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Towards enhancing rainfall projection using bias correction method: case study Egypt

H. M. Elmenoufy *1, Mostafa Morsy2, M. M. Eid2, A. El Ganzoury3, F. M. El-Hussainy2, M. M. Abdel Wahab4
*[1]Environment &Climate changes Research Institute (ECRI), El-Qanatir, Egypt
[2]Astronomy and Meteorology Department, Faculty of Science, Al Azhar University, 11884, Cairo, Egypt
[3]National Water Research Center (NWRC), El-Qanatir. Egypt
[4]Faculty of Science, Cairo University, Giza, Egypt

ABSTRACT

Climate models are numerical representations of various parts of the Earth's climate system. Due to the limitations of the output of the regional climate models (RCMs), when using the trend in proposed future adaption strategy, it is necessary to apply bias correction before they are used for the different sectors especially water resources research. The bias correction is applied to RegCM simulations that forced by RCP4.5 and RCP8.5 future scenarios from European Community-Hamburg Atmospheric Model (ECHAM5) Global Climate Model (GCM). This correction was done against the quality control and homogenized observation dataset based of Climate Research Unit (CRUTS3.24) and European Center for Medium-range Weather Forecast (ECMWF) reanalysis for 40 years (ERA-40) datasets. The results showed that the biased precipitation not uniformly distributed throughout the year and their magnitudes are regionally dependent. In addition, it is obvious that there is a time increasing in rainfall up to 20 mm based on the RegCM4 bias correction from the selected from Representative Concentration Pathways (RCP4.5 and RCP8.5) climate scenarios. Where, the increasing of rainfall reached to 6 mm during the different future three periods until 2100 depending on RCP4.5. Whereas, depending on RCP8.5 scenario the increasing in rainfall will reach to 20 mm up to 2100. On the other hand the rainfall distribution especially in Upper Egypt is larger than in RCP8.5. This increasing in rainfall amount is coincide with the historical and observed rainfall analysis that showed that there is a time increasing in rainfall amount over whole Egypt during the period of 1980 - 2015.

Keywords: Regional Climate Model, Bias Correction, Representative Concentration Pathways (RCPs), Egypt

I. INTRODUCTION

Bias corrections needed for the RCM model outputs because climate models often produce a biased representation of observed climate data. The biases in the climate model outputs can produce unrealistic results when used for hydrological modelling (Bergstrom et al., 2001), there for it needed to correct the climate model outputs (Christensen et al., 2008). Climate models for predict precipitation often need to accurately and will commonly overestimate the number of wet days with low intensity precipitation, have biases in the mean, and have effort in predicting high precipitation events (Ines and Hansen, 2006; Piani et al., 2010; Teutschbein and Seibert, 2010). Climate model simulations typically selected based on their performance at representing the observed climate over the recent past period. On the other hand, the rationale for probability of climate models derives from difficulties in ranking model performance over a reference period. According to (Knutti et al. 2010), no credible evidence exists to warrant assigning a higher confidence to models that had better simulate present-day conditions. Additionally, there is no agreement on suitable metrics for evaluating the performance of climate models (Tebaldi and Knutti, 2007). Although computer models and their simulations are critical in scientific studies about climate change, even the most detailed, high-resolution models of the global climate omit important representations of major features of the planet that affect the climate and contain parameterizations that simplify complex climatic processes (McGuffie et al., 2014).

The quality of the observations that limits the quality of the model corrections and the bias behaviour of the model, which does not change with the time, are the main two assumptions of bias correction methods. As well as, the temporal errors of major circulation systems cannot correct. Therefore, to correct these biases, several methods exist, such as, delta change approach, multiple linear regressions, analogue methods, local intensity scaling, and quintile mapping. All of these bias correction methods can be apply to monthly, seasonal, and annual forecasts. The different climate elements have different forms of bias correction methods, precipitation has been corrected using a multiplicative approach, by applying scaling factor to give the modelled precipitation as same as the mean of observations (Shabalova et al., 2003; Berg et al., 2003; Kleinn et al., 2005; Leander and Buishand, 2006; Graham et al., 2007, a; Lenderink et al., 2007). Another statistical method, Statistical Downscaling (SD) is useful in modelling future rainfall events. (Onyutha, et al., 2016) investigated the future rainfall characteristics near Lake Victoria in East Africa, using 3SD methods: change factor (Delta), simplified (simQP), and advanced (wetQP) quantile-perturbation-based approaches. The model predicted that the rainfall amounts in the wet and dry seasons would become wetter and drier in 2050s and 2090s. It also found that the difference in the results obtained from the three approaches is not statistically significant, indicating consistency of the models. However, each model has its own advantages and disadvantages, with Delta method being unsuitable to predict rainfall extremes, while wetQP method performs better in predicting both rainfall extremes and rainfall amounts in seasonal and annual periods. A side effect of such a method is that the scaling affects the extreme precipitation events more than the lower intensities, as pointed out in the previous researches (e.g. Leander and Buishand, 2006). Apart from the contentious issues surrounding bias correction, some researchers would discuss that bias correction is distinct from using change factor ("delta change") methods (e.g. Hawkins et al., 2013). Even though they may produce identical results in certain idealized situations, bias correction would not normally be expected to replicate the baseline climate perfectly, so cannot offer a correct substitute (for all variables and time resolutions) for real observations to represent the present climate. On the other hand, change factors apply the baseline climate but cannot normally expected to provide information on future changes in high frequency variability.

Bias corrections meant to correct the raw data obtained from the specific climate model in order to take into consideration natural errors in the modelling skills, and thus obtain simulated data of future climate corrected for biases. The general idea for correcting for biases is to determine a difference between observed data over a certain time period and the simulated data of the climate model over the same period. Finally, almost the corrected representation is required in impact studies and applications.

Statistical and dynamic downscaling methods are available to enhance GCM predictions relative to climatology at a local, sub-grid scale.

The main objectives of this study can summarized as follows:

a) Studying and analysing the rainfall trend during the climate period (1980 - 2015), over different climatic zones in Egypt using rain-gauges observation.

b) To investigate the rainfall characteristics and its sensitivity to climate change over Egypt.

c) Enhancing the rainfall projection over Egypt using bias correction for regional climate model (RegCM4) in future period up to 2100.

II. METHODS AND MATERIAL

A. Study Area

Egypt is located between 22° to 32° N and 24° to 36° E. It bordered on the west by Libya, on the north by the Mediterranean Sea, on the south by Sudan, and on the east by the Gaza Strip and the Red Sea as shown in Figure (1). Its coastline extends for more than 3,500 km along the Mediterranean Sea and the Red Sea coasts. The Nile delta coast, which constitutes about 300 km, hosts a number of highly populated cities such as Alexandria, Port Said, Rosetta, and Damietta. The longest straight-line distance in Egypt from north to south is 1,024 km, while that from east to west measures 1,240 km. More than 2,900 km of coastline on the Mediterranean Sea, the Gulf of Suez, the Gulf of Aqaba and the Red Sea constitute Egypt's maritime boundaries. Egypt predominantly desert, where only 35,000 km2 - 3.5% - of the total land area is cultivated and permanently settled. Most of the country lies within the wide band of desert that stretches eastwards from Africa's Atlantic Coast across the continent and into southwest Asia.

So, the Geography of Egypt characterized by two different regions: Southwest Asia and North Africa. Egypt's geological history has produced four major physical regions: Nile Valley and Nile Delta, Western Desert, Eastern Desert, and Sinai Peninsula.

Despite the Nile Valley and Nile Delta covering only about 5.5% of the total area of Egypt, they are the most important regions, being the country's only cultivable regions and supporting about 99% of the population. The Nile valley extends approximately 800 km from Aswan to the outskirts of Cairo. The Nile Valley also known as Upper Egypt, while the Nile Delta region known as Lower Egypt. In the past, flooding of the Nile during the summer provided silt and water to make agriculture possible on land that was otherwise very dry. Since construction of the Aswan Dam, agriculture in the Nile valley depends on irrigation. The Nile delta consists of flat, low-lying areas. Some parts of the delta are marshy and water logged, and thus not suitable for agriculture. Other areas of the delta used for agriculture.

Figure 1: Map of Egypt.

Egypt's climate is semi-desert, characterized by hot dry summers and moderate winters with little rainfall. Rainfall in Egypt is very low, irregular and unpredictable. Annual rainfall ranges between a maximum of about 200 mm in the northern coastal region to a minimum of nearly zero in the south, decreasing southward to about 50-100 mm in the Nile Delta region as shown in figure (2). Rainfall season is mainly ranges between October and April. The country has areas with strong wind, especially along the Red Sea and Mediterranean coasts. Sites with an annual average wind speed of (8 -10) m/sec have been identified along the Red Sea coast and about (6.0 - 6.5) m/sec along the Mediterranean coast. Due to Egypt location in the subtropical zone, between middle latitude climate zone to the north and the tropical climate zone to the south, it is exposes to varying weather regimes. However, Egypt's climate is hot, dry, deserted and is getting warmer. During the winter season (December–February), Lower Egypt's climate is mild with some rain, primarily over the coastal areas, while Upper Egypt's climate is practically rainless with warm sunny days and cool nights. While, during the summer season (June- August), the climate is hot and dry all over Egypt.

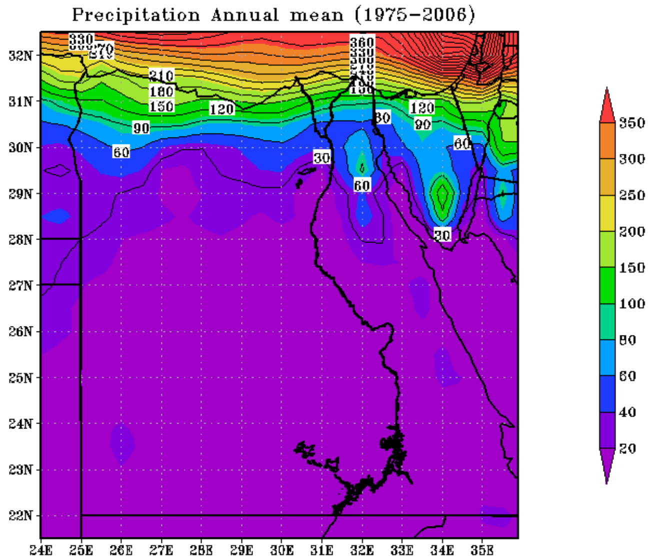

Figure 2: Average annual Rainfall (mm/year) over Egypt.

B. **Data and Methodology**

The regional community is needs knowledge about atmospheric processes and climate for different science and application purposes. To study the atmosphere processes and climate, the primary source for meteorological analysis based on the recorded data in meteorological stations. However, in the studying region the recorded historical data are provided by observations and measurements and have a scarce with many failures (few series, data sets are incomplete, limited spatial coverage, heterogeneity). As well as, the regional atmosphere and climate studies require meteorological data with relatively high spatial and temporal resolutions. An optional way to solve these problems is the data generation using numerical models. Therefore, during this study the RegCM4 regional climate numerical model applied to simulate the regional climate processes over the study area.

RegCM4 is the latest version of the Regional Climate Models (RCMs) that developed at the International Center for Theoretical Physics (ICTP). Previous studies have shown the ability of RegCM in downscaling global climate datasets over Africa (see CORDEX Africa initiative Klutse et al., 2015).

The model is a primitive equation, sigma vertical coordinate model with dynamics based on the hydrostatic version of the National Centre for Atmospheric Research/Pennsylvania State University's Mesoscale Meteorological model version 5 (NCAR/PSU's MM5; Grell.,1993). A fully detailed description of RegCM4 can found in (Giorgi et al. 2012). The models sub-grid physical processes represented by Parameterization Convection Schemes (PCSs) and related to the prediction of the monsoon convective rainfall, which is important part of total monsoon precipitation. Where, many studies have been conducted in different regions to validate the sensitivity of PCSs (Ali et al., 2015; Sinha et al., 2013; Bao, 2013; Taraphdar et al., 2010; Srinivas et al., 2013; Bhatla and Ghosh, 2015).

The initial and lateral boundary conditions that necessary to run RegCM4 for present and future scenario simulations over Egypt are taken from European Center for Mediam-range Weather Forecast (ECMWF) reanalysis data for 40 years (ERA-40) and European Community-Hamburg Atmospheric Model (ECHAM5). Two experiments have been done using RegCM4 model for historical and future projection over Egypt. The first experiment contained two runs for present day simulation (1976-2005), one based on ERA40 and the other based on ECHAM5. Whereas, the second experiment has been executed by running RegCM4 two times based on two Representative Concentration Pathway RCP4.5 and RCP8.5 scenarios from ECHAM5. All RegCM simulations performed using 10Km horizontal resolution with 6-houres temporal resolution. The Climate Research Unit (CRUTS3.24) land observation dataset for the total monthly precipitation with 0.5° x 0.5° was used and regrided to 0.1° x 0.1° horizontal resolution to be consistent with RegCM4 model output for the selected variables. Where, the regrided CRU land observation dataset was used to be compared with the corresponding RegCM4 simulations which forced by ERA-40 reanalysis datasets and ECHAM5 respectively. As well as, the CRU dataset also used for RegCM model bias correction for rainfall over Egypt to avoid the bias in RCM results. Monthly delta change factors (DCFs) were calculated for total monthly rainfall (ratios) from the baseline period (1976-2005) and the three future periods (2006-2035), (2036-2065), and (2066-2100).The general assumption taken for this method is that the modelling weaknesses of climate models do not vary in function of time. Depending on the complexity of the bias method applied, bias correction can take into account mean, historical variability and future variance. To perform the precipitation bias correction from RegCM simulations using Delta method, the total monthly precipitation was calculated at each grid point in the domain. This bias correction was done for the two RegCM outputs based on ERA-40 and ECAHAM5. Where, the following forms represent the used equations (1 and 2) for precipitation bias correction:

$$Ratio = \frac{\text{RegCM\_ECHAM5}}{\sqrt{(CRU* RegCM\_ERA40}} \qquad (1)$$

$$\text{RegCM precipitation bias correction} = \text{RegCM\_ECHAM5} * Ratio \qquad (2)$$

This bias correction method is applied for the two studied ECHAM5 scenarios (RCP4.5 and RCP8.5). On the other hand, the observed historical weather data over different climatic zones in Egypt were collected from weather stations during the period of 1980 - 2015.

III. RESULTS AND DISCUSSION

A. Historical and observed rainfall analysis

The measured rainfall data at different locations in Egypt (Lower Egypt included North coast with Nile Delta, Sinai with Red Sea, and Upper Egypt with Western desert) are collected and analyzed using regional rainfall frequency analysis approach.

For the stations in Lower Egypt, the precipitation amount varies intensely from year to year in the period 1980 until 2015. The linear trend analysis is used to study the variations and magnitudes of changes in annual rainfall for the selected period and stations. Where, in Lower Egypt the trend of rainfall generally decreased as shown in figure (3) and recorded highest rainfall (The wettest years) are 154 mm in 1991 and 129 mm in year 2015. While, the little rainfall (driest years) were during 1999, 2009, 2010, and 2014.

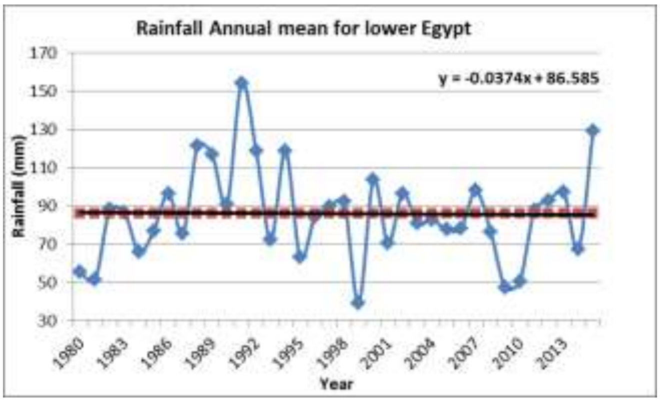

Figure 3: Mean annual rainfall for Lower Egypt.

In Sinai and Red Sea, the rainfall analyses from 1980 to 2015 showed a clear tendency towards increasing rainfall as shown in figure (4). Where, the amount of rainfall in Sinai decreases from the northeast towards the southwest and the rainfall in the eastern northern coast and red sea of Egypt varies dramatically from 1980 to 2015. Figure (4) represent the wettest years (1992, 2006, and 2013). Meanwhile, 1995 and 2010 represent the driest years.

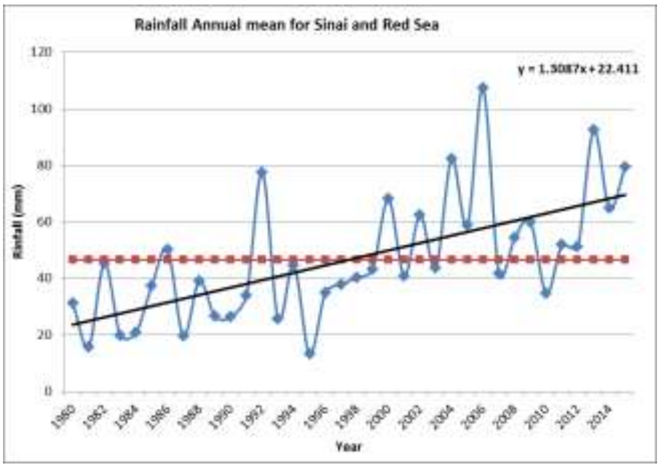

Figure 4: Mean annual rainfall for Sinai and red sea.

The rainfall in Upper Egypt is little and varies from 17 mm to 1 towards the south. Figure (5) represent the mean annual rainfall for Upper Egypt for the period 1980 – 2015. There are increasing in rainfall for many years (1982, 1991, 1992, 1995, and 2014) where the intensity of rainfall around 15 mm annually. While, most of the rest years have a little amount of rainfall below 10 mm.

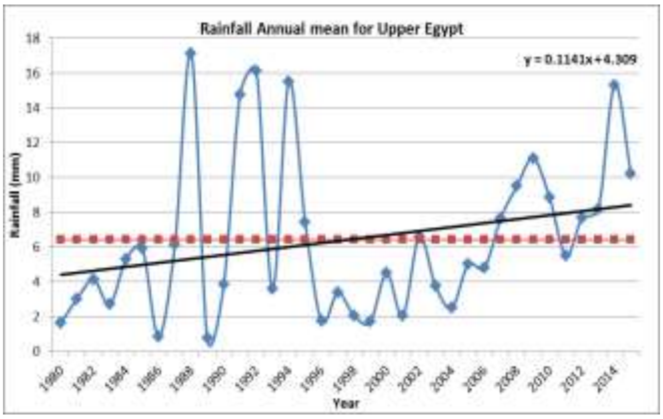

Figure 5: Mean annual rainfall for Upper Egypt.

From the trend analysis over whole Egypt the maximum rainfall was occurred during 1991, 1992, 2013, and 2015 with intensity of about 70mm. Whereas, the minimum rainfall was occurred during 1981, 1995, 1999, and 2010 as shown in figure (6).

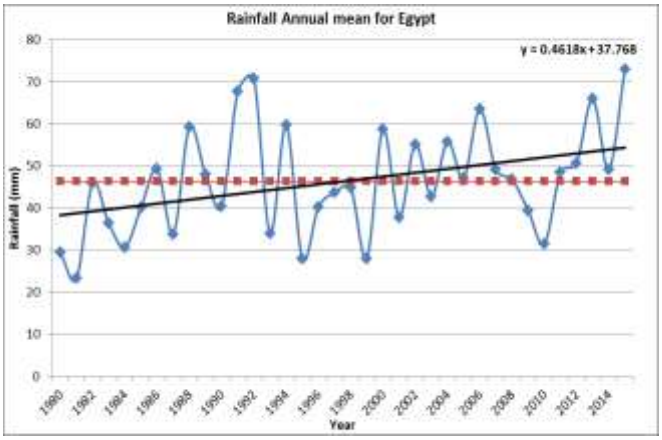

Figure 6: Rainfall trend analysis for whole Egypt.

Locally, the occurrence of torrential rains and their intensity is dependent on factors such as temperature profiles and implied instability, atmospheric moisture, and lower-level convergence. The intensity of rainfall events depends on the location and depth of the cyclones that induce precipitation and the characteristics of their environment, such as orography, sea-surface temperature and availability of moisture. However, these are not the individual conditions favouring the generation of heavy rainfall.

The atmospheric conditions at several spatial and temporal scales (i.e., large-scale circulation and regional to local thermodynamic conditions) play an important role in shaping the outcome of such extreme rain events and their associated severe consequences.

B. **Future projected rainfall analysis**

Climate models are used for a variety of purposes from dynamics study of the weather and climate system to projections of future climate.

During this study the amount and distribution of rainfall under RCP4.5 and RCP8.5 climate scenarios from ECHAM5 model is simulated using RegCM4 model. The RegCM4 for precipitation simulations is bias corrected against CRU and RegCM4 driven by ERA-40 datasets, using the Delta method equations (1 and 2), for future three periods 2006-2035, 2036-2065, and 2066-2100 based on RCP 4.5 and 8.5 climate scenarios.

1) RCP4.5 for rainfall Projection: The RCP 4.5 scenario defined as a stabilization scenario, which means the radiative forcing level stabilizes at 4.5 W/m2 before 2100 by engagement a range of technologies and strategies for reducing greenhouse gas emissions.

The projected annual precipitation amount and distribution using RegCM after bias correction depending on RCP4.5 scenario for each future period 2006-2035, 2036-2065, and 2066-2100 are presented in figure (7A, 7B, and 7C) respectively. As well as, figure (7D, 7E, and 7F) show the anomaly of annual rainfall for the same periods respectively.

During the first period (2006-2035), the amount and the distribution of annual rainfall in North Egypt will be increased between (1 - 6) mm and also will be increased in south Sinai from (1 – 5) mm. While, during the second period (2036-2065), it is concluded that the change in annual rainfall amount over Egypt vary between (1 – 4) mm, but in this period rainfall will be increased in different regions of Egypt and will be increased in the east more than the west. Furthermore, during the late period (2066-2100), it is obvious that the rainfall increasing will be between (2 - 4) mm.

Generally, under the projection of RCP4.5 scenario, there is an increasing in rainfall amount and distribution with time than the normal of historical (1976 -2005).

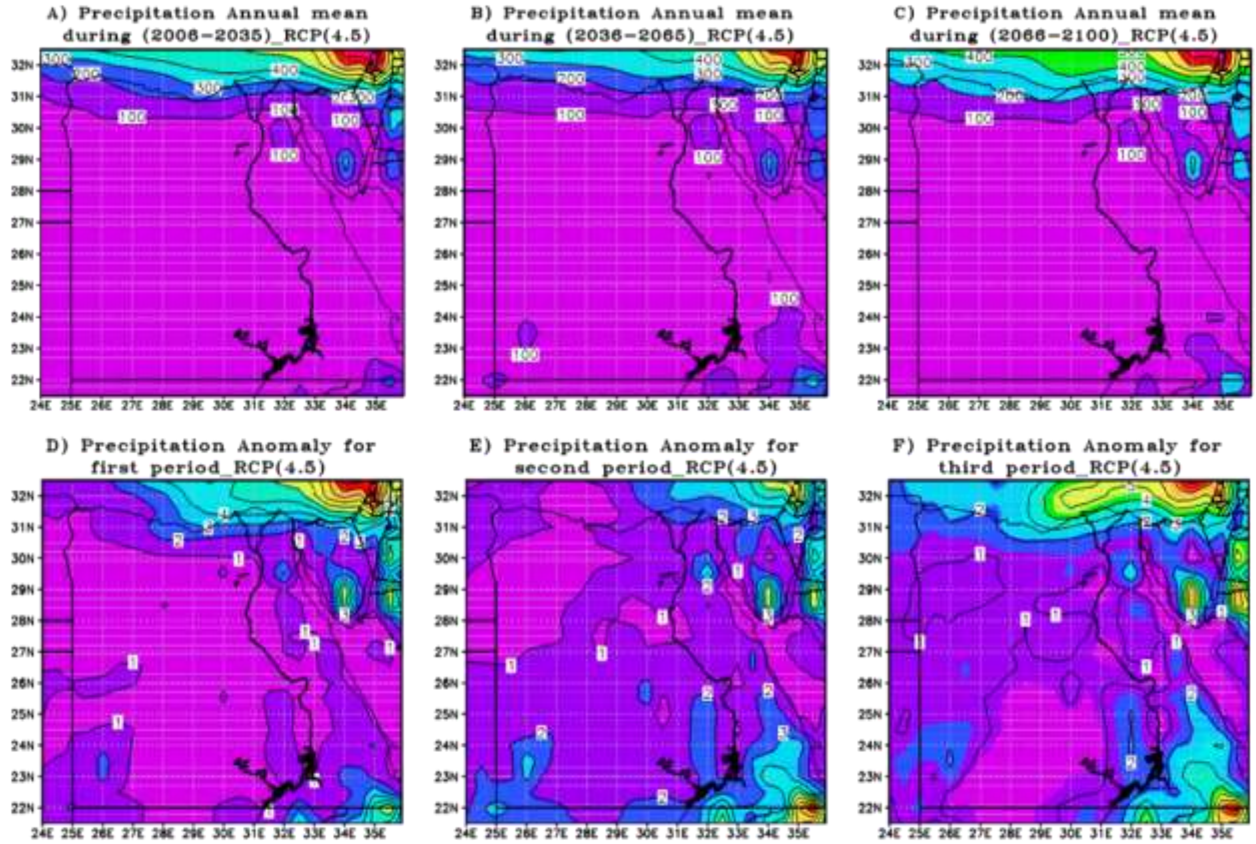

Figure 7: Annual mean of rainfall (2006-2100) at the top and its anomaly at the bottom from RegCM4 forced by ECHAM5 RCP4.5 scenario.

2) RCP 8.5 for rainfall projection: RCP8.5 scenario shows the constant increase of radiative forcing, rising to more than 8.5 W/m2 by 2100 and similarly. The total annual precipitation also calculated from RegCM4 simulation by using RCP8.5 and compared with the base period (1976-2005) of rainfall. Figure (8) display the model results. Where the annual rainfall figure (8A) and its anomaly figure (8D) show that the annual precipitation will increase in the first period from (3 – 15) mm which represent 12%. In addition, figure (8B) for annual rainfall and figure (8E) for its anomaly for the middle period prove that the rainfall will be increase with about (3 – 15) mm. In addition, the annual rainfall in the last period that presented in figure (8C) and its anomaly in figure (8F) the amount of rainfall will increase between (5 – 20) mm.

The rainfall variability occurs over a wide range of temporal scales. Knowledge and understanding of such variability can lead to improving risk management practices in different sectors like agricultural and other industries in Egypt. The differences between the future mean of three periods based on the bias-corrected of regional model (RegCM4) and the observed mean of the present climate reflect increasing in the predicted rainfall amount and distribution in the future climate.

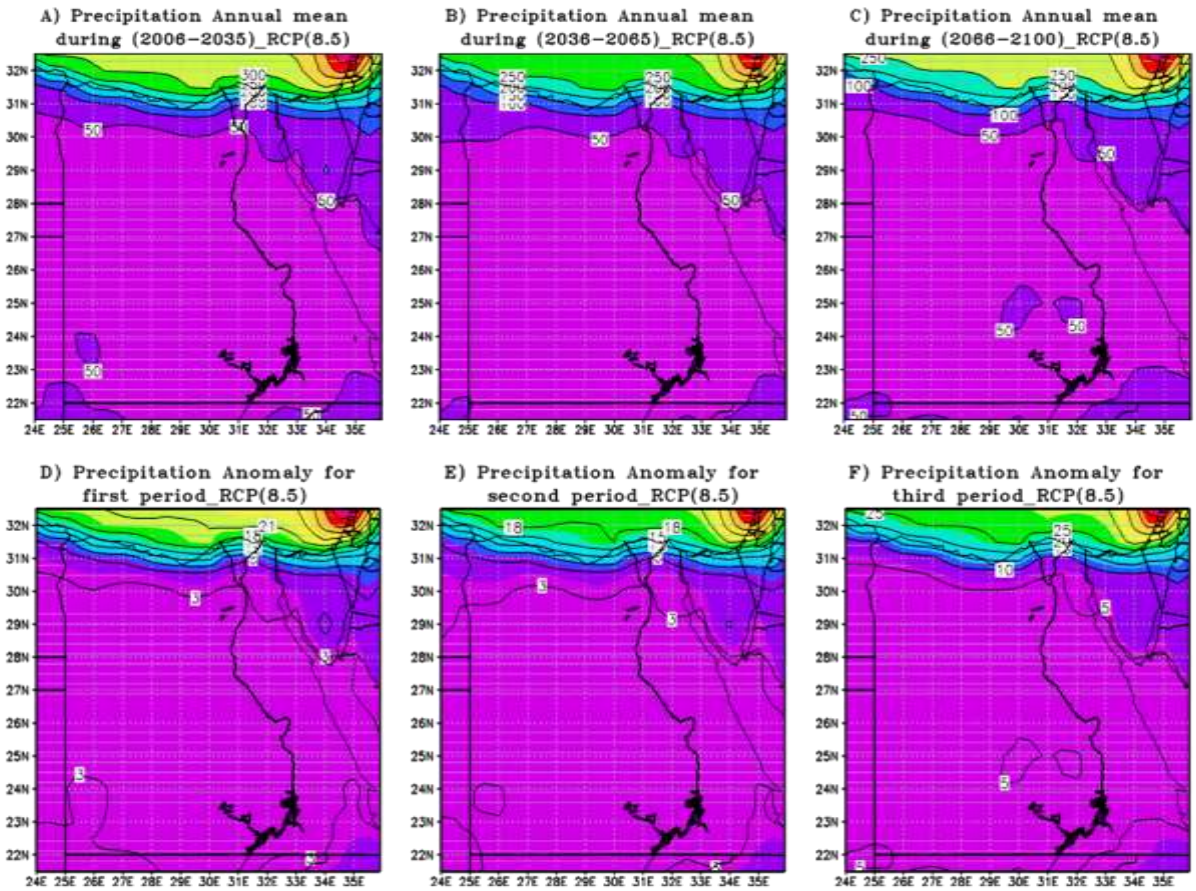

Figure 8: Annual mean of rainfall (2006-2100) at the top and its anomaly at the bottom from RegCM4 forced by ECHAM5 RCP8.5 scenario.

IV. CONCLUSION

Climate models exhibit systematic errors (biases) in their output, these errors can be due, among others, to: Limited spatial resolution (horizontal and vertical), Simplified physics and thermodynamic processes, Numerical schemes, and incomplete knowledge of climate system processes.

Such errors can and generally should be corrected before using climate model data in the different impact studies especially in hydrometeorology. The use of bias correction in this study reduces the range of such model uncertainties.

The bias correction is applied to RegCM simulations driven by RCP4.5 and RCP8.5 scenarios from ECHAM5 GCM.

The results show that the biases are not uniformly distributed throughout the year and their magnitudes are regionally dependent. Where, the results from the climate scenarios RCP4.5 for the bias corrected rainfall from RegCM4 give an increasing up to 6 mm during the different future three periods until 2100. Meanwhile, depending on RCP8.5 scenario the corrected rainfall will increase from 3 to 20 mm up to 2100. But RCP4.5 has a more rainfall distribution especially in Upper Egypt than RCP8.5. This rainfall increasing is coincide with the historical and observed rainfall analysis which showed that there is a time increasing in rainfall amount over whole Egypt during the period of 1980 – 2015.

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