ANALYSIS OF PRECIPITATION BASED ON ENSEMBLES OF REGIONAL CLIMATE MODEL SIMULATIONS AND OBSERVATIONAL DATABASES OVER ETHIOPIA FOR THE PERIOD 1989–2008

Regional Climate – CORDEX 2013
Daniel Tsegay, Agizew Nugussie, Dereje Hailu, and Rafiq Hamdi
Addis Ababa University and Royal Meteorological Institute of Belgium

ABSTRACT

This study examines the performance of multi-model numerical simulations and multi-observational databases focusing on seasonal cycles and spatial variations in precipitation over Ethiopia. Seven Regional Climate Models (RCMs) driven by the ECMWF Interim reanalysis (ERA-Interim) and generated in the framework of Coordinated Regional Climate Downscaling Experiment (CORDEX) project, and four observational databases computed using different interpolation techniques and blending strategies, were evaluated against typical observational database produced by Climate Research Unit (CRU) over Ethiopia on monthly basis. All were produced at 48.8 km grid resolution for the period 1989–2008. The preliminary results showed that ensembles (multi-model ensemble (MME) + multi-observational ensemble (MOE)) were as good as CRU in reproducing the temporal variability and the geographical distribution of precipitation. Comparison of seasonal means and temporal correlation results revealed that there were good agreements between ensembles and CRU at each grid point and in close proximity to each other. Results of rotated principal components (RPCs), rotated empirical orthogonal functions (REOFs), and the associated power spectra showed that every ensemble's element was able to simulate the seasonal cycles and homogeneous precipitation zones of CRU reasonably well. Excessive and deficient rainfall periods, which were seen in every ensemble's RPCs, matched up CRU historical records

Keywords CORDEX · Ethiopia · Precipitation · Regional climate model

1 INTRODUCTION

From time to time climate models are upgraded to higher and higher grid resolution with the intention of reproducing climate variables at finer scale and ultimately possessing more accurate and localized forecast. However, as climate models' resolution tends to be finer, the noise on grid cells is likely to be significant. An improved approach for cross checking set of regional climate models is the Coordinated Regional Climate Downscaling Experiment (CORDEX) project (Gleckler et al., 2012). This paper examines the ability of multiple model outputs and multiple observational databases in reproducing seasonal cycles, homogeneous zones, and most extreme years of precipitation over Ethiopia. Outcomes from this research provide private model successes and ensembles communal achievements that will serve as a basis for future projection studies over the least studied region, Ethiopia.

2 OBJECTIVES

***To determine dominant modes of seasonal and inter-annual precipitation variabilities and most extreme years of precipitation.**

- To identify homogeneous rainfall regions and their tele-links over Ethiopia.

3 DATA

This work incorporated monthly mean precipitation from seven model outputs and four observational databases. Observational precipitation datasets from CRU, GPCC, GAUGE, and ATP-UDEL were implemented. The simulations were found from CORDEX Downscaling Experiment. Seven model outputs were integrated from the experiment, namely TQAM-CRM5, CNRM-ALADINS2, KNMI-RACMO22T, ICTP-RegCM3, SMHI-RCA4, MPI-MCM2-3H, and MPI-ESM2-3H. The monthly mean precipitation from CRU dataset was adopted. The large-scale forcing of all RCMs was taken from ERA-Interim reanalysis at a horizontal resolution of $0.75^\circ \times 0.75^\circ$ followed by downscaling to a resolution of $0.44^\circ \times 0.44^\circ$ for the time period from January 1959 to December 2008.

4 METHODS OF ANALYSIS

Basic and advanced statistical techniques were integrated. Mean and mean differences, Pearson correlation, and Spearman rank correlation analyses were incorporated in the basic statistical tools. Advanced statistical methods included Ordinary Kriging, least-square fitting, rotated principal component analysis (RPCA), power spectral analysis, and hierarchical clustering analysis (CLA).

5 STUDY AREA

This study was done over the least (related to climate) studied region, Ethiopia.

Figure 1. Ethiopia-map. (Source: www.freeworldmaps.net).

6. RESULTS AND DISCUSSION

6.1 INTER-SEASONAL PRECIPITATION VARIABILITY

6.1.1 MEAN PRECIPITATION FOR JUNE-SEPTEMBER

Figure 2. Summer (JJAS) mean precipitation (unit: mm/day) for the period 1989-2008.

Figure 3. Summer (JJAS) mean precipitation difference (unit: mm/day) between each member of ensembles and CRU for the period 1989-2008.

Majority of the observational databases and the model results more or less reproduce geographical patterns of CRU JJAS mean precipitation for the period 1989–2008. However, model results show enhanced rainfall over Ethiopian Highlands quite the opposite HIRHAM5 and REMO underestimate precipitation in areas coinciding with the western and northwestern side-lines and the Awash Basin.

6.1.2 MEAN PRECIPITATION FOR MARCH TO MAY

Figure 4. March-May (MAM) mean precipitation in (unit: mm/day) for the period 1989-2008.

Figure 5. March-May (MAM) mean precipitation difference (unit: mm/day) between each member of ensembles and CRU for the period 1989-2008.

Most of them had similar spatial trends of precipitation. Rain climaxes were in the range 4–7 mm/day. The differences between ensembles and CRU are displayed in Figure 5. GPCC did not show significant difference with CRU. Small positive differences were observed in UDEL, GAUGE, and CRCM5 near south Omo. ALADIN52, RACMO22T, RegCM3, and RCA4 exhibited significant biases about 2.5 mm/day in the upper part of Baro-Akobo Basin (western Ethiopia) and around -2 mm/day on the slopes of the southeastern highlands. HIRHAM5 and REMO showed positive differences in the central and the western peripheries and in the southern part of Ethiopia. Above Mendobe Hills, orographic influenced precipitation bias (2.5 mm/day) was described by HIRHAM5 model.

6.1.3 MEAN PRECIPITATION FOR OCTOBER TO NOVEMBER

Figure 6. October–November (ON) mean precipitation (unit: mm/day) for the period 1989–2008.

Figure 7. October-November (ON) mean precipitation difference (unit: mm/day) between each member of ensembles and CRU for the period 1989-2008.

Ensembles geographical distributions of mean precipitation in Omo season were generally comparable pattern as CRU. Ensembles rainfall for Omo season varied from below 1 mm/day to roughly 7 mm/day. With the exception of CRMS, RACMO22T, RegCM3, and HIRHAM5, rainfall distributions for the remaining ensembles were spreaded between 0 mm/day and 3.5 ml/day (or CRU=1 mm/day). CRMS and RCA4 had peaks around 5 mm/day, while the other models had peaks around 2 mm/day. The CRU and HIRHAM5 had peaks around 1 mm/day correspondingly. The differences between ensembles and CRU are displayed in Figure 5. GAUGE was unbiased with respect to CRU. In GPCP, UDEL, CRMS, ALADINS2, RACMO22T, and RegCM3, the departures from CRU were positive near south Omo and in the fringes of southwestern Ethiopia. These positive partialities were stretched to Gambella and western Wellega by CRMS, RACMO22T, and RegCM3. ALADINS2, RACMO22T, and RegCM3 were negative in the central and eastern Omo. CRMS and RCA4 had a tendency to overrate it in central Somalia. In contrast, RCA4, HIRHAM5, and REMO revealed negative biases about -2 mm/day in the southern, southwestern, and western parts. Additionally, in the southwestern and

6.2 CORRELATIONS ANALYSES

Figure 8. Pearson correlation between CRU and each member of ensembles.

Figure 9. Spearman correlation between CRU and each member of ensembles.

Pearson correlation coefficient varied in accordance with seasons and topography. Correlation between every ensemble's member and CRU was significant in the northwestern plateau (monomodal rainfall region), moderate in the southern Ethiopia (bimodal rainfall region), but low along Main Ethiopian Rift (MER) (largely quasi-bimodal rainfall region). Generally, each ensemble's member and CRU are significantly linearly correlated (Figure 8), and admirably nonlinearly (Figure 9) correlated in the mono-modal rainfall receiving region and in the entire region respectively.

6.3 ROTATED PRINCIPAL COMPONENTS, ROTATED EMPIRICAL ORTHOGONAL FUNCTIONS AND SPECTRAL DENSITIES

Figure 10. Leading four RPCs for the period 1989-2008.

Table 1 summarizes percentage of variances for the leading four RPCs

	Percentage of variances in %				
	RPC1	RPC2	RPC3	RPC4	Total
CRU	35.80	26.39	9.84	5.40	77.43
GPCP	35.58	30.04	4.57	7.51	77.70
GAUGE	27.00	25.29	21.58	3.40	77.17
ATP-UDEL	38.97	25.96	6.69	2.58	74.19
UQAM-CRCM5	33.96	31.29	5.99	2.18	73.42
CNRM-ALADIN52	42.00	30.43	6.08	2.63	81.18
KNMI-RACMO22T	37.55	26.84	10.3	3.16	77.85
ICTP-RegCM3	31.13	17.35	1.82	15.24	75.08
SMHI-RCA4	40.21	27.21	6.77	4.62	78.81
DMI-HIRHAM5	36.37	25.74	5.47	3.13	70.71
MPI-REMO	30.18	25.36	11.89	2.94	70.37

Figure 11. Correlation based leading four REOFs.

Figure 12. Normalized spectral densities of the four leading RPCs.

RPC1

RPC1s' percentages of variances for ensembles and CRU explained large fraction of their corresponding joint variances. Skipping GAUGE that had 27.00%, RPC1s' percentages of variances were in the interval 30.18–42%. CRU's value, 36.80%, was approximately at the middle of the range (36.09%). Every ensemble's REOF1 resembled CRU's REOF1 Figure 11(a). They explained better correlation results in general over the upper half of Ethiopia, and in particular over the northwestern plateau. Spectra of RPC1s are displayed in Figure 12(a). Ensembles and CRU possessed strong signal at 0.83 month⁻¹ (12 months) that stands for unimodal rainfall (JJAS/Kiremt season). The three wettest JJAS precipitation years were 1998, 1999, and 2001. Deficient rainfalls were observed in 1993, 1997, and 2002. The abundant Kiremt rains were in consistent with the incidences of La Niña events though the 2001's JJAS seasonal rainfall was connected with weak La Niña development. Deficient Kiremt rainfalls that happened in 1997 and 2002 were in harmony with El Niño events. The inadequate JJAS rain, which was recorded in 1993, matched the occurrence of weak El Niño.

RPC2

RPC2s of CRU and ensembles in Figure 10(b) accounted for 25–31% of total variance except for RegCM3 (17.35%). Every ensemble's REOF2s (shown in Figure 11(b)), as that of CRU's REOF2, covered southern and southeastern Ethiopia with better correlation scores in the southeastern part. Their spectra (in Figure 12(b)) had strong signal at 6 months (0.167 month⁻¹) that is half of the length of one year. They oscillated twice per year which is equivalent to two rainy seasons closely resembling in their widths and amplitudes (so-called bimodal type-2). They showed two distinct rainy periods (MAM and ON) separated by well-marked dry periods. Excessive rainfall seasons recognized by RPC2 were: (i) MAM of 1997 (intense flood) and (ii) ON of 1997 (intense rainstorm), 2008 and 2006. Deficient rainfalls were observed in: (i) MAM 1999, 1998, and 2001 and (ii) ON 1991, 1996, and 2003. The intense MAM seasonal rainfall occurred in 1997 coincided with strong El Niño development while the excessive ON rainy periods matched the 1997's, 2006's, and 2008's positive IOD events. In 1997, IOD ceiling caused flood in southern Ethiopia. Deficient MAM rainfalls coincided with La Niña events in 1998, 1999, and 2001. Insufficient ON rain happened in 1996 was in good agreement with the incidence of negative IOD. Nevertheless, it is unclear how deficient rain happened in ON 1991 and 2003.

RPC3

Ensembles and CRU's RPC3s percentages of variances, counting out GAUGE and RegCM3, were found between 4% and 12%. In CRU and all ensembles, the double rain peaks/pulses of Afar were well explained by RPC3s although the first rain pulse (JJAS) was better in amplitude, width and had relatively stable climax rainfall month than that of the second pulse (MAM). Spectra of RPC3s (Figure 12(c)) possessed two unequal peaks that stands for quasi-bimodal type except CRM3. Unbalanced peaks suggested occurrence of long and short rain seasons (e.g. Kiremt and Belg) separated by either 6 months (as RACMO22T, RegCM3, and RCA4) or 4 months (as GAUGE, UDEL, ALADIN52, and REMO) or both (as CRU, GPCP, and HIRHAM5). With regard to abundant Kiremt seasonal rainfalls, RPC3s' extreme positive scores share typically RPC1s' top results. The wettest Kiremt years were 1998, 2001, and 1999. Likewise, the wettest Belg years were 1993 and 1989. Since RPC3s were characterized by several deficits, we skipped the driest years.

RPC4

RPC4s is drawn in two panels. The first panel exhibits similar pattern with CRU (Figure 10(d-I)). They are eight in number and labeled as group-I. The rest three (UDEL, ALADIN52, and RegCM3) differ from CRU are collected in Figure 10(d-II) and named as group-II. CRU spatial and temporal patterns were reproduced reasonably by group-I. RPC4s in group-I and in CRU accounted for 2.18–7.51% of the total variance and had almost the same area coverage (Figure 11(d)), similar precipitation patterns, and extreme events (Figure 10(d)) as that of CRU's and ensembles' RPC2s (Figure 10–12(b)) although RPC4s were more correlated with the southwestern portion than that of the southeastern lowlands. Spectra of RPC4s (except for RegCM3 that was unimodal, and HIRHAM5 and REMO models that were bimodal type-1) were comparable to CRU's RPC4 spectrum (in Figure 12(d)).

The other unmentioned principal components captured the rest random variations departing from overall regional values.

Based on the spectra peaks, rainfall can be divided into unimodal (one season) and bimodal (two seasons) types. Bimodal is further splitted up to bimodal type-1 and bimodal type-2. Based on the spectra peaks, rainfall can be divided into unimodal (one season) and bimodal (two seasons) types. Bimodal can be further splitted up to bimodal type-1 and bimodal type-2. These methods reaffirmed the classification made by NMSA. Monomodal rainfall pattern in the northern, quasi-bimodal in the eastern, and bimodal rainfall pattern in southern and southeastern Ethiopia.

6.4 CORRELATION BETWEEN MEAN OF NORMALIZED RPC1S AND WIND AT 1000HPA

Figure 13. Correlation between mean of RPC1s and wind (from NCEP) at 1000Hpa.

At 0 month lag, RPC1 is strongly correlated with the winds flowing over the Sahel regions; Azores high and Eastern part of Mediterranean Sea. At 1 month lag, RPC1 is positively correlated to the Somali jet.

6.5 CLUSTERS

The second criterion is based on similar precipitation peaks above mean and minimum-distance clustering method.

Figure 14. Contour map of merged clusters based on similar precipitation peaks above grid mean and minimum-distance clustering method (a) KNMI (b)MPI (c) GPCP and (d) SMHI.

Peaks of rainfall primary follow forward and retreat of ITCZ. Rainfall peaks at each zone primary follows the position of ITCZ, at the finer scale is significantly influenced by topography.

7. CONCLUSION

We demonstrated the ability of multi-observational databases and multi-model numerical simulations in reproducing intra-seasonal, seasonal, and inter-annual precipitation variability over Ethiopia. Seven model outputs generated in the frame work of CORDEX project and four observational databases from different sources were integrated. We chose CRU historical rainfall records as reference for evaluation of the ensembles. For analysis, the monthly averaged precipitation data at resolution of 48.8 km and its anomalies were used for the period 1989–2008.

Evaluation of seasonal means and seasonal differences show that majority of ensembles more or less reproduce the spatial patterns of CRU precipitation in spite of few significant uncertainties that can arise from various sources of errors. The results obtained from Person correlation analysis indicate every ensemble's member and CRU significantly agree in amplitude and phase at each grid point in the northwestern plateau whereas Spearman correlation analysis correlate them very well throughout Ethiopia. The leading four RPCs, REOFs, and the associated power spectra demonstrate that ensembles are as good as CRU in explaining seasonal cycle, classifying homogeneous precipitation zones, and identifying extreme rainfall events. They differentiate rainfall in to unimodal, quasi-bimodal and bimodal rainfall types. Abundant/deficient JJAS seasonal rainfalls are in consistent with La Niña/El Niño events; quite the opposite, excessive/deficient MAM seasonal rains coincide with El Niño/La Niña developments. Excessive/deficient ON rainfalls are in harmony with positive/negative IOD incidences

ACKNOWLEDGEMENTS

We acknowledge WCRP's Working Group on Regional Climate, and the Working Group on Coupled Modelling (WGCM), coordinator of CORDEX and CMIP5 for producing and making available their model outputs. We are also thankful to Addis Ababa University and Royal Meteorological Institute of Belgium for all the valuable co-operations extended to us during the research period.