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The Role of Moisture Schemes in Regional Climate Modeling of Precipitation over the Horn of Africa

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Abstract

This study aims to evaluate the performance of the latest Regional Climate Model version 4 (RegCM4) to simulate the precipitation over the Horn of Africa. Although there are several aspects in which the model can be improved, the focus of this study is to tackle the problem of its moisture scheme. RegCM4 moisture scheme has fourteen moisture scheme parameters, which can be tuned within the allowed physical limits. Each of the fourteen moisture parameters have been varied around the current default setting and over 80 model runs have been performed for a domain defined by 60km resolution, 18 vertical levels covering spatially the whole Africa and the major circulation patterns that derive climate over the region. We have found physical sound set of moisture scheme parameters to be used in the fourteen moisture scheme parameters that have significantly reduced bias in RegCM4 precipitation; improved correlation of RegCM4 precipitation with respect GPCP and CMAP; and captured seasonal and interannual variations over most of the 12 delineated homogeneous regions of Horn of Africa.

Key words: Moisture, scheme, RegCM4, Model, Precipitation

1. Introduction

The Horn of Africa (HOA) has distinct climate characteristics compared to the rest of the continent (Vojtesak et al. 1990). The HOA is replete with complex terrain comprising of some of the known tropical high mountains and the Great Rift Valley System (GRVS).

The complex HOA terrain presents enabling environment where local and large scale climate systems frequently interact to create highly variable climate in both space and time. At the same time, inter-annual variability of the HOA climate is linked to perturbations in the global SSTs, especially over the equatorial Pacific and Indian Ocean basins, and to some extent, the Atlantic Ocean (Ogallo 1988; Nicholson 1997 and Mutai et al. 2000). These three global oceans, all at the same time or each at different times, intriguingly influence the interannual variability of the HOA climate.

Interactions and feedbacks among these multiple climate drivers over the region present challenges in quantitative understanding of regional climate variability and changes based on typical empirical techniques (Ogallo et al. 1988; Ogallo 1989)). Therefore, there is a need to employ physically-based, regional climate models (RCM) that can offer scope and capability to unveil cause-effect relationships between regional climate variability and individual or combination of processes. However, representation of the multiple sources of forcing to the HOA climate also poses a great challenge to RCM as well.

For hydrological cycle, the presence of clouds and resulting precipitation is the primary control on the cycles (pal et al. 2000). The ERA-Intrim reanalysis corrects some of the errors of the ERA-40 reanalysis particularly in the hydrological cycles variables over the tropics. It is also important to accurately represent cloud processes in many modeling application.

Clouds are often poorly represented in both regional and global climate models (RCMs and GCMs) respectively (pal et al. 2000).

In this research we considered SUBEX (subgrid explicit moisture) parameters processes of bottom model level with no clouds (ncld), autoconversion rate for the land and ocean (qland and qoce), autoconversion threshold (Qthc) for the land and ocean (guland, guloce), minimum relative humidity over the land and ocean (rhland, rhoce), maximum relative humidity (rhmax), maximum cloud cover (fcmax), effect of temperature (tc0) on SUBEX, rain drop evaporation rate coefficient (Cevap), Cloud liquid water content for convective precipitation (cllwcv), Max cloud fractional cover for convective precipitation (clfrcvmax) and rain drop accretion rate (Caccr) are varied within the allowed physical limits such that the default settings are enclosed within the variations for the normal year of summer 2000.

This study aims to evaluate the performance of the Regional Climate Model version 4 (RegCM4) to simulate the precipitation over the Horn of Africa of the delineated region. It evaluates the ability of regional climate model (RegCM4) to reproduce the observed rainfall amounts and distribution over the topographically varied region of the HOA.

2. Method and Materials

2.1 Description of study Area

Geographically, the western half of the HOA is dominated by the Great Rift Mountain system which runs nearly the entire length of east Africa and extending into the Arabian Peninsula in the extreme north (Vojtesak et al.1990). The topography of HOA extends from -182 to 5780m above sea levels. The peak of mountain is found in the north western and central parts of Ethiopia as depicted on figure 2.1. Highlands regions encompass mostly in Ethiopia than other countries of HOA.

The mountains have a marked influence on climate and weather in the HOA, presenting a major natural barrier between modified maritime and continental tropical air masses to the west, and Indian Ocean (IO) maritime tropical air to the east (Vojtesak et al.1990). Large-scale tropospheric circulation features influencing the HOA are largely controlled by the Asian monsoon, a seasonal reversal of winds caused by hemispheric-scale, continent-ocean temperature gradients (Ramage et al. 1971; Slingo et al. 2003).

The terrain slopes upward from east to west, transitioning from lowlands at the shorelines, then to rolling hills and plateau, until meeting the Great Rift mountain chain (Figure 2.1).

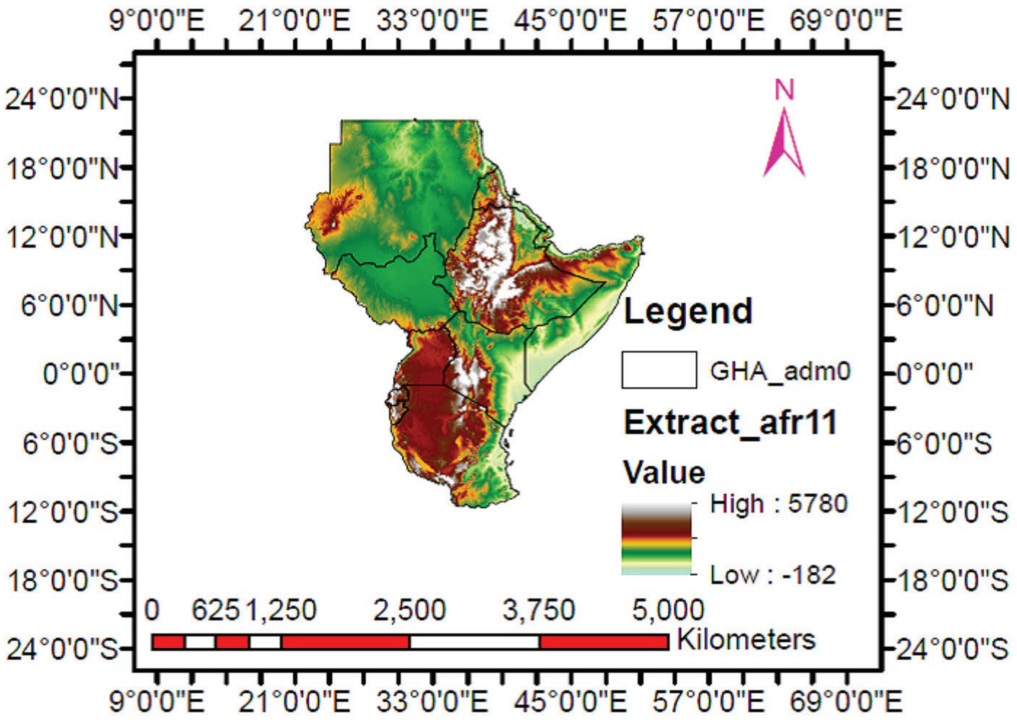

Figure 2.1. *The topography of Horn of Africa Region (study area)*

3. Method

3.1 Boundary conditions

3.1.1 Surface boundary conditions

Orography is incorporated in the model as the lower boundary condition in a terrain following vertical coordinate system (Giorgi et al. 1993). Pressure has been widely used as a vertical coordinate in modeling and theoretical studies. However, there were deficiencies of the sigma treatment of orography. This scheme may not handle sharp terrain gradients effectively (Indeje et al. 2001). The orography data used in this study were taken from the global 2.5° horizontal resolution orography file archived at International Research Institute (IRI). These data were interpolated to the model horizontal grid resolution of 60 km using the linear interpolation scheme. The land-use data adopted in the model were interpolated from 2.5° resolution data archived at National Centers for Atmospheric Research (NCAR). The time dependent SST was interpolated from 1°X1° grid of the monthly mean observed data. The surface pressure, air temperature, humidity are some of surface boundary condition variables (Giorgi et al. 1993).

3.1.1 Lateral boundary and initial conditions

This scheme consists of Newtonian and diffusion terms that gradually drive the model solution of wind components, temperature, water vapor mixing ratio, and surface pressure toward specified large scale values inside the lateral buffer zone. The lateral boundary condition variables are:

- . Wind
- . Temperature
- . Water vapor; and
- . Surface pressure.

As the size of the horizontal domain decreases, the specification of the velocity components and temperature along the boundaries affects the mean values of these quantities over the entire domain to an ever increasing degree (Giorgi et al. 1993). Thus, on a domain of 224 x 96, a set of boundary conditions may be computationally stable and produce smooth results, but even small errors in the treatment of precipitation, temperature or velocity may profoundly affect the mean kinetic and internal energy budgets over the domain.

Initial conditions in a numerical simulation represent the mean space time characteristics of the atmosphere at the beginning of the numerical experiment. The fields for both lateral and initial conditions are obtained ECMWF reanalysis. After completion of ERA-40, effort was devoted to development of a new reanalysis system derived from the latest version of the operational European Center for Medium Range Weather Forecast (ECMWF) system. In 2006 a new reanalysis was started from January 1989, to produce an interim reanalysis (ERA-Interim) for the data rich 1990s and 2000s, to be continued as ECMWF Climate Data Assimilation System (ECDAS) until superseded by a new extended reanalysis.

The main advances of the ERA-Interim data assimilation over the ERA-40 system are: 12 hour 4D Var, T255 horizontal resolution, better formulation of background error constraint, new humidity analysis, improved model physics, quality control of data drawing on experience from ERA-40 and variation bias correction of satellite radiance data, improvements in radiosonde temperature and surface pressure bias handling, more extensive use of radiances, improved fast radiative transfer model and assimilation of rain affected Sea Surface Model (SSM) radiances through 1D-Var.

ERA-Interim uses mostly the observations prepared for ERA-40 supplemented by data for later years from ECMWFs operational archive. Boundary forcing fields are taken from ERA-40 until 2002, and from ECMWF operations for later dates. However, a few new dataset have been acquired. The ERA-INTERIM is a reanalysis of the global atmosphere covering the data rich period since 1989 and continuing in real time. As ERA-Interim continues forward in time, updates of the Archive will take place on a monthly basis.

The ERA-INTERIM project was initiated in 2006 to provide a bridge between ECMWFs previous reanalysis, ERA-40 (1957-2002), and the next generation extended reanalysis envisaged at ECMWF. The main objectives of the project were to improve on certain key aspects of ERA-40, such as the representation of the hydrological cycle, the quality of the stratospheric circulation, and the handling of biases and changes in the observing system. These objectives have been largely achieved as a result of a combination of factors, including many model improvements, the use of 4-dimensional variational analysis, a revised humidity analysis, the use of variational bias correction for satellite data and other improvements in data handling.

The atmospheric model is coupled to an ocean-wave model resolving 30 wave frequencies and 24 wave directions at the nodes of its reduced one-degree latitude/longitude grid.

The main characteristics of the ERA-Interim system and many aspects of its performance are described in ECMWF.

The sensitivity of models runs of five up to eight sets of experiments for each individual SUBEX parameters of the subgrid explicit moisture processes are done.

ERA-Interim data set is used for initial conditions (ICs) and exponential lateral boundary conditions (LBCs) during sensitivity runs of each of the fourteen parameters as well as long year runs using default and new set of parameters. Sea surface temperature from optical interpolation weekly (OI-WK) are used as surface boundary conditions. For the ICs and LBCs quantities each reanalysis dataset is interpolated to the grid of the RegCM4 and the first set of interpolation fields is used as ICs for the simulation. The physics of convective precipitation scheme used in this experiment is a Grell Arakawa-Schubert (Grell AS) scheme. The RegCM4 was run with the same horizontal resolution of 60km and 18 vertical levels. The domain is 39.9°to west and 80.44° degree in the East direction and from 24.6° to south and 25.1° North direction as shown in Fig 2.2.

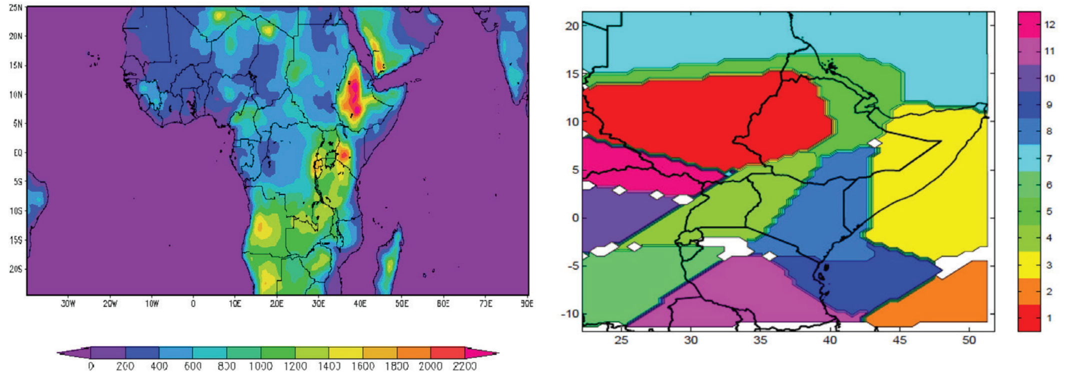

Figure 2.2: RegCM4 Simulation Domain and Delineated regions of Horn of Africa

3.1.1 Validation Data Set: CMAP and GPCP Precipitation

In this study, RegCM4 Precipitation is compared with Global Precipitation Climatology Project (GPCP) and CPC Merged Analysis of precipitation (CMAP). Rain-gauge measurement is the traditional and oldest method for monitoring rainfall. However, because of practical observational limitations it suffers from numerous gaps in space and time, often making its use in climate diagnostic studies is less reliable. On the other hand, rainfall estimates based on satellites is spatially and temporally comprehensive when calibrated using rain-gauge measurements (Xie and Arkin 1998). Xie and Arkin (1998) produced a global precipitation data set called CMAP to assist in problems encountered when relying just on rain-gauge observations. CMAP is a global precipitation data set that uses a global 2.5° X 2.5° grid resolution, temporally distributed monthly/pentad from January 1979 - present. The Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis is globally complete, monthly analysis of surface precipitation grids at 2.5° X 2.5° resolution is available from January 1979 to the present. It is a merged analysis that incorporates precipitation estimates from low orbit satellite microwave data, geosynchronous orbit satellite infrared data, and surface rain gauge observations (Adler et al. 2003). The merging approach utilizes the higher accuracy of the low orbit microwave observations to calibrate, or adjust, the more frequent geosynchronous infrared observations. The dataset is extended back into the premicrowave era (before mid-1987) by using infrared-only observations calibrated to the microwave based analysis of the later years. The combined satellite based product is adjusted by the rain gauge analysis. The dataset archive also contains the individual input fields, a combined satellite estimate and error estimates for each field.

This monthly analysis is the foundation for the GPCP suite of products, including those at finer temporal resolution. The 23-yr GPCP climatology is characterized along with time and space variations of precipitation.

3.1.1 Analysis of Bias, RMSE and Correlation

The performance of the four options of convective schemes in RegCM4 is evaluated quantitatively by analyzing the bias, root mean square error and correlation of the simulations relative to the observation datasets using the methods found in (Wang et al. 2003; Diro et al. 2008).

The primary measure of simulation skill is the model bias (a time average of the error), defined as

$$bias = \frac{1}{N}\left[\sum_i \sum_j \left(a_{i,j}^M - a_{i,j}^O\right)\right] \qquad (2.1)$$

where N is the total number of grid points within a given region; subscripts **i**, **j** are the horizontal grid point indices in the zonal and meridional directions, respectively; **a** can be any meteorological parameters either daily mean or monthly mean; superscripts **O** and **M** refer to the observed and model simulated quantities, respectively.

The root mean square error (RMSE) is defined as

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{N}} \sum_{\mathrm{i}} \sum_{\mathrm{j}} \left(a_{i,j}^M - a_{i,j}^O\right)^2} \qquad (2.2)$$

A correlation coefficient measures the strength and direction of a linear association between two variables. The correlation coefficient between simulated and observed quantity is defined as where the over bar denotes spatial mean.

$$Corrcoef = \frac{\left[\sum_i \sum_j \left(a_{i,j}^M - a_{i,j}^{\overline{M}}\right)\left(a_{i,j}^O - a_{i,j}^{\overline{O}}\right)\right]}{\sqrt{\left[\sum_i \sum_j \left(a_{i,j}^M - a_{i,j}^{\overline{M}}\right)^2 \left(a_{i,j}^M - a_{i,j}^{\overline{O}}\right)^2\right]}} \qquad (2.3)$$

4. Results

A total of eighty four model runs during sensitivity model runs and two additional model experiments for long period to assess the improvement in simulation of precipitation based on new set of SUBEX parameters versus the default setting were performed. In the following section, we consider both sensitivity studies and long year run.

4.1 Sensitivity Studies for Moisture Scheme Parameters

In this study sensitivity runs were performed for fourteen moisture scheme parameters resulting in total eighty four runs and each individual SUBEX parameters of the subgrid explicit moisture processes experiments were done. These experiments were done from moisture scheme of bottom model level with no clouds (ncld) to maximum cloud fractional cover for convective precipitation (clfrcvmax) which is varied within the allowed physical limits such that the default settings are enclosed within the variations for the normal year of summer 2000.

Table 3.1 shows sensitivity studies accomplished for 14 SUBEX variables. The second row shows the model runs which include the default and additional runs of up to seven experiments while the first column shows the SUBEX variables. The improvement in precipitation prediction based on the new values of the parameters was evaluated using correlation, RMSE and bias of RegCM4 with corresponding CMAP and GPCP values.

Table 3.1: Sensitivity experiments based on JJAS runs of the normal year of 2000.

Subex Param.	**default**	**run1**	**Run2**	**Run3**	**Run4**	**Run5**	**Run6**	**Run7**
Ncld	1	0	2	3	4			
Fc_{max}	0.80	0.50	0.60	0.70	0.90	1.00		
Qland	0.25exp-3	0.5exp-4	0.15exp-3	0.5exp-3	0.75exp-3	0.1exp-2	0.5exp-2	0.1exp-1
Qoce	0.25exp-3	0.5exp-4	0.15exp-3	0.5exp-3	0.75exp-3	0.1exp-2	0.5exp-2	0.1exp-1
Guland	0.4	0.3	0.5	0.6	0.7	0.8		
Guloce	0.4	0.3	0.35	0.45	0.5	0.55		
Rh_{max}	1.01	0.80	0.85	0.90	0.95	1.00	1.03	1.05
Rhland	0.80	0.65	0.70	0.75	0.85	0.95		
Rhoce	0.90	0.70	0.75	0.85	0.90	0.95		
tc0	238.0	230	234	242	246	250	260	270
C_{accr}	3	1	2	4	5	6		
C_{evap}	0.10exp-2	0.35exp-2	0.50exp-2	0.60exp-2	0.75exp-2	0.85exp-2		
Cllwcv	0.3exp-3	0.1exp-3	0.2exp-3	0.4exp-3	0.5 exp-3	0.6exp-3		
$Clfrcv_{max}$	0.25	0.15	0.20	0.35	0.40	0.45		

4.2 Long Years Runs (1989 - 2008) with new set of SUBEX Parameters

The extent of improvement to precipitation simulation with respect to old and new parameter values were described in detail (Table 3.2).

The new parameters the subgrid explicit moisture scheme (SUBEX) improves the agreement between simulated and observed precipitation for the seasons of the years except that of summer which has high roots mean square error (RMSE) than the default SUBEX parameters and Grell AS convective scheme (Fig. 3.1). Furthermore, evaluation of RegCM4 simulation for 1989-2008 showed that the modified moisture scheme (SUBEX) does not only reproduce the 19 years average rainfall realistically but also captures interannual variability adequately over the Horn of Africa.

In RegCM4, both the convective and SUBEX schemes work on subgrid scales; however, their approaches are different. The convective schemes try to diagnose if convection will occur in portions of the grid and allow emulating updrafts in the atmosphere and form precipitation through updrafts. However, the large scale precipitation scheme SUBEX does not emulate up drafts, but instead processes the moisture that is already aloft in the atmosphere. In this process it forms clouds and precipitation if critical thresholds of moisture are surpassed.

In RegCM4, the convective scheme is called before the SUBEX scheme. This implies that some SUBEX precipitation could be generated by moisture moved aloft by the convection that moves moisture aloft but that the convective scheme itself does not rain out.

Separation of convective and stratiform rain was dependent on which scheme generated the rainfall.

Table 3.2: New SUBEX parameter values selected based on best performance in capturing CMAP and GPCP precipitation

subex parameter	**Perivious values**	**accepted values from CMAP**	**Accepted Values from GPCP**
Ncld	1	2	2
Fc_{max}	0.80	0.50	0.50
Qland	0.25 exp-3	0.1 exp-1	0.1 exp-1
Qoce	0.25 exp-3	0.15 exp-3	0.15 exp-3
Guland	0.4	0.3	0.3
Guloce	0.4	0.55	0.55
Rh_{max}	1.01	1.01	1.01
Rhland	0.80	0.90	0.90
Rhoce	0.90	0.95	0.95
tc0	238	246	246
C_{evap}	0.100 exp-2	0.75 exp-2	0.75 exp-2
C_{accr}	3.0	3.0	3.0
Cllwcv	0.3 exp-3	0.3 exp-3	0.3 exp-3
$Clfrcv_{max}$	0.25	0.20	0.20

Fig. 3.1 shows correlation of RegCM4 precipitation reproduced using new SUBEX parameters (marked as new) and default (marked as Grell-AS) values with CMAP(left panel) and GPCP (right panel). There is substantial improvement in reproducing observed precipitation patterns using the new set of SUBEX parameters over nearly all clusters.

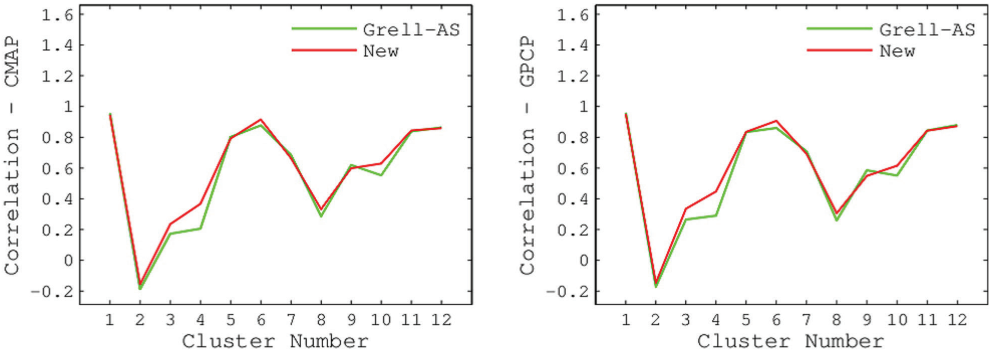

Figure 3.1: Correlation simulated precipitation based on new and old SUBEX with CMAP (left panel) and GPCP (right) for the long year model run.

Figure 3.2 shows the simulated precipitation based on new and old SUBEX parameters with CMAP and GPCP for the long years model run is evaluated by using statistical methods to visualize its accuracy with the old model (Grell-As) for different year intervals. The root mean squared error (RMSE) and bias are implemented statistics for evaluating the overall quality of the simulated precipitation. The Root Mean Squared Error (RMSE) is the square root of the average squared distance of data point. RMSE (upper panels) and bias (lower panels) as depicted in (Fig.3.2). There is a slight rise in the RMSE over some regions in cluster 6, and 10 – 12.

However there is significant improvement in the bias for clusters in the region, especially over the region in cluster 4, 6, 8, 10 - 12.

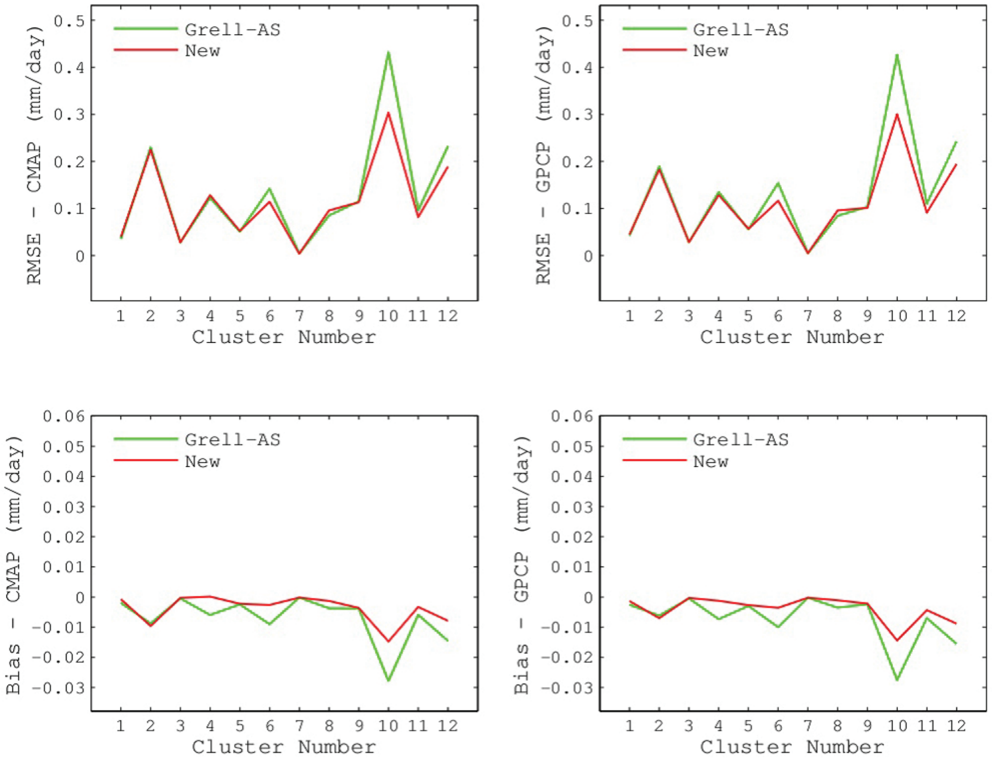

Figure 3.2: RMSE (top) and Bias (bottom) of simulated precipitation based on new and old SUBEX parameters with CMAP (left panel) and GPCP (right) for the long years model run

Fig.3.3 shows the seasonal mean RMSE (top panels) and Bias (bottom panels) of simulated precipitation based on new parameters (red) and old (green) with CMAP (left) and GPCP (right) for the whole Horn of Africa regions. The correlation of the simulated precipitation using new parameters with the observational data set had declined during the JJAS period, which is a wet season for most of northern part of the horn of Africa.

From our previous result of cluster analysis in this study, this is probably an artifact introduced due to averaging over the whole domain which is characterized by different seasons. It is considered imperative that RCMs be tested concerning the ability to reproduce historical observations of both mean climate and temporal variability for more extended periods.

Therefore, we evaluated the ability of the new SUBEX parameters to reproduce the 1990 – 2008 (19 years) time series for the all the clusters in the region and inter-annual variability within each delineated regions.

The degree of similarity between modeled and observed inter-annual rainfall variability is a valuable model diagnostic that measures the sensitivity moisture schemes over Horn of Africa precipitation.

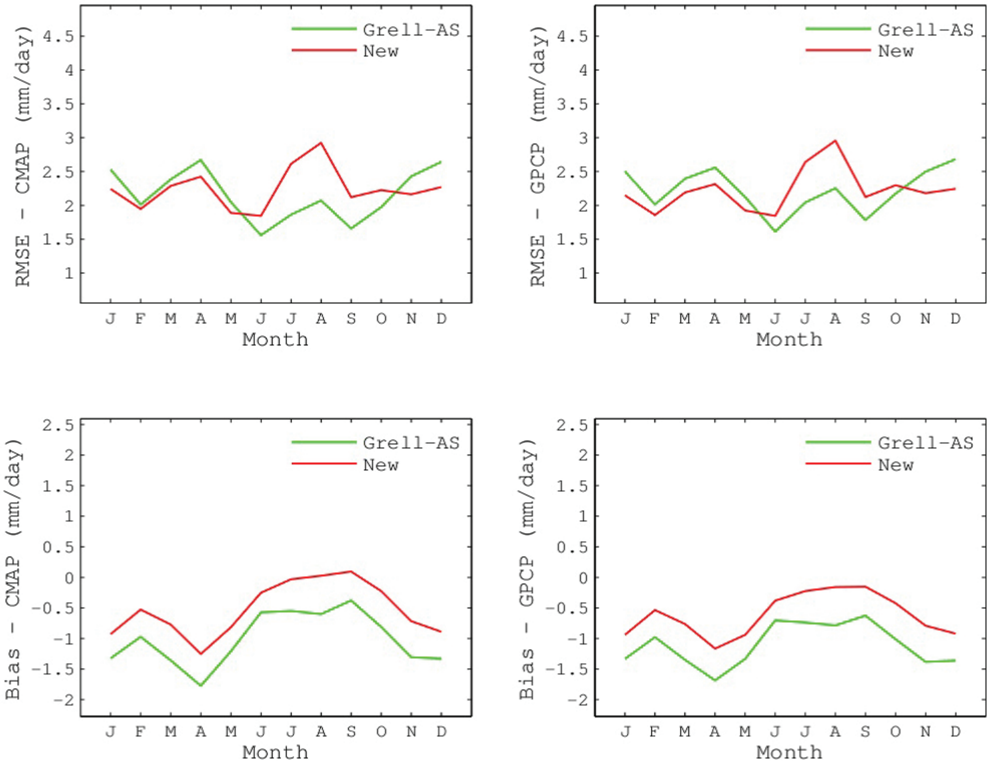

Figure 3.3: RMSE and Bias of simulated precipitation based on new and old SUBEX parameters with CMAP (left panel) and GPCP (right) for the long year model

Fig. 3.4 (top panel) shows remarkable improvement in both magnitude and pattern of precipitation produced using the new parameters. There are several instances at which there is improvement in magnitude which exceeds 2mm/day in contrast to simulation on the basis of default values.

Fig. 3.4 (middle panel) shows the time series for cluster 2 which is over Indian Ocean. Both old and new set of parameters have bad performance in capturing the observed pattern as well as magnitudes over the whole simulation period. There is either small or significant over clusters 3, 4, 7, 8, and 9 as shown in Figs. 3.4 (bottom panel), 3.5 (top panel), 3.6. The clusters include regions characterized by low lands, deserts, and semi arid climate. Most of these regions lie in east, northeast, south parts of Horn of

Africa, mostly along and towards south and eastern side of the great rift valley. This signals that our choice particularly regarding rain drop evaporation is not optimal. On the other hand, the new simulation has captured observed inter-annual rainfall variability over clusters 1, 6, 11, 12 remarkably and partly over clusters 5 and 10 as shown in Figs. 3.4 (top panel), 3.5 (bottom panel), and 3.7 (middle and bottom panels). These regions are either on north-western side of Great Rift Valley or south of equator. The north part of Ethiopian main rift valley region is part of the region with moderate improvement.

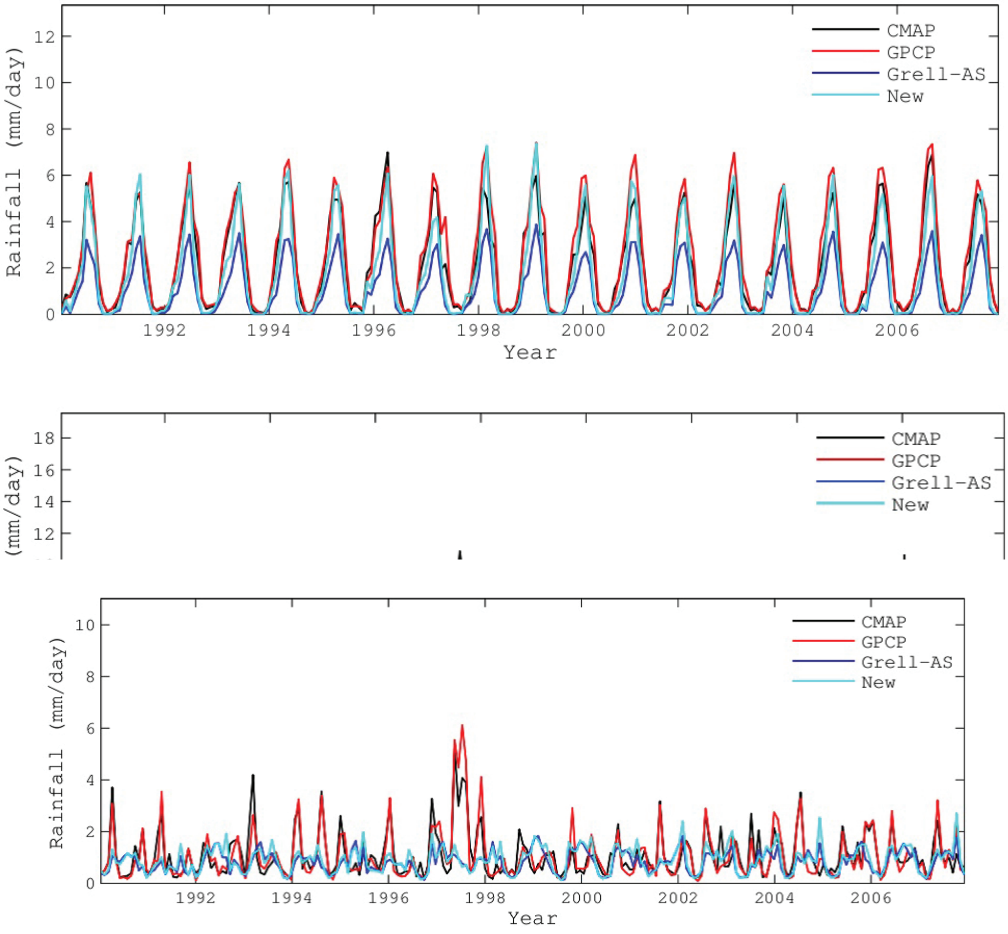

Figure 3.4: Rainfall time series: CMAP (black); GPCP (red); Old SUBEX parameter (marked as Grell-AS, blue); and New parameters (light green) for cluster number-1 (top), 2 (middle) 3 (bottom).

The clusters 4, 5 and 6 are depicted in Fig.3.5 with two observational data (GPCP and CMAP) by considering Old and New SUBEX parameters. Over the three cluster (cluster-4, 5 and 6) the New SUBEX parameter performed better than the Old SUBEX (Grell-AS) parameters. Temporally it showed better results simulated rain fall in capturing precipitation over these clusters locations.

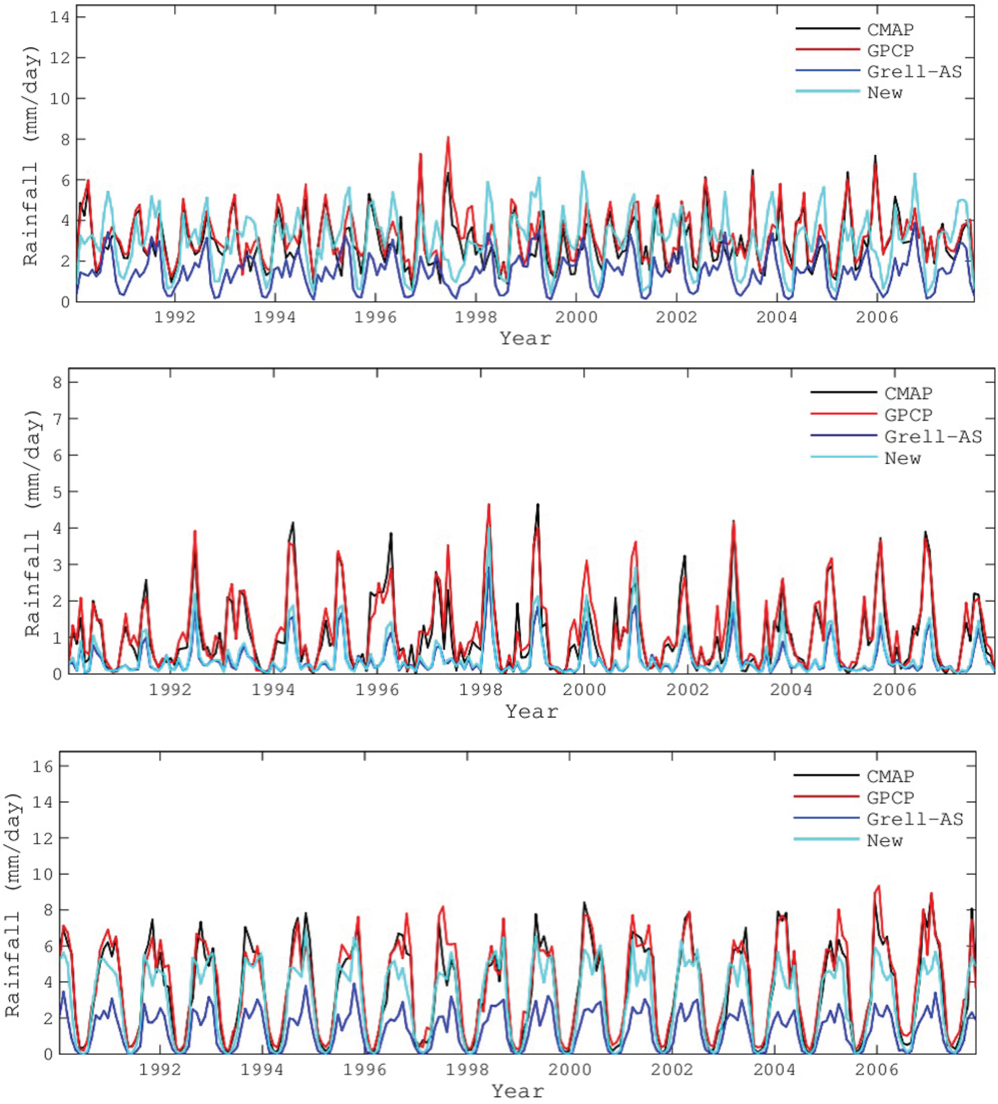

Figure 3.5: Rainfall time series: CMAP (black); GPCP (red); Old SUBEX parameter (marked as Grell-AS, blue); and New parameters (light green) for cluster number-4 (top), 5(middle), 6 (bottom).

In comparison to cluster 4-6, the New and Old SUBEX parameter over clusters 7 and 9, poor capturing ability were observed by New and Old SUBEX parameters (Fig 3.6). However, over cluster 8, simulated New SUBEX parameters showed better performance than the Old SUBEX parameters (Grell-AS).

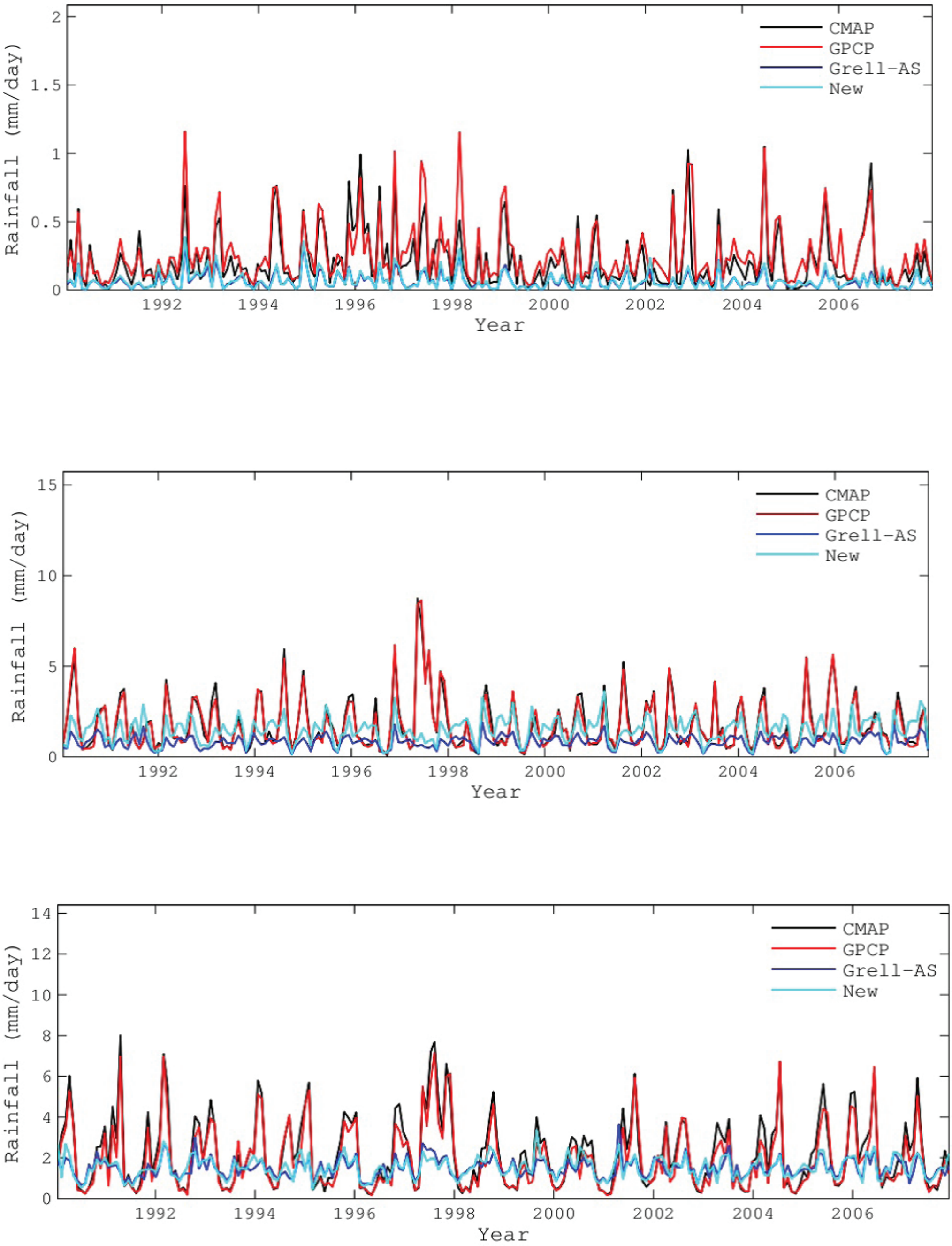

Figure 3.6: Rainfall time series: CMAP (black); GPCP (red); Old SUBEX parameter (marked as Grell-AS, blue); and New parameters (light green) for cluster number-7 (top), 8(middle) and 9 (bottom).

Over cluster 10-12 of delineated regions of parts of Horn of Africa, New SUBEX parameters performance is observed. This simulated scheme showed strong potential capturing precipitation over these three clusters (10, 11 and 12). Such strong comparison was not observed by Old SUBEX parameters with observational values. Therefore, higher capturing ability was observed by New simulated model in comparison with the observational values (GPCP and CMAP).

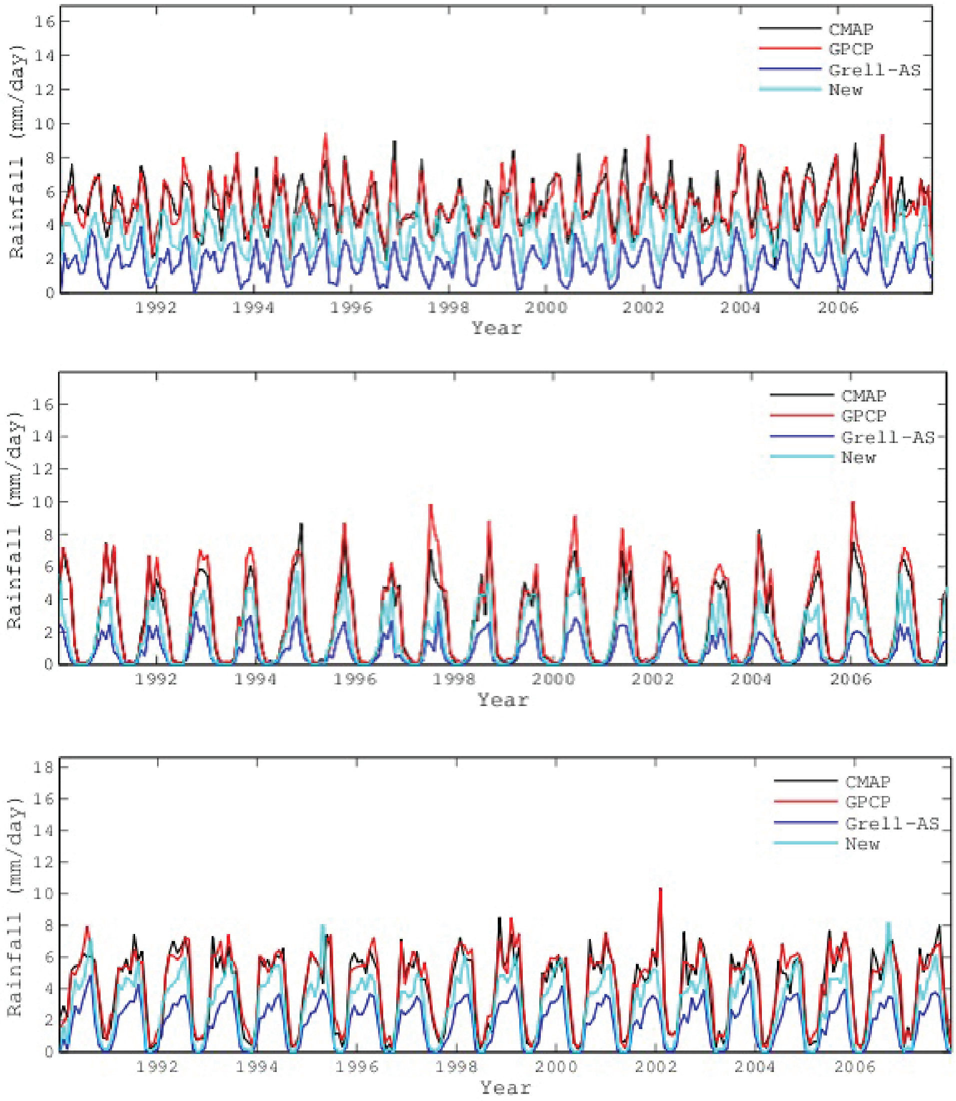

Figure 3.7: Rainfall time series: CMAP (black); GPCP (red); Old SUBEX parameter (marked as Grell-AS, blue); and New parameters (light green) for cluster number-10 (top), 11 (middle) and 12 (bottom).

Conclusion

The nonconvective precipitation, which is parameterized through subgrid explicit moisture scheme (SUBEX) in RegCM4 and its predecessors, is improved through optimal set of parameters for the horn of Africa region. The optimal set of SUBEX parameters are selected such that there is a large and significant correlation of simulated precipitation with observed precipitation of CMAP and GPCP; there is small RMSE and Bias in RegCM4 precipitation compared to these data set.

We have found optimal set of moisture scheme parameters which has significantly reduced the existing discrepancy between observation and simulated rainfall by RegCM4. The comparison of the two long years runs have shown significant difference between the simulations (New and Old SUBEX parameter). To assess either the new parameters have altered the simulated precipitation in the direction which agrees with observation, we have compared both simulations with CMAP and GPCP. The result of the comparison has shown that there are significant improvements for some of the clusters located in north-western part of horn of Africa which includes western Ethiopia highlands and low lands as well as part of Sudan. There are also some clusters with significant improvement on south-western of the region. However, low lying regions in south-easter which includes south-eastern part of Ethiopia, Somalia, part of Kenya and adjoining Indean Ocean have shown little or no change in capturing the observed precipitation pattern and inter annual variations. This is probably an indication that further improvements are needed in particular with respect to rain drop evaporation rate. In summary, we have found better set of parameters that can replace the old parameters for further climate studies over the western and south-western and north-western part of the horn of Africa.

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