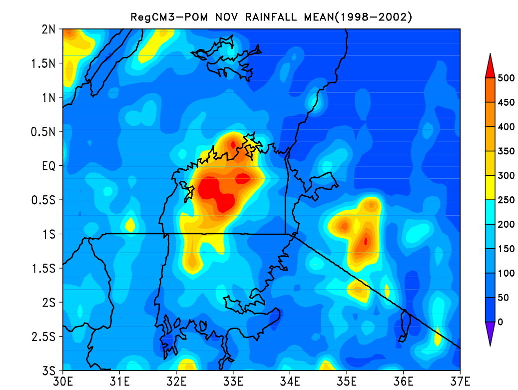
3 Results and Discussions

3.1 Comparison of simulated and satellite (TRMM) rainfall

First, we evaluate the performance of RegCM3-POM model in representing the diurnal and intra-seasonal variability of Lake Basin rainfall. RegCM3-POM simulated monthly mean rainfall is compared with TRMM estimates over Lake Victoria Basin for five years (1998-2002) within the period of the TRMM mission (1998-present). TRMM data over the lake is currently one of the most comprehensive observational surrogates available for evaluating simulated rainfall over the lake since high resolution in situ observed data are not available. The precipitation Radar aboard the TRMM Microwave Imagery (TMI) satellite is capable of detecting below cloud rainfall, and thus a suitable tool for estimating rainfall over Lake Victoria that has a strong diurnal cycle of cloudiness (Ba and Nicholson, 1998).

The simulated rainfall maximum occurs over the western/northwestern sector of the lake, with peak rainfall amounts located slightly to the southwest. TRMM rainfall maximum is located to the southwestern section of the lake surface as well, although the peak amount is about 180mm compared to over 280mm simulated by the model. In addition, the model simulations show a region of rainfall maximum to the east of the Lake (approximately located over Kisii-Kericho-Nandi highlands), which is conspicuously missing in TRMM. Since this is the first year of the TRMM mission, it has been noted that many errors in the algorithms used in computing satellite rainfall estimates had not been corrected (Kummerow et al., 2002).

(a)



(b)

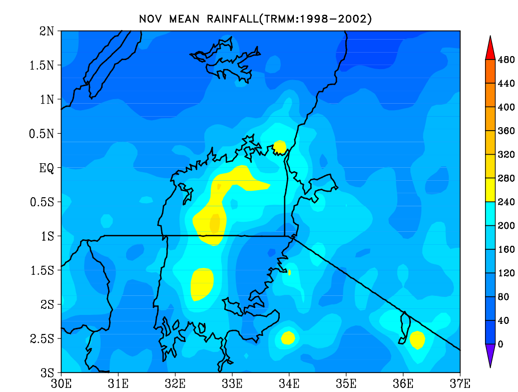


Figure 2: November mean monthly rainfall over the lake basin (a) model simulations (b) Satellite (TRMM) estimate

Overall, the coupled RegCM3-POM model realistically reproduces the spatial and temporal variability of Lake Victoria Basin rainfall (figures 2). In particular, it is evident in the model simulations that over-lake rainfall amount is greater than that of the surrounding land areas by almost 50%, in agreement with TRMM estimates.

3.2 Diurnal cycle of circulation and precipitation pattern over the Lake

Figures 3a and 3b shows an overlay of the simulated mean circulation onto the rainfall pattern over the Lake Basin associated with the peak hours of land breeze and lake breeze, respectively. The peak of the nocturnal circulation is often experienced between mid-night and early morning hours when the lake surface is much warmer than the surrounding land areas (Fraedrich, 1972). On the other hand, the peak lake breeze circulation occurs between late afternoon and early evening, when the adjoining land surface is much warmer than the lake surface. Figure 3a shows the simulated mean circulation pattern in the morning at 3 LST for the month of November. The circulation pattern over the Lake Basin is characterized by flow convergence over the western sector of the lake in agreement with previous studies. Figure 3b shows the mean circulation pattern over the Lake Basin at 15LST, the approximate time when the lake breeze circulation is fully developed. The model reproduces the lake breeze front located to the east of the lake. In particular, the model resolves the outflow from the lake surface associated with the lake breeze. The lake breeze front is located about 2^{o} (200km) to the east of the lake, which is consistent with earlier studies (e.g Asnani, 1993) that have indicated that the horizontal extent of lake breeze circulation sometimes extend over 200km inland to the east of the Lake. It also important to note that the maximum/minimum regions of convective precipitation are, as would be expected, collocated with the flow convergence/divergence patterns.

It is apparent from the model simulations that the lake breeze circulation is more conspicuously and well resolved compared to nocturnal (land breeze) circulation. The lake breeze front is also only clearly shown to the east of the lake, indicating that the thermal contrast between the lake and land is more pronounced to the east, compared to the west of the lake. The simulated land breeze circulation is also relatively weaker and the land breeze front is also confined within the western rim of the lake surface.

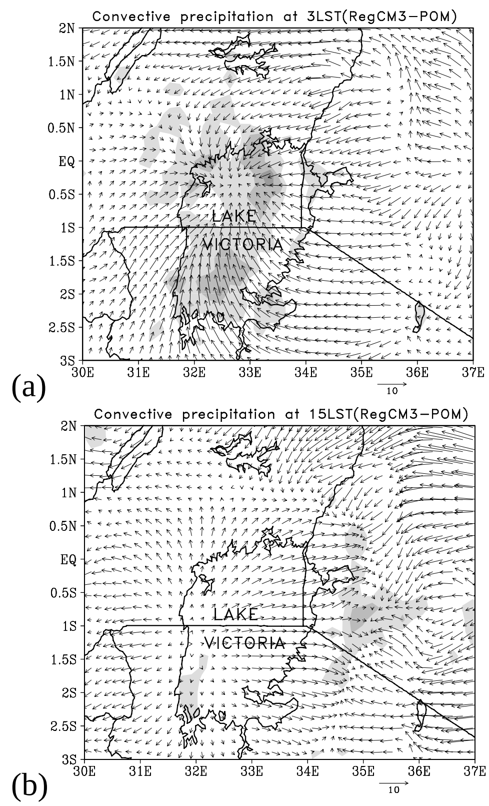


Figure 3: Overlay of 850hPa mean flow on convective precipitation over the Lake Basin (a) 3 LST (b) 15 LST

3.3 Contribution of large scale moisture to the Lake Basin rainfall variability

We performed a suite of sensitivity experiments (table 1) by systematically reducing the amount of large-scale moisture advected into the lake basin through the four lateral boundaries of the model domain. Figure 4 presents the response of the simulated Lake Basin rainfall to changes in large-scale moisture advected into the interior domain via the eastern lateral boundary located across the western Indian Ocean. Several studies have shown that seasonal rainfall variability over eastern Africa is significantly influenced by the SST gradients (moisture anomalies) over the equatorial Indian Ocean (Saji et al., 1999; Mutai et al., 2000). Figures 4a, 4b and 4c show

Table1: Summary of Numerical Experiments

EXPTS	East BC	West BC	South BC	North BC
1	Q-20%	Default	Default	Default
2	Q-50%	Default	Default	Default
3	Q-80%	Default	Default	Default
4	Default	Q-50%	Default	Default
5	Default	Default	Q-50%	Default
6	Q-50%	Q-50%	Q-50%	Q-50%

simulated rainfall variability for November 2000 of the three experiments performed with the lateral boundary moisture reduced by 20%, 50% and 80%, respectively. The short rains season for 2000 over East Africa is treated in this study as having near normal meteorological conditions and thus suitable period for evaluating our sensitivity/anomaly experiments.

It is evident from our results that the simulated rainfall amount reduces systematically as the amount of moisture entering the interior domain through the eastern boundary is reduced. As expected, it is also apparent that the eastern side of the lake exhibits more sensitivity to the reduction (changes) in large scale moisture entering the eastern lateral boundary. The simulated rainfall diminishes drastically when the large scale moisture is systematically reduced compared to other areas around the lake (figure 4). Conversely, we observe no dramatic reduction in the simulated rainfall over the western parts of the lake. When the large scale moisture advected through the eastern boundary was reduced by half (50%), the corresponding decrease in the simulated rainfall, compared to control (figure 4b) was quite dramatic over the entire lake basin. The over-lake rainfall also reduces significantly (by about 50%) compared to control (see table 1). With almost all the large scale moisture (80%) entering the interior domain (lake basin) through the eastern boundary cut off, the reduction in the simulated rainfall amount is quite dramatic over the entire Lake Basin, except over the western/southwestern sector of the lake surface.

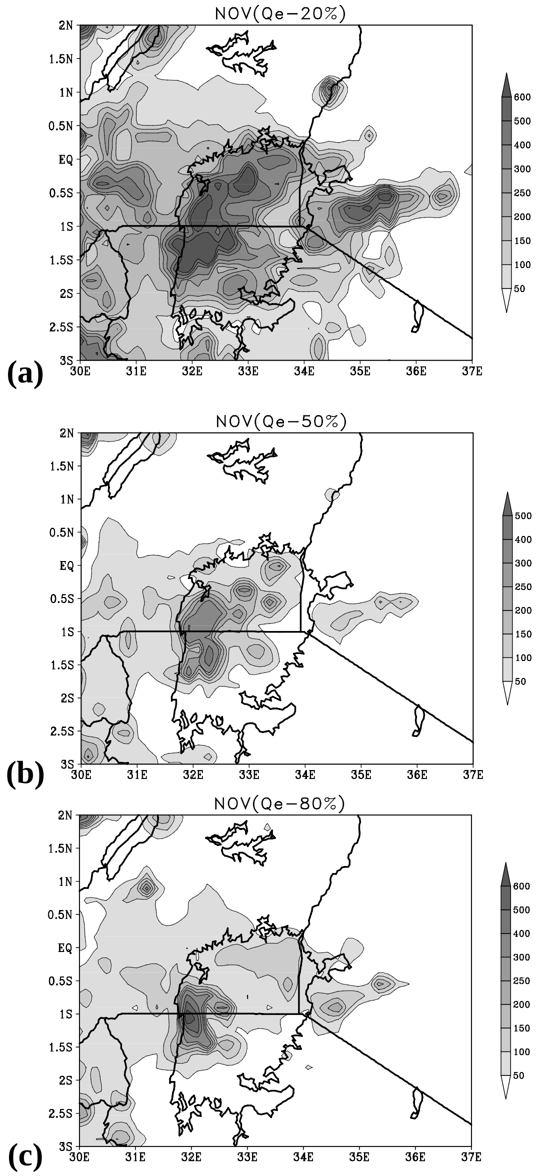


Figure 4: Simulated rainfall (mm) over Lake Victoria basin with large moisture through eastern boundary reduced by (a) 20% (b) 50% (c) 80%

When large-scale moisture entering the western boundary of our domain is reduced by 50%(figure 5c), the corresponding reduction in the simulated rainfall is negligible, compared to the control experiment. However, a rather surprising feature is the slight increase in the amount of rainfall simulated over the western sector of Lake Victoria, which possibly indicate the non-linearity in the response and feedback between the local and large interactions. Similar results are obtained when large-scale moisture entering the southern boundary is reduced by 50 %(Qs-50: figure 5b).

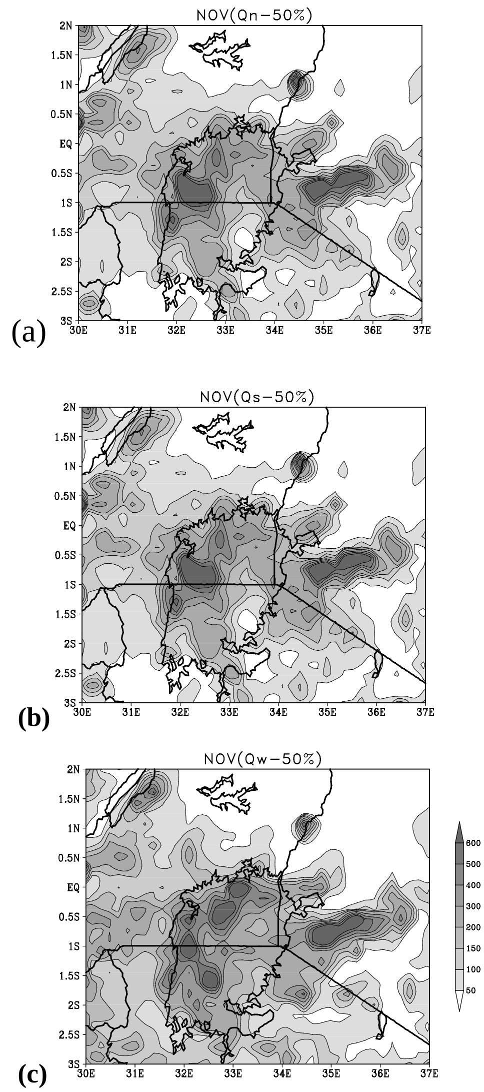


Figure 5: Simulated monthly mean rainfall over the Lake Basin in November(1998-2002) with large scale moisture reduced by 50%(a) northern boundary (b) southern boundary (c) western boundary

Overall, the results of the model experiments with lateral boundary moisture perturbations show that moisture advected through the eastern boundary significantly enhances rainfall over the Lake Basin. This suggests that, the eastern border of the lake suffers/gains from the large-scale moisture deficit/surplus transported by the prevailing easterly/southeasterly flow from western Indian Ocean. It is also apparent from our simulations that the large-scale moisture anomalies from the northern and western boundaries do not have significant impact on the precipitation amount over entire the Lake Basin during the short rains season. However, moisture influx from the southern boundary slightly enhances rainfall over the southwestern and western sectors of the lake. We also note that there is strong intra-seasonal dependency on the large-scale moisture on the eastern boundary (i.e the primary source of moisture). Thus the basin-wide rainfall variability is quite sensitive to moisture influx through the eastern boundary in October and November, but less sensitive in December (not shown).

3.4 Effects of lower boundary forcing on Lake Victoria Basin climate variability

We also investigated the role of local topography and land surface changes on Lake Victoria Basin and regional climate variability. In order to isolate and/or understand some of these factors, we conducted three anomaly control experiments in addition to the control as follows:

(a) **Experiment 1(CTRL):** Control case in which the terrain and land surface characteristics are unaltered.

(b) **Experiment 2(TALL):** Land surface characteristics are undisturbed, but the maximum terrain height around the Lake Basin is at the elevation of the lake surface

(c) **Experiment 3(TPEA):** Same as Experiment 2, but only the terrain height to the east of the Lake, facing western Indian Ocean is reduced to 1300m(the approximate elevation of the lake surface).

(**d) Experiment 4(LBOG)**: Experiments b and c are repeated for cases when the lake is replaced with bog/mash in order to examine the basin-wide climate response to the changes in both lake surface characteristics and topography. Altogether, a total of five numerical experiments were performed (table 2).

We adopt the simulated rainfall and vertical (omega) velocity for our diagnostic analysis of the response of Lake Basin climate to changes in boundary forcing outlined above. The over-lake rainfall simulated in the control run is mainly compared with TRMM rainfall estimates. Figures 6a-b show the simulated mean vertical velocity at 3LST and 15LST, in the TPALL experiment. In terms of the response of vertical motion velocity to lower boundary forcing Figure 6a shows that in the TPALL simulations, the western sector of the lake is characterized by strong upward motion, with maximum vertical velocity located approximately over the center of the lake (33^{o}E, 1^{o}S). The rising motion extends over a very deep column, from the lake surface (~900mb) to around 300mb. This upward motion is associated with very deep convection and thunderstorms as indicated in Freadrich (1972) and Asnani(1993). The eastern side of the lake is however characterized by weak vertical motion. This flow pattern is consistent with the expected diurnal variability over the Lake Basin associated with lake-land breeze circulations. Nevertheless, the region of the strongest rising motion is located over the center of the lake.Thus in the absence of strong downsloping winds over the eastern border of the lake, the eastern branch of the land breeze is relatively weaker than normal (control) and does not extend farther to the west of the lake surface. Conversely, the western branch becomes relatively stronger and extends more offshore into the interior of the lake than in the control. This is consistent with the vertical velocity difference presented in figure 5a that show net subsidence over the western sector of the lake and net uplift over the center of the lake.

The likely mechanism that contributes to the above scenario can be explained as follows. Smooth topography east of the lake leads to weaker downslope flow, which does not enhance land-breeze circulation as compared to the control. When the eastern branch of the land breeze is relatively weaker than normal the western branch of the nocturnal circulation may penetrate into the interior of the lake as shown in figure 6a

In the late afternoon (figure 6b), smooth topography over the eastern border of the lake means that the upward motion is much weaker and is also located around 34.5^{o}E, close to the shoreline(figure 5b). A surprising result is the subsidence over the highlands east of the lake (around 35^{o}E). This possibly suggests that the late afternoon thunderstorms experienced over the Kericho-Nandi-Kisii highlands (located over the eastern border of Lake Victoria) are significantly influenced by orographic lifting of the moisture embedded in the prevailing monsoon circulations, but relatively less dependent on the moisture transport from Lake Victoria. The vertical velocity difference(not shown) also show that there is net subsidence over the highlands east of the lake (around 35^{o}E) and net upward motion along the eastern coastline.

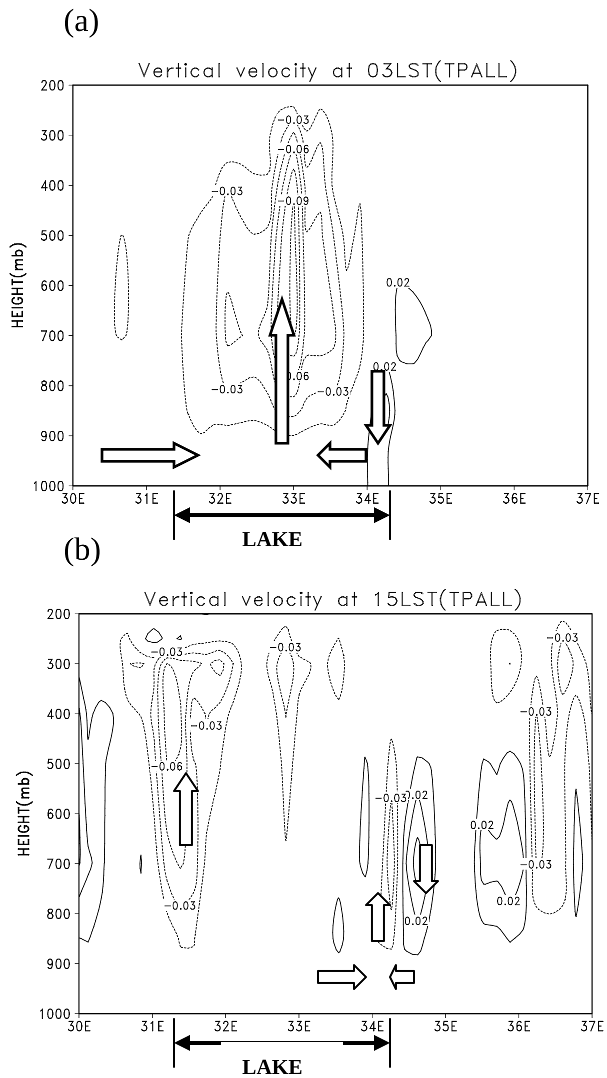


Figure 6: Vertical (omega) velocity profiles (m/s) in the TPALL experiments (a) 3LST (b) 15LST

In order to examine the role of orographic lifting over the eastern side of the Lake Basin on the lake-land breeze circulations, an experiment in which only the maximum terrain height over the eastern boundary of the lake was reduced to the 1300m AMSL (TPEA) was performed. In the early morning (3LST: figure 7a), when the nocturnal land breeze circulation is fully developed, the simulations show rising motion over the center of the lake. However, the upward motion is weak (reaching a maximum of about 0.1ms^{-1} at the center of the lake). Also the subsidence (sinking motion) to the east of the lake is very weak. The difference between TPEA and CTRL experiments (not shown) indicates net upward motion over the center of the lake and net subsidence (sinking motion) over the western rim. This implies that the simulated branch of the land breeze circulation from the eastern side of the lake is relatively weaker than in the control run. The results indicate that the land breeze originating from the western side of the lake is relatively stronger than it is in the control run. The main effect is near the coastal regions of the lake and there is little effect in the deep interior of the lake at night.

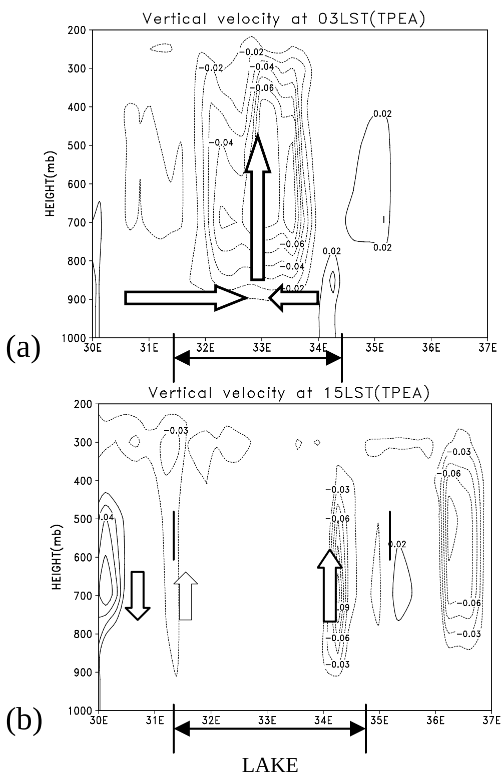


Figure 7: Vertical (omega) velocity profiles (m/s)in the TPEA experiments (a) 3LST (b) 15LST

Two possible physical mechanisms may be responsible for forgoing scenario. First, the steep topography over the eastern border of the lake influences the strength of the eastern branch of the nocturnal circulation (land breeze). This happens through the generation of katabatic(downslope) flow that combines with, and enhances, the down valley land breeze flow triggered by land-lake thermal gradient to produce strong nocturnal flow directed to the lake. Secondly, if the elevated highlands are colder than the surrounding land, the downsloping (katabatic) flow may help to further decrease the surrounding air temperature as it speeds down the topography. This may also lead to a stronger land-lake thermal gradient that eventually strengthens the land breeze. In the late afternoon (figure 7b), the ascending motion to east of the lake is relatively weaker, and more confined to the shoreline (34^{o}E) in the TPEA compared to the control run. The difference between the vertical velocities in the two simulations (not shown) indicate that there is net upward motion confined along the eastern rim of the lake and net subsidence (sinking motion) located slightly inland (between 34.5^{o}E and 35.5^{o}E).

Again similar, but opposite mechanisms suggested for the differences in vertical motion between TPEA and CTRL simulations in the early morning holds true for the late afternoon hours as well. In this case, the reduced terrain height over the highlands to the east of the lake results into weak upward motion (in the absence of elevated heating). However, given the relatively weak wind speeds over the lake (westerly winds), the lake breeze front does not appear to extend farther inland to the east, but remain confined along the lake perimeter. Furthermore, the lower the terrain height over the eastern borders of the lake, the more penetrative the prevailing easterlies leading to flow convergence closer to the lake shore than expected (control). This implies that the elevated heating over the Kericho-Nandi-Kisii highlands mostly triggers strong upslope flow during the day. This may play two major roles with respect to the strength, horizontal extent and convective activity associated with the lake breeze. First, we hypothesize that the elevated heating over the highlands to the east of the lake triggers strong upslope flow, which then creates favorable conditions for entraining (inducing) flow from the lake and thus helps the lake breeze to extend farther inland than would otherwise be the case. Secondly, due to orographic uplifting and its consequences on the horizontal extent of lake breeze explained above, the region of strong vertical motion (lake breeze front) forms more inland than in the case with less steep topography which does not generate strong upslope winds.

3.5 Effects of changes in the physical characteristics of Lake Victoria on basin-wide rainfall climate variability

The impact of the changing lake surface conditions on the basin-wide climate is examined by replacing the lake with bog/mash. Given the recent invasion of Lake Victoria by the water hyacinth weed, this represents a realistic change scenario over the lake surface.

The simulated response of the lake basin circulation at 3LST is characterized by weak upward motion over the western sector of the lake (figure 8a) that extends from around lake surface to about 400mb level. On the other hand, a relatively strong downward motion is simulated to the east of the lake, extending from the surface up to around 500mb levels. The LKBOG minus CTRL simulations show a net downward motion over the center of the lake (figure 9a) and extend over a very deep layer (900mb-200mb). This is consistent with the fact that in the LKBOG experiment less heat is retained during the day compared to the CTRL experiment, due to changes in both the surface albedo and thermal capacity of the swamp. Consequently, at night the lake-land thermal contrast that triggers the nocturnal circulation is significantly suppressed. Hence, the nocturnal circulation characterized with convergence over the western sector of the lake is also suppressed remarkably.

In the late afternoon the upward motion to the east of the lake is enhanced in the LKBOG experiment (figure 9b), compared to the control simulations. This is caused by fact that unlike the dynamic lake, bog/mash conditions triggers stronger evaporation since it does not retain most of the heat received from solar radiation. This leads to stronger evaporative cooling that consequently creates sufficient land-lake thermal gradient that in turn drives a lake-breeze-like circulation.

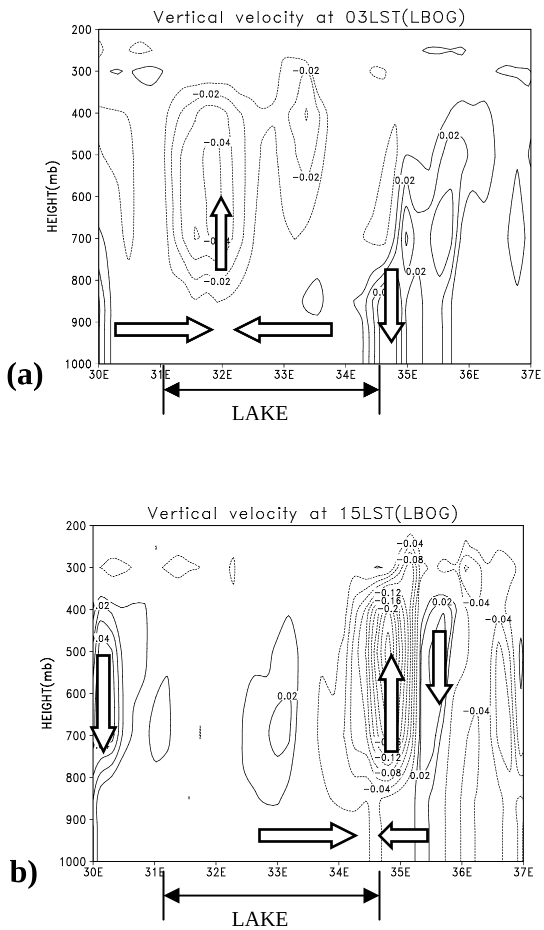


Figure 8: Vertical (omega) velocity profiles in the LBOG experiment

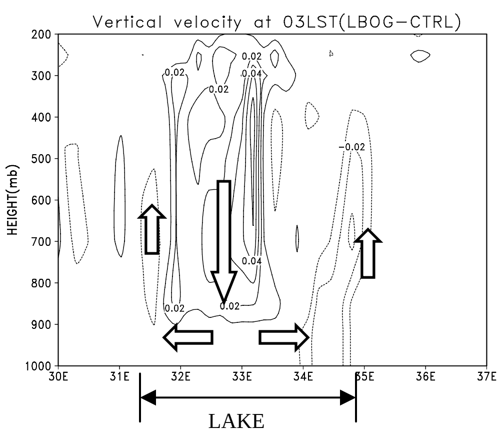


Figure 9a: Profiles of LBOG-CTRL vertical velocity differences at 3LST

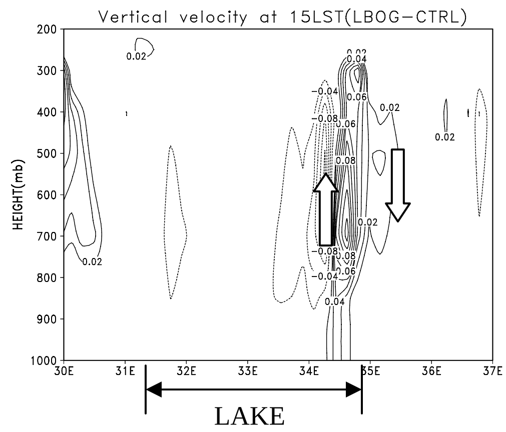


Figure 9b:Profiles of LBOG-CTRL vertical velocity differences at 15LST

3.6 Anomalous rainfall response to lower boundary forcing

The simulated rainfall differences between the anomalies runs in November 2000 (i.e. LKBOG, TOPALL and TOPEA) and CTRL are shown in figure 10. In figure 10a, the LKBOG minus CTRL is characterized by rainfall deficit over the western half of the lake and rainfall surplus over the eastern shoreline of the lake. However, immediately outside the lake perimeter to the east, there is little or no difference between the LKBOG and CTRL simulations. The most striking feature is that over the eastern rim of the lake the simulated amount of rainfall is almost twice the amount in the control simulations.

Two possible mechanisms could be responsible for the increase/decrease in the rainfall amount simulated over the eastern/western shoreline when the lake is replaced with bog/mash. First, we hypothesize that the significant reduction in the simulated rainfall over the western sector could be attributed to the 3LST anomalous subsidence over the lake surface (figure 9a). The subsidence of motion over the lake area in the night could be due to the fact that the bog/mash has relatively lower thermal capacity. This means that the 'lake' will cool faster at night, significantly suppressing nocturnal circulation since the land-lake thermal gradient is weaker.

The second mechanism may be attributed to increased evaporation over the lake surface during the day. This leads to evaporative cooling, thus creating sufficient thermal gradient with the surrounding land areas, in turn leading to relatively strong circulation (lake-breeze-like) directed toward the warmer surrounding. However, this circulation is not as strong as the lake-breeze circulation simulated in the control and thus has constrained horizontal extent. This explains why the approximate location of Lake Breeze front (also collocated with region of maximum precipitation) is close to the eastern shoreline in the LKBOG simulations, while in the CTRL it is located farther inland.

The rainfall anomalies associated with land surface forcing are also exhibited in the horizontal (west-east) cross-section of rainfall distribution over the Lake Basin (figure 9). Comparisons among LKBOG, TPEA, TPALL and CTRL experiments, show lake surface conditions (LKBOG experiment) and orography(TPALL and TPEA experiments) significantly influence the distribution and pattern over the Lake Basin. It is evident that the steep topography to the east of the lake does influence the amount of rainfall simulated over the entire basin, whereas the topography to the west side of the lake (over Rwanda-Burundi-Uganda-Tanzania boundary) do have negligible impact on the diurnal variability of rainfall over the Lake Basin, at least during the short rains season.

Another feature present in the horizontal cross-section of rainfall simulated in the three anomaly experiments (not shown), is that topography does not have significant impact over the eastern sector of the lake, compared to the western sector.

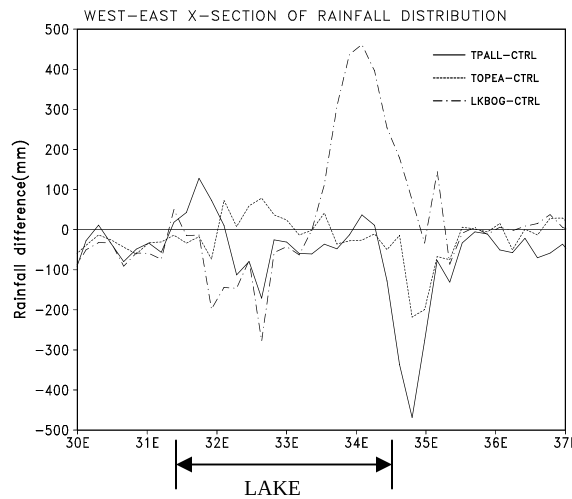


Figure 10: Variations of the horizontal cross section of simulated rainfall over the Lake Basin in the TPALL, TPEA and LBOG experiments

4 Summary and Conclusions

In this study, the downscaling ability of the fully coupled RegCM3-POM modeling system to reproduce multi-scale variability of Lake Victoria Basin climate and the associated physical mechanisms has been demonstrated. In general, the mean monthly rainfall simulated over the Lake Basin, particularly over the lake surface is shown to be in fairly good agreement with the satellite estimates (TRMM data). The simulated diurnal cycle of rainfall over the four quadrants of the Lake show a uniform pattern of hourly rainfall fluctuations. Peaks occurring between midnight and early morning hours characterize the overall diurnal variability.

Two mechanisms are manifested in our model results regarding interactions between topographic and lake-induced circulations and subsequent impact on Lake Basin rainfall variability.

(1) The steeper topography over the eastern border generates very strong downslope(katabatic) winds at night since the air over the mountain top is relatively colder than the air down the Valley. As the colder air from the mountain tops mixes with air down the valley and air over land areas adjacent to lake, the thermal gradient between the land surface and the lake is enhanced. Consequently a relatively stronger land breeze circulation is generated. The stronger the land breeze circulation, the more favorable it is for strong convection and precipitation to develop over the central and western sectors of the Lake. The opposite is the case when the terrain height is reduced as is also evident in our simulations.

(2) The horizontal extent of the late afternoon lake breeze circulation is also

affected by steep topography over the eastern border of the lake. Due to elevation, the mountain tops heats faster during the day than the surroundings. This creates a thermal low that in turn induces very strong upslope (anabatic) winds on both sides of the mountain. The stronger the upslope flow on the lee side the more it tends to pull the lake breeze front farther inland. Hence, when the terrain height is reduced, the horizontal extent of the lake breeze circulation also reduces. This leads to significant reduction in the simulated afternoon rainfall associated with the lake breeze circulation. The simulated rainfall is also confined along the eastern shoreline, but does not extend farther inland compared to the control simulation.

The apparent influence of the large-scale moisture transported via the prevailing easterly monsoons in enhancing precipitation over the Lake Basin is clearly manifested in our simulations. This is evident in the simulated rainfall patterns and amounts in the runs with large-scale moisture entering the four lateral boundaries of the interior domain (Lake Victoria Basin) systematically reduced/increased. Large-scale moisture advected through the eastern boundary (located across equatorial western Indian Ocean) enhances over-lake rainfall and more especially over the surrounding land areas to the east and southeast of the lake. However, a rather surprising result is that there is negligible influence on the basin-wide rainfall variability due to changes in large-scale moisture entering the Lake Basin domain through the western boundary of our domain during the short rains.

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References

Anyah, R. O. (2005): Modeling the variability of the climate system over Lake Victoria Basin, *Ph.D dissertation*, North Carolina State University, pp.287

Anyah, R.O., and F. H. M. Semazzi (2004): Simulation of the response of Lake Victoria basin climate to lake surface temperatures.*Theor. Appl. Climatol*,**79**,55-69

Asnani G. C(1993): Tropical Meterology Vol. 1 and Vol. 2 Indian Institute of Tropical Meteorology Pashan: Pune 1012pp

Denis B, R Laprise and J Côtê (2002): Donwscaling ability of one-way nested regional climate models: The big-brother experiment

Dickinson R.E, R.M Ericco, F. Giorgi and G.T Bates(1989): A regional climate model for the Western United States. *Climatic Change*, **15**, 383-422

Fraedrich, K (1972): A simple climatological model of the dynamics and energetics of the nocturnal circulation at Lake Victoria. *Quart. J. Royal Meteor*. *Soc*, **98**, 332-335

Giorgi F, G.T Bates and S Nieman (1993): The multiyear surface climatology of a Regional Atmospheric Model over the western United States*. J. Clim*, **6,**75-95

Giorgi F, Marinucci MR., Bates GT (1993a): Development of a second-generation regional climate model (RegCM2), Part I: Boundary layer and radiative transfer processes. *Mon Wea. Rev.* ,**121**,2794-2813

Giorgi, F. Marinucci, MR., Bates, GT (1993b) Development of a second generation regional climate model (RegCM2), PartII:Convective processes and assimilation of boundary conditions. *Mon. Wea Rev* ,.**121**, 2814-2832

Giorgi, F., and L. Mearns(1999):Introduction to special section. Regional climate modeling revisited. *J. Geophys. Res*., **104**,6335-6352

Giorgi F (2002): Variability and trends of sub-continental scale surface climate in the twentieth century. Part II: AOGCM simulations. *Clim Dyn* , **18**,693-708

Grell G.A. (1993): Prognostic evaluation of assumptions used by Cumulus parameterizations. *Mon Wea Rev.,* **121**, 764-787

Hostetler S, G.T Bates and F Giorgi (1993): Interactive nesting of a lake thermal model within a regional climate model for climate studies. *J. Geophys. Res.,***98**,5045-5057

Hostetler, S., and F. Giorgi (1992): Use of a regional atmospheric model to simulate lake-atmosphere feedbacks associated with Pleistocene Lakes Lahontan and Bonnevile, *Clim Dyn*, **7**, 39-44

Hsie, E.Y., R.A. Anthes, and D. Keyser, 1984: Numerical simulation of the frontogenesis in a moist atmosphere. *J. Amos. Sci.*, **41**,2581-2594

Jones R.G, J.M Murphy and M Noguer(1995): Simulation of climate over Europe using a nested regional climate model. Part 1: Assessment of control climate including sensitivity to location of lateral boundaries. *Quart J Royal Meteor. Soc*, **121**,1413-1449

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Wollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo CK, Ropolewski C, Wang J, Leetma A, Reynolds R, Jenne R and Joseph D(1996) The NMC/NCAR 40-Year Reanalysis Project. *Bull Amer Metor Soc***:77**,437-471

Kalnay, E.(2003): Atmospheric Modeling, Data Assimilation and Predictability. Cambridge University Press, Cambridge UK, 341pp

Kelly, J.G.W., J.S. Hobgood, K.W Bedford, D.J. Schwab(1998): Generation of three-dimensional lake forecasts for Lake Erie. *Weather and Forecasting,* **13**,659-687

Kummerow, C., J, Simpson, O. Thiele, W. Barnes, A.T.C. Chang, E. Stocker, R.F. Adler, A. Hou, R. Kakar, F. Wentz, P. Ashcroft, T. Kozu, Y. Hong, K. Okamoto, T. Iguchi, H. Kuroiwa, E. Im, Z. Haddad, G. Huffman, B. Ferrier, W. S. Olson, E. Zipser, E. A. Smith, T.T. Wilheit, G. North, T. Krishnamurti, and K. Nakamura (2000): The status of the Tropical Rainfall Measuring Mission(TRMM) after two years in orbit *J. Appl. Meteor*., **39, No.12**,1965-1982

Laprise, R., M.K. Ravi Varma, B. Denis, D. Caya, and I. Zawadzki(2000): Predictability in a nested limited area model. *Mon Wea Rev*., **128,** 4149-4154

Leung, L.R., and S.J. Ghan(1999): Pacific Northwest climate sensitivity simulated by a regional climate model driven by a GCM. Part I: Control simulation. *J. Clim.,***12**, 2010-2030

Leung, L.R., L.O Mearns, F. Giorgi and R.L. Wilby(2003): Regional Climate Research Needs and Opportunities. *BAMS*,**Jan.2003**,89-95

McGregor J.L (1997): Regional Climate Modeling. Meteorol Atmos Phys., 63,105-117

Mukabana, J.R.,and R.A. Pielke(1996): Investigating the influence of synoptic scale winds and meso-scale circulations and diurnal weather patterns over Kenya using a meso-scale numerical model. *Mon Wea Rev.,* **124**,:224-243.

Mistry, V. V, and D. Conway (2003): Remote forcing of East African rainfall and relationships with fluctuations in levels of Lake Victoria. *Int J. Climatol.***,23**, 67-89

Nicholson, S.E (1998): Historical Fluctuations of Lake Victoria and other lakes in the northern Rift Valley of East Africa. *Environmental Change and Response in East African Lakes* (J. T. Lehman, ed.), Kluwer, Dordrecht, 7-35

Nicholson, S.E and X. Yin(2001): Rainfall conditions in equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. *Climatic Change*, **48**, 387-398

Okeyo, A.E.(1987): The influence of Lake Victoria on the convective activities over the Kenya Highlands. *J Meteor. Soc. Japan,* **Special volume**, 689-695

Pielke, R.A(2002): Mesoscale Meteorological Modeling(2nd Ed). Academic Press, pp.676

Qian, J., Seth, A., and S. Zebiak (2003): Reintialized versus continuous simulations for regional downscaling. *Mon Wea Rev*., 131, 2857-2874

Seth, A., and F. Giorgi (1998): The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate. *J Clim*.,11,2698-2712

Small, E.E., F. Giorgi and L.C Sloan(1999) Regional climate model simulation of precipitation in Central Asia: Mean and interannual variability. *Journal of Geophysical Research*, **104**, 6563-6582

Song Y, F.H.M Semazzi, L. Xie and L.J Ogallo(2004): A coupled regional climate model for Lake Vcitoria basin of East Africa. *Int. J. Climatol*. **24**, 57-75

Staniforth, A (1997): Regional modeling. A theoretical discussion. *Meteorol Atmos Phys*, **63**, 15-29

Sun L, Semazzi FHM, Giorgi, F, Ogallo LA (1999a): Application of the NCAR Regional Climate model to Eastern Africa. Part 1: Simulation of the short rains of 1988**.** *J Geophys Res***., 104**, 6529-6548

Sun L, F.H.M., Semazzi, F. Giorgi, and L.A. Ogallo(1999b): Application of the NCAR Regional Climate model to Eastern Africa. Part II: Simulation of interannual variability of short rains*. J Geophys. Res.,* **104**, 6549-6562

Yin, X., S.E. Nicholson, and M.Ba(2000): On the diurnal cycle of cloudiness over Lake Victoria and its influence on evaporation. *Hydrological Sciences*, **45(3)**, 407-424

Yin, X., S.E. Nicholson (2002): Interpreting annual rainfall from the levels of Lake Victoria. *J. Hydrometeorol*, **3(4),** 406–416

Wang Y, L.R.Leung, J.L McGregor, D-K Lee, W-C Wang, Y Ding and F Kimura(2004):Regional climate modeling: Progress, Challenges and Prospects. *J. Metorol. Soc. Japan,***12**:825-847