THE PROJECTION OF MEAN TEMPERATURE AND PRECIPITATION FOR ETHIOPIA, BANGLADESH, AND NETHERLANDS

by

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ABSTRACT

THE PROJECTION OF MEAN TEMPERATURE AND PRECIPITATION FOR ETHIOPIA, BANGLADESH, AND NETHERLANDS

Climate change is an important problem for today and it will also continue to be an important problem for the future. The purpose of this thesis is to analyze the future of the climate through climate modelling in 3 countries which are geographically significant, namely Ethiopia, Bangladesh and the Netherlands. First of all, we simulated todays climate for the years between 1970 – 2000 by using RegCM 4.3.5.5 which is the regional climate modelling for analysis of regional climate change. We used ECHAM5, which is the atmospheric global climate model, as the forcing data when making this simulation and analyzed average surface temperature and precipitation variables. We compared model simulation for 1970 – 2000 obtained by using RegCM 4.3.5.5 with the data from CRU which is the observational station data to examine correctness of our model. As a result, it was concluded that geographical features, climate events and topography have a significant effect in climate modelling as well. Differences which occurred especially in modelling average precipitation volume indicated us that it is more difficult to model precipitation than temperature. Following the verification of todays data for Ethiopia, Bangladesh and the Netherlands, data of ECHAM5 A1B scenario was used and thus seasonal average surface temperature and precipitation values obtained for the climate model for the years of 2020 – 2050 being the future time by using RegCM 4.3.5.5. As a result of comparison of todays and futures data, it was found that considerable increases will occur in temperature between the years of 2020 – 2050.

ÖZET

ETİYOPYA, BANGLADEŞ VE HOLLANDA İÇİN ORTALAMA YAGIŞ VE SICAKLIK PROJEKSİYONU

Bugün için önemli bir sorun olan iklim değişikliği, gelecek için de çok önemli bir sorun olmaya devam edecektir. Bu tezin amacı; coğrafik olarak önemli olan 3 ülkede, Etiyopya, Bangladeş ve Hollanda, iklim modellemesi yaparak, gelecek analizinde bulunmaktır. Öncelikle, sezonsal iklim değişikliği analizi için bölgesel iklim modellemesi olan RegCM 4.3.5.5 kullanılarak $1970 - 2000$ yılları arası günümüz iklimini simule ettik. Bu simulasyonu yaparken atmosferik küresel iklim modeli olan ECHAM5i girdi verisi olarak kullandık ve ortalama yüzey sıcaklığı ve yağış değişkenlerini analiz ettik. Elde ettiğimiz günümüz iklim modeli simulasyonunu, gözlemsel istasyon verisi olan CRU ile karılaştırılıp, modelimizin doğrululuğunu inceledik. Sonuç olarak, iklim modellemesinde, coğrafik özelliklerin, iklim olaylarının ve topografyanın önemli bir etkisi olduğuna karar verildi. Özellikle ortalama yağış miktarının modellemesinde meydana gelen farklılıklar, bize yağışın sıcaklıktan daha zor modellendiğini gösterdi. Etiyopya, Bangladeş ve Hollanda için günümüz verilerinin doğrulanması sonrasında, ECHAM5 A1B senaryosu verileri kullanılıp RegCM 4.3.5.5 ile gelecek zaman olan $2020 - 2050$ yılları arasına ait olan iklim modelinin sezonsal ortalama yeryüzü sıcaklık ve yağış değerleri elde edilmiştir. Geçmiş ve gelecek verileri karşılaştırılması sonucu, 2020-2050 yılları arasında sıcaklıkta önemli artışlar olacağı tespit edilmiştir.

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LIST OF ACRONYMS/ABBREVIATIONS

AMIP	Atmospheric Model Inter-comparison Project
BATS	Biosphere-Atmosphere Transfer Scheme
CCM1	Community Climate Model Version 1
CCM2	Community Climate Model Version 2
CCM3	Community Climate Model Version 3
CLM	Community Land Models
CMIP	Coupled Model Inter-comparison Project
CRU	Climate Research Unit
DJF	December,January,February
ECHAM	European Centre Hamburg Model
ECHAM5	European Centre Hamburg Model
ECMWF	European Center for Medium range Weather Forecasting
ENIAC	Electronic Numerical Integrator and Computer
ENSIP	El-Nino Simulation Inter-comparison Project
GCMs	General Circulation Models
GHGs	Greenhouse Gases
ICBC	Initial Conditions, Boundary Conditions
ICTP	International Centre for Theoretical Physics
IPCC	Intergovernmental Panel on Climate Change
JJA	June,July,August
LAMs	Limited area models
MAM	March,April,May
MIT	Massachusetts Institute of Technology
MM4	Mesoscale model Version 4
MM5	Mesoscale Model Version 5
NCAR	National Center of Atmospheric Research,USA

NCAR/PSU	National Center for Atmospheric Research / Pennsylvania State University
PMIP	Paleoclimate Modelling Inter-comparison Project
RCM	Regional Climate Model
RCM	Regional Climate Model
RegCNET	Regional Climate Research NETwork
RegCM	Regional Climate Model
RegCM1	Regional Climate Model version 1
RegCM2	Regional Climate Model version 2
RegCM2.5	Regional Climate Model version 2.5
RegCM3	Regional Climate Model version 3
RegCM4	Regional Climate Model version 4
SMIP	Seasonal Model Inter-comparison Project
SO_2	sulphur dioxide
SON	September,October,November
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
SUBEX	Sub-grid Explicit Moisture Scheme
UCLA	University of California,USA
UNEP	United Nations Environment Program
WMO	The World Meteorological Organisation

1. INTRODUCTION

Basically, climate modelling is helping us through understanding the changes in climate. Understanding these changes have formed one of the hardest subjects of modern-day physics. For instance, increase in the amount of clouds causes cooling but at the same time as it causes an increase in water vapour, it can also cause a warming. Which effect will be dominated depends on all clouds of Earth, sizes, shapes and structures of the particles which creates the clouds [1].

In climate models, it is needed to start with simplest ones which give general conditions of climate. These models can contain just one variable of climate. For example, while studying the modelling of Earth, it is considered that the Earth is globe, it does not have atmosphere, and light comes from the sun and the world lights up. This is the preliminary stage of climate modelling. Later on, we estimate the surface temperature of Earth. For instance, how much energy reaches the Earth from the Sun and how much of this energy is reflected by Earth? These parameters become very important after this stage and by finding an answer to these parameters through simple calculations, we can estimate the surface temperature of the Earth. After that respectively, adding atmosphere, greenhouse gases and another some parameters, we keep going to study on this model and look what is happening about climate of the world. All these are patches the modelling to carry further. When we put together these sub-models, the sophistication of the models is enhanced. These sophisticated models are known as General Circulation Models (GCMs). These GCMs have successfully modelled the circulation movements of the atmosphere and ocean. It means that there are two ways for the sunlight coming to equator to carry to poles. One of them is through the oceans with large currents and the other is through the atmosphere with small current movements. As all these are loops, this models can be called general circulation models [1-5].

In Climate Change Chapter, we focused on the description of climate change and the causes of climate change including natural factors and human activities. We examined these two concepts which are very crucial in terms of the impacts on the future climate. Moreover, this chapter considers IPCC scenarios and climate models performing the forecasting of future climate. Climate models creating the scenarios prepared by IPCC is helping us to understand and analyze the future climate better.

In Methodology Chapter, we explained Regional Climate models and the structure of RegCM 4.3.5.5 which is regional climate model developed by ICTP. In addition, Climate observations require the methods of tools based on the physics, therefore we examine physics used in the model and model mechanism.

In Result and Discussion Chapter, using GCM data for the past period $1970-2000$ and the future period $2020-2050$ is run using RegCM 4.3.5.5 and the output of past data is compared with CRU data. After the validation of the output for the period $1970-2000$, the GCM ECHAM5 A1B scenario is used for forcing to obtain climate simulation for the period $2020-2050$. Changes in the seasonal and monthly average surface air temperature, and average precipitation has been observed, analyzed and contrasted with the period $1970-2000$.

1.1. CLIMATE CHANGE

1.1.1. What is the climate change?

Climate is the statistics of the meteorological variables including temperature, humidity, atmospheric pressure, wind and precipitation in a particular region over long periods. Geographical features of a particular region like its latitude, terrain, altitude, and nearby water bodies affect the climate significantly. Temperature and precipitation as surface variables are mostly used for classification of climate. The classical period for averaging these variables is 30 years as defined by The World Meteorological Organisation (WMO) [6]. Climate change can be defined as long-term changes in the average weather conditions or a change in the distribution of weather events with respect to an average over periods of time that range from decades to millions of years. It can be thought that climate change may occur in a specific region, or across the whole Earth [7]. It results in large part from human activity rather than natural causes, and it will have many life-threatening, damaging effects in the decades ahead. Due to the combustion of fossil fuels, atmospheric concentration of carbon dioxide and the major greenhouse gases, more than the Sun's heat is keeping near the Earth's surface and pushing the planet into climate change. Carbon dioxide and other greenhouse gases have always been present in the atmosphere, and it renders the Earth habitable place. However, emission of greenhouse gases has aggregated constantly since the industrial revolution. Eventually, global mean temperature have ascended both on land and in the oceans. Melting of polar ice and storms are increasing intensively. Plant and animal species are affected adversely, and hardly adapt to a shifting climate. Agricultural production, droughts, rising of sea level, floods and the spread of diseases will be worse than the present day [8].

1.1.2. What are the causes of climate change?

Climate is dynamic and always changing over natural cycle. The stunning evidence of climate changes are obtainable today from tree rings, pollen samples, ice cores and sea sediments. The cause of climate change can be divided in two main categories in terms of natural factors and human activities.

1.1.2.1. Natural factors.

There are several natural factors causing climate change. Continental drift, volcanoes, ocean currents, orbital variation, and comets and meteorites are underlying factors for the changes.

Continental Drift

It is believed that the continents were adjacent and united as a one big landmass about 200 million years ago. South America and Africa had fit into each other on map of the world. Then they had started to drift apart due to the tectonic movements in Earth's core. This idea come from the some evidence such as the relation and similarity between not only plant and animal fossils, but also broad belts of rocks found on widely separated continents. This drift continuing slowly but steadily even today is responsible for climate change due to impacts of landmass in terms of physical features and position of water bodies [9].

Volcanoes

Big amount of sulphur dioxide (SO_2), water vapour dust and ash are released into the atmosphere because of the volcanic eruptions. Although volcanic activity lasts a few days, the gases affects climate for years. These gases hang up in the upper side of the atmosphere and cause cooling by blocking the incoming rays of the sun. When sulphur dioxide comes together with water, sulphuric acid consists in the form of tiny droplets. These droplets, which are very efficient reflectors of sunlight, can stay buoyant for several years [9].

Orbital Variation

One of the natural drivers of climate change is the interaction between the Earth and Sun. The change in the shape of the earth's orbit, which is named eccentricity, changes the amount of solar energy received with a 100.000 year cycle. [9]. Variation of the angle of the axis of the earth, which is called obliquity, is between 22.1 degree and 24.5 degree. Thanks to this variation on a 41.000 year cycle, seasonal differences occur in both hemisphere [11]. The earth's slow wobble as its spin on axis called precession. This wobble or precession

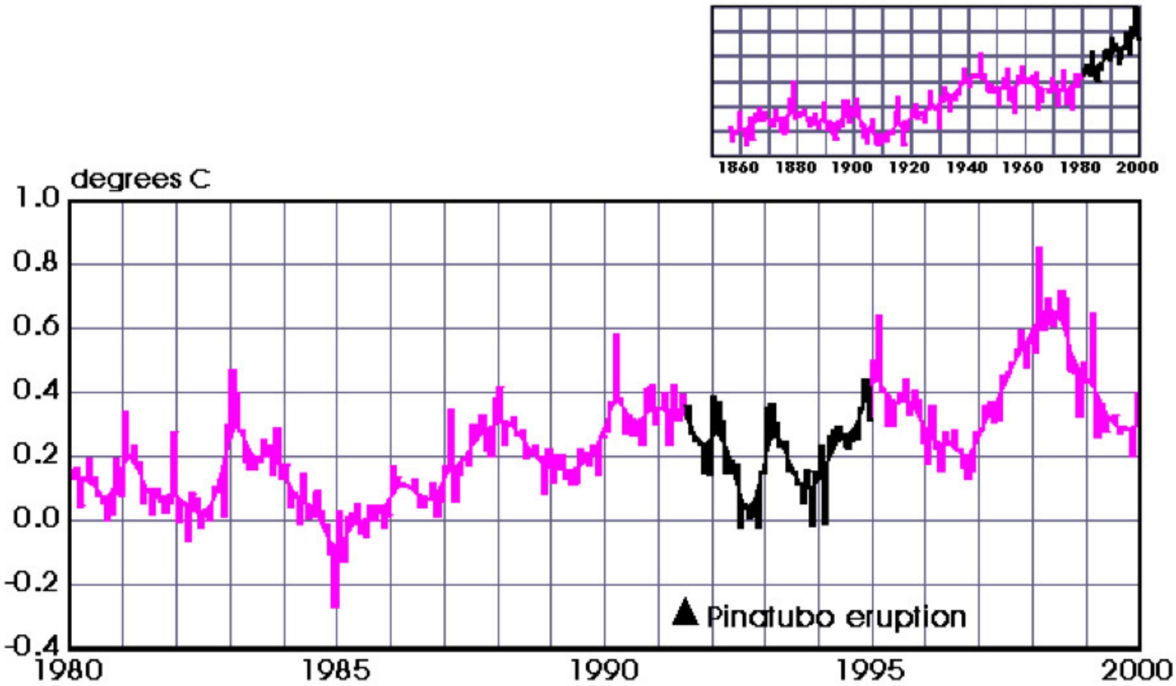

Figure 1.1. Global-mean monthly temperature for the period 1980-1999, showing the effects of the eruption of Pinatubo in 1991. The upper graph shows the complete global-mean temperature record as context [10].

has a periodicity of 23.000 years. Variations in the Earth's eccentricity, obliquity, and preccession are known as the Milankovitch Cycles, has a primary importance to explain that climate change, and subsequent periods of glaciation [12].

Ocean Currents

The major part of climatic circulation is the oceans. About 71% of the world is covered by the oceans. Sun's radiation is absorbed by the oceans more than atmosphere and land surface. The oceans are surrounded by landmass, and ocean currents transport serious amount of heat across the planet through the channels. In addition to this, Winds forms ocean current patterns by pushing the sea surface horizontally. Some of part of the world is influenced by ocean currents more than others. It is known that places at the same latitude can have different climatic patterns due to the ocean currents. While one place experienced low degree in the temperature, the other is far colder in spite of being at same latitude [9]. Together with these impacts of ocean currents, the oceans create as a greenhouse effect. The excess of the heat evaporate from the oceans and form to the water vapour that contributes to the formation of clouds. The clouds shade the surface and have a cooling effect.

1.1.2.2. Human activities. After the industrial revolution in the 18^{th} century large amount of fossil fuels have been used for industrial activities. People moved from rural areas to cities for better life conditions by having jobs. Because of the upward trend of population, lands have been cleared from the vegetation to built houses. The population has increased incredibly in urban areas, correspondingly natural resources have been used affluently for transportation, consumption, industrialization, and construction. All these activities needed more and more energy and the energy obtained from fossil fuels. To sum up, the main contributor of the greenhouse gases comes from combustion of fossil fuels.

Greenhouse Gases and their sources

The most important greenhouse gas in the atmosphere is carbon dioxide beyond doubt. The rise the emission of carbon dioxide results from combustion of fossil fuels, deforestation, land clearing and usage, agriculture, and other activities. Electricity mostly generated in thermal power plants is covering the main necessity of power in the cities. These thermal power plants use fossil fuels and are responsible for the emissions of greenhouse gases. Similarly, vehicles run on fossil fuels and generated greenhouse gases.

Using paper in the schools, and in the offices causes deforestation gradually. In addition to the waste of paper, timber using in the construction of house is one of the main reason of deforestation. Another important gas in the atmosphere is methane. One fourth of all methane is released by domesticated animals such as goats, pigs, camels, horses, and sheep, during the cud-chewing process. Apart from the cud-chewing process, methane also comes from rice and paddy fields during the maturing periods. When the soil is covered with water and becomes anaerobic, the bacteria and other organisms decompose organic components in the soil to form methane[9].

Associated with carbondioxide (CO_2) and methane (CH_4), chlorofluorocarbon (CFC) and nitrous oxide (N_2O) contribute to ozone depletion in the upper atmosphere. Many CFCs have been widely used as refrigerants, propellants (in aerosol applications), and solvents. N_2O relese when fuel is burned at high temperatures, come principally from burning of biofuels instead of fossil fuel as energy sources, and and from fertilizer use in biofuel production. It also plays a major role acid rainfall [13].

1.1.3. IPCC (Intergovernmental Panel on Climate Change)

IPCC was established by the World Meteorological Organization (WMO) and United Nations Environment Program (UNEP). This organization was founded to provide objective source of information about the climate change to the decision makers and other group of people working on it. The role of IPCC is very significant in terms of comprehensive, objective and open basis worldwide literature in understanding of the risk of anthropogenic climate change. In basis, there are total 35 scenarios made by IPCC. Also four of these scenarios are major ones [1].

1.1.3.1. The Scenarios of IPCC. In 2001, IPCC developed four major scenario sets, A1, A2, B1, B2 to evaluate future carbon pathways. A1 is based on a future world of very rapid economic and population growth. Theme of A1 scenario developed world having more efficient technologies and convergent world among regions, capacity building and increased cultural and social interactions. Sub-scenarios of A1 is A1FI, A1B, and A1T. A1FI is based on fossil intensive energy sources. A1B is based on balance of energy consumption (using equal proportion of every fuel).A1T is based on non-fossil energy sources. A2 is based on heterogeneous world. The underlying theme of A2 is rapid economic growth, and developed but less integrated world. B1 is based rapid economic growth, less integrated, and convergent world. The underlying theme is reduction in material intensity and the introduction of clean and resource-efficient technologies. It emphasises the interest in global solutions to economic, social and environmental maintainability. B2 is based on rapid economic growth, developed, less integrated and more convergent world. The emphasis is on local solutions to economic, social and environmental maintainability.

Table 1.1. The summary of IPCC's socio-economic SRES scenarios' characteristics.

IPCC scenarios	**A1**	**A2**	**B1**	**B2**
Name	World Markets	International Investment	Global Sustainability	Regional Government
Population growth	At low level	At high level	At low level	At normal level
World GDP growth	At very high level	At normal level	At high level	At medium level
Level of convergence: Rate of GDP per capita in rich vs. poor countries	At high level	At low level	At high level	At normal level
Emissions	At high level	At medium high level	At low level	At medium low level

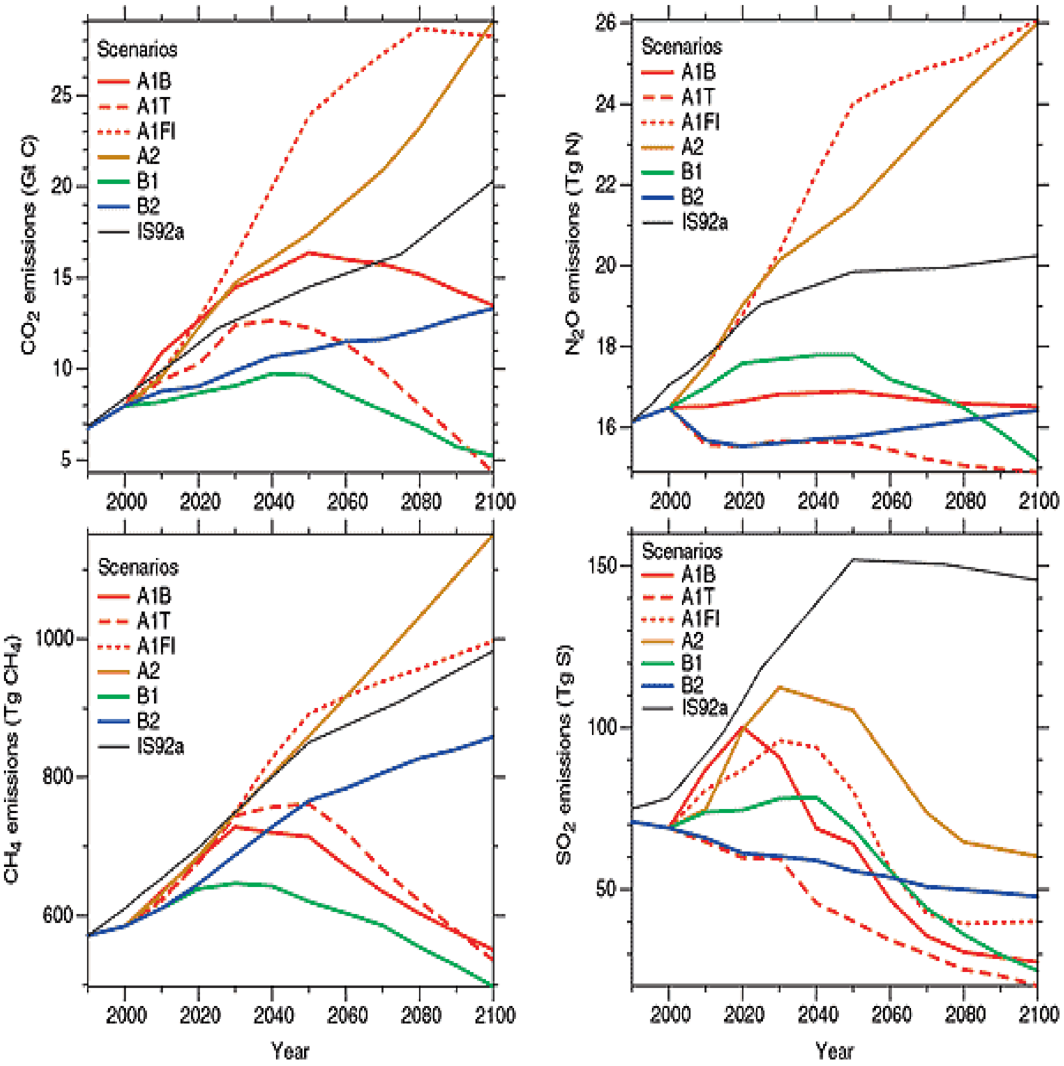

Figure 1.2. Anthropogenic emissions of CO_2, CH_4, N_2O and sulphur dioxide for the six illustrative SRES scenarios, A1B, A2, B1 and B2, A1FI and A1T. For comparison the IS92a scenario is also shown. [Based on IPCC Special Report on Emissions Scenarios].

2. METHODOLOGY

2.1. Climate Models

Climate modelling differs from weather forecasting fundamentally with respect to the time scales involved and the change on different physical processes and parameters. For instance, concentrations of greenhouse gases remain constant in a weather forecast, but they have significant role in a climate model. Firstly, in 1903 Wilhelm Bjerkness developed the weather forecasting depending on physical laws. According to Bjerkness, the weather based on major seven variables such as pressure, temperature, air density, air water content and three components of wind velocity. The changes in these variables consist of existing physical laws which are Newton's second law of motion, continuity equation for air, the ideal-gas law, the hydrostatic equation, thermodynamic energy equation. In his opinion, meteorological equations could not be solved analytically, that's why he developed the graphical calculus technique. In 1919, Lewis Fry Richardson enhanced a different method to solve these equations analytically. As there were a great number of calculations in the implementation of method, Richardson's study was not taken into consideration until 1946. In 1946, Along with John Von Neumann and the other two scientists produced the first electronic digital computer in the world so called ENIAC which is Electronic Numerical Integrator and Computer, Richardson's study about calculations of method became meaningful in practice with ENIAC. In 1948, under the leadership of Jule Charney, a group of scientists made numerical forecast in first time by using ENIAC with a one dimensional model [14]. In 1956, Norman Philips made first the general circulation experiment using quasi-geostrophic model with two layers. In 1963, Smagorinsky, Manabe and their scientist friends made 9 level primitive equations model [15] In between 1960s and 1970s, other groups, University of California, USA (UCLA), National Center of Atmospheric Research, USA (NCAR) and UK Meteorology Office started to work on general circulation models [5]. In 1980s, first coupled model simulation was designed. It means that the interactions between atmosphere and land surface could be taken into account.

In 1990s, model comparisons became important. Many variety models were designed and these models were compared with each other according to their strong and weak ways. Some of them are following;

- AMIP(Atmospheric Model Inter-comparison Project)
- AMIP(Atmospheric Model Inter-comparison Project)
- CMIP(Coupled Model Inter-comparison Project)
- SMIP(Seasonal Model Inter-comparison Project)
- ENSIP(El-Nino Simulation Inter-comparison Project)
- PMIP(Paleoclimate Modelling Inter-comparison Project)

From 2000 to present day, Multi Model Seasonal Prediction Systems could be made and the centers working on the climate system keeps going on to develop these models. The fourth report of IPCC published includes the future climate prediction from present to 2100 of coupled atmosphere-ocean models [1, 2, 5].

The most sophisticated and complex climate models GCMs (General Circulation Models) is using commonly recent years. All models from the simplest to the most sophisticated create some assumptions and they make some simplifications. The basic climate models are zero or one dimensional energy balance models. These basic models have low computational costs and distinct formulations so that the interactions between individual parameters or processes and the climate can be seen and their dependence evaluated. Complex climate models are more realistic but computational expensive and contain so many independent variables and relationships that it is usually not possible to follow cause and effect directly.

Table 2.1. Contribution of Climate Modelling.

Scientist	**Contributions**
Vilhelm Bjerknes	Graphical Calculus based on weather maps (which means graphical method for solving the fundamental equations, there is no direct solution) A set of seven primitive equations including three hydrodynamic equations of motion, the continuity equation, the equation of state and the equations expressing the first and second laws of thermodynamics. Deficiencies; Lack of faster calculating method Lack of accurate data No practical use [16]
Lewis Fry Richardson	First Numerical Weather Prediction Simplified versions of Bjerknes's primitive equations Attempted to make direct solution of the equations of motions (previously used both graphical and numerical methods for solving differential equations) Divided the atmosphere into a set of grid cells Deficiencies; Computational complexity and impracticality of the process inthe pre-computer era Disastrous results of the single trial forecast (which means his work based on solitary example) Results based on initial data have no real life meaning [17]

Table 2.2. Contribution of Climate Modelling (cont.).

Jon von Neumann	First electronic digital computer (ENIAC - Electronic Numerical Integrator and Computer) Simulated entire the atmosphere which provide to predict climate The non-linear differential equations and the numerical solutions of partial differential equations Portrayed that there is a limitation on the time step for a given space step Estimated the computational power needed to integrate the equations of motion and integrated the primitive equations [18]
Jule Charney	-Collaborated with von Neumann made in ENIAC -The results of ENIAC were the first numerical predictions of a 2D model approximating the actual flow at a mid-level in the atmosphere -His theory is about quasi- geostrophic dynamics proceeding systematic approximations to the equations of fluid motions which provide large scale atmospheric circulations to be defined mathematically -First prediction of cyclogenesis with a 3D model in 1954 -Worked on initialization problem in 1955 [18-21]
Karl Heinz Hinkelman	-Addressed the importance of suitable initial conditions for primitive equation integrations -Discussed that high frequency oscillations could be controlled by appropriate initialization -First application of the primitive equations creating a good simulation [22]

Table 2.3. Contribution of Climate Modelling (cont.).

Norman A.Phillips	-First General Circulation Model (first long-range simulation) with three dimensions which based on primitive equations of Bjerknes and Richardson -Simulated hemispheric motion on the high speed computer and also simulated time of approximately 1 month -Used two level quasi-gestrophic model on a beta plane channel -Analyzed the energy interchanges of the wave and saw that these data matched qualitatively with observations of baroclinic systems in the atmosphere -Focused on initialization problems later on [18, 23, 24].
Smagorinsky	-First coupled model (atmospheric and ocean models) -9 level, hemispheric primitive equations [25, 26].
Manabe	-Contributed in coding to the model by focusing on the mathematical structure of the model -Performed first carbon dioxide doubling experiments with GCMs to couple atmospheric and ocean models and to simulate very long runs of GCMs under carbon dioxide doubling [26].

2.1.1. Process of Climate Models

Climate models use quantitative methods to simulate the interactions of the atmosphere, ocean, land surface, ice, sulfur, carbon and chemistry. These models are enhanced in order to determine the climatic situations and explain the researches on climate subjects.
1960s - Atmosphere

1980s - Atmosphere + Land
1990s - Atmosphere + Land + Ocean
1990s - Atmosphere + Land + Ocean + Ice
2000s - Atmosphere + Land + Ocean + Ice + Sulphur
2000s - Atmosphere + Land + Ocean + Ice + Sulphur + Carbon
2000s - Atmosphere + Land + Ocean + Ice + Sulphur + Carbon + Chemistry

Table 2.4. Common Inputs of the Components of a Model.

Common Atmospheric Inputs	**Common Land Surface Inputs**	**Common Ocean Dynamics Inputs**
Pressure Distribution	Soil Moisture Content	Circulation Patterns
Atmospheric Aerosol Content	Vegetation Indices	Sea Ice Content
Albedo		
Precipitation		
Evaporation		
Temperature		

2.1.2. Dynamic Equations of Atmospheric Modelling

A numerical model of the atmosphere includes some definitions in proper computer form with necessary approximations of the basic dynamics and physics of the different components of the atmosphere and their interactions. When a physical process is described in terms of an algorithm (it means that a process of step-by-step calculation) and simple parameters (the quantities that are contained in a mathematical equation). All these processes are called as parametrization [1, 4].

The atmosphere can be formulated as a set of equations with some unknowns [2, 4, 5];

- Three components of velocity (u,v,w)

- Pressure
- Temperature
- Specific humidity
- Density

The dynamical equations are the horizontal momentum equations (Newton's Second Law of Motion). In these, the horizontal acceleration of a volume of air is balanced by the horizontal pressure gradient and the friction. Because the Earth is rotating, this acceleration includes the Coriolis acceleration. The friction in the model mainly arises from motions smaller than the grid spacing, which have to be parametrized. [1, 4]

Newton's Second Law (Momentum Balance):

$$\vec{F} = m.\vec{a} \tag{2.1}$$

$\vec{F}$: force, m : mass, $\vec{a}$: acceleration

Pressure gradient force, gravity, viscous friction are the forces which cause atmospheric motion. In other words, these forces accelerate atmosphere.

$$\frac{d\vec{V}}{dt} = -\frac{1}{\rho}\vec{\nabla}p - \vec{g} + \vec{F}_{fric} - 2\vec{\Omega} \times \vec{v} \tag{2.2}$$

Ω : angular velocity of Earth $\vec{v}$: velocity, p : pressure, $\vec{g}$: gravity, $\vec{V}_{fric}$: frictional force

Continuity Equation (Conservation of Mass):

·The continuity equation contains conservation of mass.

$$\frac{\delta P}{\delta t} = -\vec{\nabla}.(\rho\vec{v}) \tag{2.3}$$

·Conservation of Water Mass:

$$\frac{\delta Pq}{\delta t} = -\nabla.(\rho\vec{v}q) + \rho(E - C) \tag{2.4}$$

E : evaporation, C : condensation

First Law of Thermodynamics (Conservation of Energy):

The first law of thermodynamics is usually derived by considering a system in thermodynamic equilibrium, that is, a system which is initially at rest and after exchanging heat with its surroundings and doing work on the surroundings is again rest.

$$Q = C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{do}{dt} \tag{2.5}$$

Q : heating rate per unit mass, C_p: specific heat

State Equation:

The equation of state connects the quantities of pressure, volume and temperature for the atmosphere.

$$p = \rho R_g T \tag{2.6}$$

R_g : gas constant

Most of the equations in the model are differential equations, which means they describe the way in which quantities such as pressure and wind velocity change with time and with location. If the rate of change of a quantity such as wind velocity and its value at a given time are known, then its value at a later time can be calculated. Constant repetition of this procedure is called integration. Integration of the equations is the process whereby new values of all necessary quantities are calculated at later times, providing the model's predictive powers.

2.2. The Climatic Research Unit (CRU)

Since 1982, gridded datasets of surface temperature data over land areas for the globe has been obtainable by courtesy of the Climatic Research Unit (CRU) at the University of East Anglia (UEA). These station data CRU have obtained from the weather stations around the world, and have made improved and constituted monthly averages from the National Meteorological Services (NMSs). The outputs for the period 1970-2000 of the simulation modelling via RegCM 4.3.5.5 is comparing the station data CRU in order to analyse and authentication of simulated data. However, developed countries have more station that is make data available rather than developing countries. It leads to high or low bias related with the countries development level while comparing the simulated data.

2.3. Global Circulation Data ECHAM5

The spectral weather prediction model of the European Center for Medium Range Weather Forecast (ECMWF) have been developed into The European Community-Hamburg (ECHAM) Global Circulation Model. ECHAM is an atmospheric climate model, improved at the Max Planck Institute for Meteorology. It shaped the atmospheric component of the MPI-ESM [27]. ECHAM5 is the fifth generation of the atmospheric general circulation model of ECHAM. It has a hybrid sigma-pressure vertical coordinate. In the ensemble members used in these experiments, ECHAM has a horizontal T42 spectral resolution (2.8 latitude- longitude) and has 19 vertical levels, with the top extending to 10 hPa. The model's prognostic variables are vorticity, divergence, surface pressure, temperature, specific humidity, and the mixing ratio of total cloud water. The mass flux scheme of Tiedtke is employed for both deep and shallow convection [28].

2.4. Why do we need Regional Climate Models?

Global Circulation Models has a horizontal resolution (grid size) around 300 km. This grid size can be made smaller according to computer power. Weather and climate based on large scale when compared with the grid size are described reasonably well. These scales comparable with grid size are described as the regional scale when it is thought the results from global models have serious limitations such as orographic variation, changes in surface characteristics, topography, land cover inhomogeneity. It means that, the effects of forcing and circulations existing on the regional scale need to be properly represented [1][29].

The Regional Climate Modeling techniques have been developed in order to overcome these limitations. Regional climate information is a very critical factor in order to reach and see the effects of the climate changed. The information is needed in regional scale. Regional climate models are the decisions made according to comparisons of the interactions between planetary scales and local (regional) scales. Circulations and forcings in planetary scales determine the statistics of weather events and these weather events also determine the climate of a region. Regional circulations and forcings controls the climate change marks, regionally, even all these foster climate in large scale [1, 29].

2.5. Regional Climate Models (RCMs)

A number of Regional Climate Models (RCMs) have been developed in the last two decades. The RegCM is the first regional climate model which is designed and developed by the Regional Climate Research Network, which is a network prevail among the scientists coordinated by the Earth System Physics department of the Abdus Salam International Centre for the Theoretical Physics (ICTP). The RegCM is a widespread regional climate model because of being an open source, portable and user friendly. It can also be applied to any region of the world [30].

Until 1989, climate scientists were using limited area models (LAMs) for numerical weather predictions by way of 1-5 days simulations. In 1989, Dickinson et al. suggested to adopt the nesting approach for solving climate problems by generating statistics of a large number of short LAM simulations which are driven by general circulation model fields. Used model was a suitably modified version of the mesoscale model MM4, which belongs to National Center for Atmospheric Research / Pennsylvania State University (NCAR/Penn State). After 1989, the first LAM simulations were completed in climate mode for 1 month. They used the European Center for Medium range Weather Forecasting (ECMWF) forecast model analyses of observations and GCM fields. This simulation, which was based on MM4 with suitably modified radiative transfer scheme and land surface process scheme,

Table 2.5. GCM vs. RCM.

GCM (General Circulation Models)	**RCM (Regional Climate Models)**
GCMs are the inputs of RCMs	It provides no interactions back on to the global model.
GCM provides the evaluation of boundary information for the RCM.	It provides comprehensive modeling based on physically downscaling.
There is a limitation in range of applications. (only usable in global applications.)	It is useful in a wide variety of applications including paleoclimate, seasonal prediction, climate change, process studies.
Horizontal resolution (grid size) of around 300 km.	Horizontal resolution through multiple nesting (10-50 km horizontal resolution).
The effects of regional circulation and forcing are not represented well.	It is able to account for small scale forcing, atmospheric circulations and climate variables.
It provides information about the response of the global circulation to large scale forcing and circulations.	
Behavior generated by GCM has a poor representation of real behaviour on the regional scale.	
GCM needs more computer power because of the data size.	It is more usable than GCMs on personal computers.

is regarded as the first version of RegCM which is called RegCM1 [31]. Later versions of RegCM has developed in the early 1990s. This version was RegCM2, in the late 1990s, has developed RegCM2.5 and in the 2000s RegCM3 has come up [32-38].

RegCM has been the first limited area model developed for long term regional climate simulation, it has participated to numerous regional model inter-comparison projects, and it has been applied by a large community for a wide range of regional climate studies, from process studies to paleoclimate and future climate projections [34, 38].In 2010, RegCM4 was designed by developing the previous version of RegCM3. When compared the RegCM4 with previous four versions including RegCM1, RegCM2, RegCM2.5, RegCM3, there is new content consisting of land surface, planetary boundary layer schemes, air-sea flux schemes, a mixed convection, tropical band configuration, modifications to the pre-existing radiative transfer and boundary layer schemes. Also RegCM4 is more flexible, portable and user friendlier than the previous versions [38].

2.5.1. The Structure of RegCM4.3

There are various components of RegCM system:

- Terrain
  - Elevation
  - Land Use (Vegetation)
  - Domain
    - Horizontal resolution
    - Vertical resolution
- Initial and Boundary Conditions:
  - Sea Surface Temperature
  - Data for initial and lateral boundary conditions
  - Lateral boundary conditions
- Post-Processing
  - Command line tools and visualising tools (NetCDF, CDO, GrADS etc.)

Table 2.6. Development of RegCM.

Model	**Development**
RegCM 1	Dynamics from the NCAR/PSU&MM4 Physics from the NCAR CCM1-MM4
RegCM 2	Dynamics from the Hydrostatic NCAR/PSU&MM5 Physics from the NCAR CCM2-MM5
RegCM 2.5	Dynamics from the Hydrostatic&MM5 Physics from the ENCAR CCM3-MM5 Coupled Lake Model Coupled Tracer Transport Scheme
RegCM 3	Dynamics from the hydrostatic&MM5 Physics upgrades for convective and non-convective precipitation, air sea fluxes Coupled with a simple chemistry or aerosol scheme Sub-grid land surface scheme
RegCM 4	Compared to first four (previous versions), RegCM4 contains new ; land surface planetary boundary layer schemes air-sea flux schemes a mixed convection tropical band configuration modifications to the pre-existing radiative transfer and boundary layer schemes flexibility, portability, user friendliness

Statistical Packages (MATLAB, R Language etc.)

We have to determine the model's grid configuration. Terrestrial variables and three dimensional isobaric meteorological data are horizontally interpolated from a latitude-longitude mesh to a high resolution domain on either a map projections. Map projections in the RegCM following [38] ;

- Polar Stereographic (for high latitudes)
- Lampert Conformal (for mid-latitudes)
- Normal Mercator (for low latitudes)
- Rotated Mercator (for extra choice)

We need to interpolate the data on pressure surfaces of the modelling system to the vertical coordinate of the model. RegCM 4.3.5.5 uses vertically sigma coordinate system, which includes eighteen pressure levels. The vertical coordinate is terrain-following which means that the lower grid levels follow the terrain when the upper surface is flatter. Intermediate levels progressively flatten as the pressure decreases as going to the upper level of the model. The horizontal grid of the RegCM 4.3.5.5 has a Arakawa-Lamb B-staggering which means that grid system describes and separates the evaluation of the sets of quantities [38, 39].

2.5.2. The Physics of the Model

The physics of the model contains ;

- Parametrization of moist processes including evaporation, condensation, formation and dispersal of clouds
- Parametrization of absorption, emission and reflection of solar radiation and of thermal radiation

- Parametrization of convective processes
- Parametrization of exchange of momentum (friction), heat and water vapour at the surface.

All these parametrizations are expressed in different schemes and sub-models in the RegCM. The latest version of RegCM (RegCM4) uses the radiation scheme of the NCAR CCM3. It uses BATS (Biosphere-Atmosphere Transfer Scheme) and CLM (Community Land Models) as the Land Surface Model. The model includes the BATS in default case of RegCM and CLM is optional. BATS has twenty vegetation types ;

Table 2.7. BATS Vegetation Types.

1- Crop/mixed farming	11- Semi-desert
2- Short grass	12- Ice Cap/Glacier
3- Evergreen needle-leaf tree	13- Bog or Marsh
4- Deciduous needle-leaf tree	14- Inland water
5- Deciduous broad-leaf tree	15- Ocean
6- Evergreen broad-leaf tree	16- Evergreen shrub
7- Tall grass	17- Deciduous shrub
8- Desert	18- Mixed Woodland
9- Tundra	19- Forest/Field Mosaic
10- Irrigated Crop	20- Water and Land Mixture

2.5.3. Model Mechanism

2.5.3.1. Dynamic Equations. The model dynamic equations and numerical discritization are described by Grell *et al.* [41] .

Horizontal Momentum Equations:

$$\frac{\delta p^* u}{\delta t} = -m^2(\frac{\delta p^* uu/m}{\delta x} + \frac{\delta p^* vu/m}{\delta y}) - \frac{\delta p^* u\dot{\sigma}}{\delta \sigma} - mp^*[\frac{RT_v}{(p^* + p_t/\sigma)}\frac{\delta p^*}{\delta x} + \frac{\delta \phi}{\delta x}] + fp^* v + F_H u + F_v u, \tag{2.7}$$

$$\frac{\delta p^* v}{\delta t} = -m^2(\frac{\delta p^* uvm/m}{\delta x} + \frac{\delta p^* vv/m}{\delta y}) - \frac{\delta p^* v\dot{\sigma}}{\delta \sigma} - mp^*[\frac{RT_v}{(p^* + p_t/\sigma)}\frac{deltap^*}{\delta y}] + fp^* u + F_H v + F_v v, \tag{2.8}$$

u, v is the velocity , T_v is the virtual temperature , ϕ is the geopotential height , f is the Coriolis parameter R is the gas constant for dry air , m is the map scale factor , $p^* = p_s - p_t$, $\dot{\sigma} = \frac{d\sigma}{dt}$,
F_H, F_V is the effects of horizontal and vertical diffusion.

Continuity and Sigma-dot Equations:

The vertical integral of Equation is used to compute the temporal variation of the surface pressure in the model;

$$\frac{\delta p^*}{\delta t} = -m^2(\frac{\delta p^* u/m}{\delta x} + \frac{\delta p^* v/m}{\delta y}) - \frac{\delta p^* \dot{\sigma}}{\delta \sigma} \tag{2.9}$$

The calculation of the surface-pressure tendency;

$$\frac{\delta p^*}{\delta t} = -m^2 \int_0^1 (\frac{\delta p^* u/m}{\delta x} + \frac{\delta p^* v/m}{\delta y}) d\sigma \tag{2.10}$$

$\frac{\delta p^*}{\delta t}$ is the surface pressure tendency, $\dot{\sigma}$ is the vertical velocity in sigma coordinates

Thee vertical velocity in sigma coordinates $\dot{\sigma}$ is computed at each level in the model from the vertical integral of Equation (2.9)

$$\dot{\sigma} = -\frac{1}{p^*} \int_0^\sigma [\frac{\delta p^*}{\delta t} + m^2 (\frac{\delta p^* u/m}{\delta x} + \frac{\delta p^* v/m}{\delta y})] d\sigma' \tag{2.11}$$

σ' is the dummy variable of integration, $\dot{\sigma}(\sigma = 0) = 0$

Thermodynamic Equation and Omega Equation:

The thermodynamic equation is

$$\frac{\delta p^* T}{\delta t} = -m^2 (\frac{\delta p^* u T/m}{\delta x} + \frac{\delta p^* v T/m}{\delta y}) - \frac{\delta p^* T \dot{\sigma}}{\delta \sigma} + \frac{R T_v \omega}{c_{pm}(\sigma + P_t/P_{ast})} + \frac{p^* Q}{c_{pm}} + F_H T + F_V T \tag{2.12}$$

c_{pm} is the specific heat, Q is the diabatic heating, $F_H T$ is the effect of horizontal diffusion,
$F_v T$ is the effect of vertical mixing and dry convective adjustment,

ω is,

$$\omega = p^*\dot{\sigma} + \sigma\frac{dp^*}{dt} \tag{2.13}$$

where,

$$\frac{dp^*}{dt} = \frac{\delta p^*}{\delta t} + m(u\frac{\delta p^*}{\delta x} + v\frac{\delta p^*}{\delta y}) \tag{2.14}$$

$c_{pm} = c_p(1 + 0.8q_v)$, c_p is the specific heat at constant pressure for dry air, q_v is the mixing ratio of water vapour

Hydrostatic Equation:

To compute the geopotential heights from the virtual temperature T_v;

$$\frac{\delta\phi}{\delta ln(\sigma + p_t/p^*)} = -RT_v[1 + \frac{q_c + q_r}{1 + q_v}]^{-1} \tag{2.15}$$

$T_v = T(1 + 0.608q_v)$, q_v, q_c, q_r is the water vapour, cloud, ice, and rain water or snow, mixing ratio.

2.5.3.2. Physics Parametrizations (Sub-models within the model). The model has several major parameters including Radiation scheme, Land Surface model, Planetary Boundary Layer Scheme, Convective Precipitation Scheme, Large Scale Precipitation, Ocean Flat Parametrisation, Prognostic Sea Surface Skin Temperature Scheme, Pressure Gradient Schema, Lake Model, and Aerosols and Dust (Chemistry Model) to model climate better.

Radiation scheme

RegCM 4 uses the radiation scheme of the Community Climate Model version 3 (CCM3) developed by the National Center for Atmospheric Research (NCAR) CCM3, which is described in Kiehl *et al.* [35]. There is 18 spectral intervals from 0.2 to 5 μm. The thickness of the cloud layer is presumed the same with the model layer, and a different cloud water theme is thought of the middle and low clouds.

Land Surface model

RegCM 4 includes two land model, BATS and CLM. BATS is the package designed to contribute the role of vegetation and interactive soil moisture in modifying the surface-atmosphere exchanges of momentum, energy, and water vapour [42]. CLM is the land surface model improveded by the National Center of Atmospheric Research (NCAR)[40]. CLM contains five possible snow layers and ten unevenly spaced soil layers.

Planetary Boundary Layer Scheme

The planetary boundary layer scheme is ground on a nonlocal diffusion idea. In this idea, counter-gradient fluxes resulting from large-scale eddies in an unstable, well-mixed atmosphere has been calculated Holtslag *et al.* [43]

Convective Precipitation Scheme

Convective precipitation is computed using one of three schemes: Kuo-Anthes scheme [**?**] Grell scheme [41], and MIT-Emanuel scheme [44, 45].

o Kuo Scheme: In the case of the excessive of the moisture convergence and convectively unstable the vertical sounding, Kuo Scheme is activated.

o Grell Scheme: According to this scheme, clouds has an updraft and a downdraft circulations. The cloudy air and the circumaural air does not mix each other except at the top and bottom of the circulations.

o MIT-Emanuel Scheme: The scheme takes into account the clouds inhomogeneous and supposes the movements of convective fluxes as updrafts and downdrafts.

Large Scale Precipitation

Subgrid Explicit Moisture Scheme (SUBEX) is used for dealing with non-convective clouds and precipitation. SUBEX considers for the sub-grid differences in the clouds. The mean grid cell relative humidity to the cloud fraction, and cloud water is attached in the scheme [**?**].

Ocean Flat Parametrization

Perceivable heat and imperceptible heat and momentum fluxes are taking into account between the sea surface and lower atmosphere.

Prognostic Sea Surface Skin Temperature Scheme

The sea surface temperature (SST) is proved from interpolated data from weekly or monthly data every six hour. The data are generated from satellite retrievals and obtain the information from the top few meters of the ocean.

Pressure Gradient Scheme

Usage of the full fields and the hydrostatic deduction scheme are used for calculating the pressure gradient force in this scheme. Generally former is used for calculation and the extra way to do this calculation.

Lake Model

Fluxes of heat, moisture, and momentum are calculated from meteorological data and the lake surface temperature and albedo. Heat is moved vertically between lake model layers by eddy and convective mixing. Ice and snow may cover part or the entire lake surface.

Aerosols and Dust(Chemistry Model)

The main idea in Chemistry Model is the wind conditions, the soil characteristics and the particle size. Soil aggregate saltation and sandblasting processes are used to calculate the dust emission level [**?**, **?**].

In order to take into account counter-gradient fluxes resulting from large scale eddies in an unstable and well mixed atmosphere, RegCM 4.3.5.5 uses the planetary boundary layer scheme. In order to calculate the convective precipitation, RegCM 4.3 has got three different scheme: Kuo scheme, Grell scheme, MIT-Emanuel scheme. Besides, RegCM 4.3 uses Sub-grid Explicit Moisture Scheme (SUBEX) in determining the large-scale precipitation (to handle non-convective clouds and precipitation dissolved by the model). Sensible heat, latent heat and momentum fluxes between the sea surface and lower atmosphere are being computed via the Zeng Scheme. This part can be described as the parameterization of ocean flux. In order to make appeared the important effects of model climatology on mostly tropical oceans, prognostic sea surface skin temperature scheme is added to RegCM 4.3.[41] Pressure Gradient Scheme involves in two methods to calculate pressure gradient force. One of them is usage of full fields and second one is that hydrostatic deduction scheme which makes use of perturbation temperature. The lake model can be interactively coupled to the atmospheric models. In the lake model, fluxes of momentum, heat, moisture are computed depends on meteorological inputs and the lake surface temperature and albedo. Lastly, in the chemistry model which contains aerosols and dust emission processes. Also it depends on the soil characteristics, the particle size and the wind conditions. This model become effective in the model for domains like desert and semi-desert land cover [30,32-38,46].

2.6. Model Description

2.6.1. Setting up the environment for the model

First of all, we need to set up environment by forming the file regcm.in where the model is getting the information about topography, boundary conditions, and climatic events over the selected region.

The first step is to create the DOMAIN file to localize the model on a selected region. The terrain command line enables us to do it by creating a domain file. There are the localized topography, land use database, projection information, and land sea mask in the

DOMAIN file. After forming the domain, we check the domain by plotting the topography and land use using the GrADS program. We need to generate the sea surface temperature for the model in the second step. We execute the SST command line and it gives us the SST file including the sea surface temperature to be used in generating the initial and boundary conditions for the model for the period determined in the regcm.in file. In the next step, we need to create Initial Conditions and Boundary Conditions ICBC files contain the surface pressure, surface temperature, horizontal wind components, temperature and mixing ratio for the RegCM domain for the period and time determined in the file regcm.in.

2.6.2. RegCM Model Simulation

After setting up the environment with first three steps, we are ready to run the model RegCM 4.3.5.5. We save time due to parallel programming of the model. After running the program, we have the ATM files containing the atmosphere status from the model. The SRF file includes the surface diagnostic variables and the RAD file contains radiation fluxes information. In this thesis, we use the SRF file to obtain information about the mean surface air temperature and precipitation. Then, we incorporate and shape the output data by using CDO and GrADs command lines. Lastly, we plot the output data by using NCL program as a map.

2.6.3. The Parameters using in file the regcm.in

- iy : This is number of points in the N/S direction

It is calculated according to 50 km horizontal resolution for each domains.

- jx : This is number of points in the E/W direction

It is calculated according to 50 km horizontal resolution for each domains.

- kz : Number of vertical levels There is 18 vertical level.

- nsg : For subgridding, number of points to decompose.

- Domain cartographic projection.

- Middle latitudes (around 45 degrees) - Lambert Conformal(LAMCON)
- Polar latitudes (more than 75 degrees) - Polar Stereographic (POLSTR)
- Low latitudes (up to 30 degrees and crossing the equator) - Mercator (NORMER)
- Crossing more than 45 degrees extent in latitude - Rotated Mercator (ROTMER)

We have used LAMCON projection for Netherlands domain, and NORMER projection for Ethiopia and Bangladesh domains.

- ds : Grid point horizontal resolution in km

We have used 50 km horizontal resolution in the model.

- clat : Central domain point for latitude

(belongs to Ethiopia, Bangladesh, or Netherlands)

- clon : Central domain point for longitude

(belongs to Ethiopia, Bangladesh, or Netherlands)

- ibdyfrq : boundary condition interval (hours)

We have chosen 6 hours- intervals.

- sstyp : Type of Sea Surface Temperature used

\- ERSST, ERSKT, CCSST, EH5RF, EH5A2, EH5B1, EHA1B,etc.

We have used EH5RF for the period 1970-2000 and EHA1B for the period 2020-2050.

- datty : Global analysis dataset.

\- ERA40, EIN15, NNRP2,etc.

We have used ECHAM5 global circulation dataset.

- gdate1 : Start date for ICBC data generation

- gdata2 : End date for ICBC data generation

- calendar : Calender to use (Gregorian, noleap or 360 day)

We have used Gregorian calendar for the model.

- icup : Cumulus convection scheme

1- Kuo-Anthes
2- Grell
3- Betts-Miller (DOES NOT WORK)
4- Emanuel
5- Tiedtke (UNTESTED)

We have used Grell cumulus convection scheme for Netherlands Region, and Emanuel cumulus convection scheme for Ethiopia and Bangladesh regions.

- igcc : Cumulus Closure Assumptions

1- Arakawa & Schubert
2- Fritsch & Chappell

We have used Fritsch & Chappell cumulus assumption for Netherlands domain and Arakawa & Schubert cumulus assumption for Ethiopia and Bangladesh domains.

- scenario: Scenario to use

\- IPCC Scenario to use in A1B,RF,A2,B1,B2
\- RCP Scenarios in RCP3PD,RCP4.5,RCP6,RCP8.5

We have used IPCC SRES scenarios A1B.

- BATs land surface type is used in the model as a default

- Other parameters have been used in the default settings defined in the model.

3. RESULTS AND DISCUSSIONS

3.1. Ethiopia

Ethiopia located in East of South Africa and does not have coastline, although its location is very close to the Red Sea for about 100-150 kilometers. Different geological features of the country lead to significant impact on the climate, especially due to having differing altitudes.

Average temperature is always high, although level of temperature varies region to region. Temperature of the area nearest Red Sea is always higher than inlands. Warmest month is April and May inland, and August in the east part of the area. Like the warmest month, the coolest month differs from east part seen July and June, and inland of the region seen in January.

Mean precipitation differs from area to area, because of the elevation and seasonal changes in monsoon winds. The greater part of Ethiopia is highlands and these areas receive by far the most rainfall, almost 400mm in July, August and September, unlike the highlands, land in the lower altitude receive much less, below 50mm [47].

Ethiopia was run with RegCM 4.3.5.5, using Emanuel Scheme for cumulus convection and Arakawa & Schubert Scheme for cumulus closure,and Normal Mercator (NORMER) for cartographic projection.

3.1.1. Seasonal Climate Analysis

Here we have investigated the changes in climatic variables; surface air temperature, and precipitation, which are mostly used in climate impact studies to better understand the climate change. Comparison of seasonal mean changes in surface air temperature and precipitation have been analyzed four climatological seasons separately with a spatial resolution of 50 km.

3.1.1.1. Average Surface Air Temperature. In the Figure 3.1, it has been illustrated he comparison between the output simulated data using RegCM 4.3.5.5 by forcing ECHAM5 and observations CRU dataset for the period 1970-2000 over the Ethiopia domain. Generally performance of the model is reasonable. However, northwestern part of the domain shows cold bias up to 5 °C, particularly during DJF. It is due to the effects of the local topographical forcing and placing monsoon regions well as the model description of physical process. Other reason of the cold bias in northeastern area is station data placed in the coastline . A warm bias of $2-3\,^{\circ}$C is seen in a very few parts of the domain.Because of the domain's specific climatic features, it is seen cold and warm bias locally, but major part of the domain has a bias less than 1 °C. Although there are rare station data , Figure 3.1 demonstrate a nice average seasonal temperature over the domain .

3.1.1.2. Average Precipitation. In the Figure 3.2, the comparison between the output simulated data using RegCM 4.3.5.5 by forcing ECHAM5 and observations CRU dataset for the period $1970-2000$ over the Ethiopia domain have been shown. All season during the 30-years period show positive precipitation bias means that this area receives around 6mm/day less precipitation compared to the performed simulation. One of the reasons of bias is that Ethiopia has a few weather stations. It purports that when we interpolated CRU data into our gridded system used in RegCM 4.3.5.5, data can be missed or because fairly different because of the geographical features. For example, if some values of interpolated data overlap on a mountain, bias in precipitation will be positive and high according to elevation, because the highlands receive more rain. In addition to these, south part of the area are mostly covered by deserts, so combining geographical and climatic characteristics generates bigger bias, particularly in rainy season. On the other hand, the biggest bias has been observed in SON due to the monsoon climate. The driver of this situation is simulation model, takes into account some natural climatic events like monsoon and this reflects to the model output as the bias. In Figure 3.2, some geographical features and climatic events have an impact on bias range significantly.

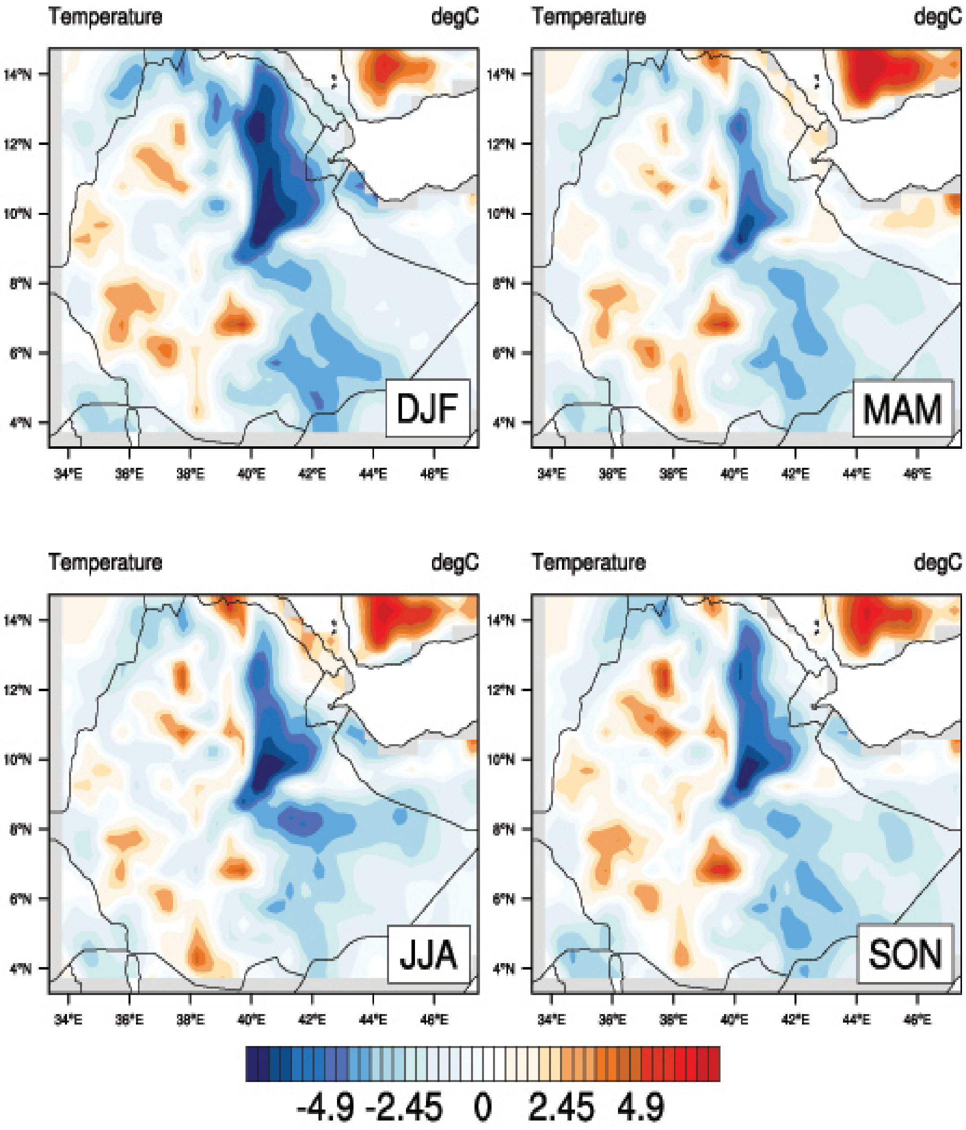

Figure 3.1. Bias of the Seasonal Mean Surface Air Temperature over Ethiopia.

3.1.2. Monthly Climate Analysis

<u>3.1.2.1. Mean Surface Air Temperature.</u> (for the period 1970-2000 with respect to station dataset)

The difference of the mean surface air temperature in the area of interest is illustrated

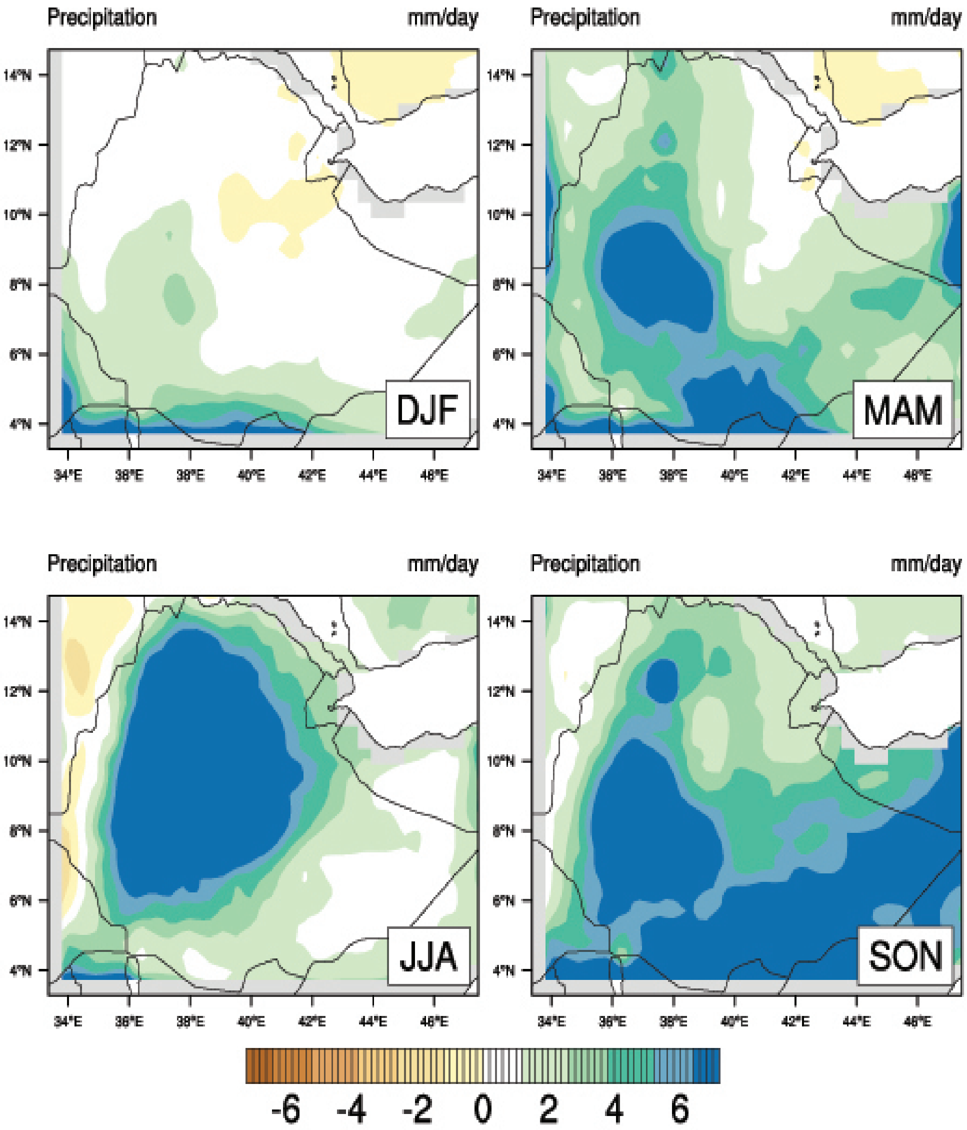

Figure 3.2. Bias of the Seasonal Mean Precipitation over Ethiopia.

in the Figure 3.3, which shows 0.5 – 1 °C bias in January, February, March, and April. In November and December have bias below 1 °C . The rest of the months during the 30-years period is quite smooth and has lower difference that can be ignored. It means that the simulation performed by using RegCM is noticeably acceptable over the region. If it is considered in full of the region, the warmest month is May and the coolest month is January. However, the mean temperature is always high, above 21 °C.

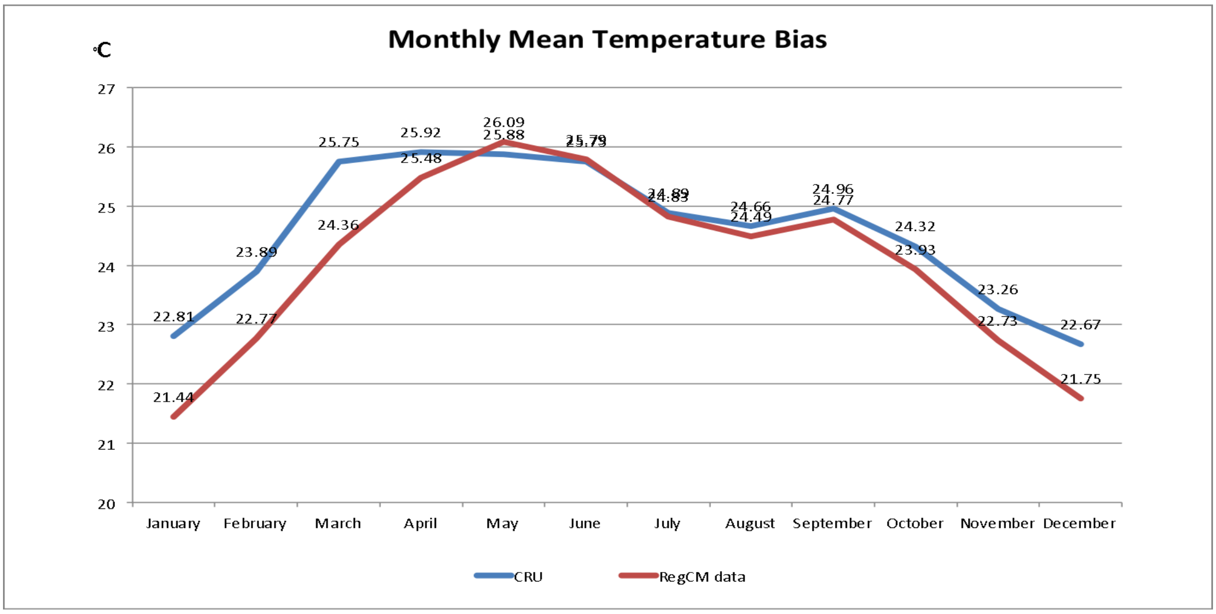

Figure 3.3. Monthly Mean Surface Air Temperature data which is simulated by ECHAM5 using RegCM 4.3.5.5 compared with observations CRU dataset for the period 1970-2000 for Ethiopia.

3.1.2.2. Mean Precipitation . (for the period 1970-2000 with respect to the station dataset CRU)

In the Figure 3.4. the bias range is very wide from 1 mm/day to 8 mm/day in every month. Reason is this situation, Ethiopia is in the tropics and have experienced monsoon rainfalls. According to these climatic features of the domain, the regional climate model shows very high bias, particularly in rainy months.

3.1.3. Projection of Climatology for the Future

3.1.3.1. Projection of Seasonal Changes. In this section, we examined seasonal changes for the period 1970-2000 with respect to the period 2020-2050.

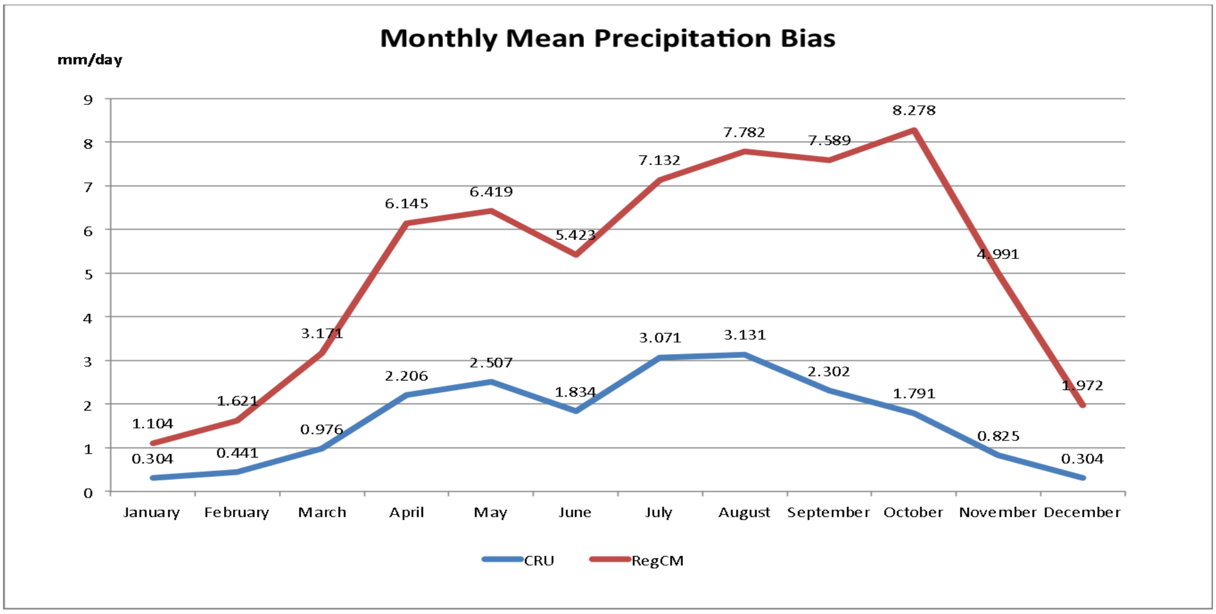

Figure 3.4. Monthly Mean Precipitation data which is simulated by ECHAM5 using RegCM 4.3.5.5 compared with observations CRU dataset for the period 1970-2000 for Ethiopia.

Difference in Temperature

Ethiopia has always hot weather during the year, yet the temperature of the surface air will be warming up more than ever between the years 2020 and 2050. Almost up to 2 °C raise in temperature will be existed in dry and hot season. The warming will be at the maximum principally in MAM over northern part of the region.

Difference in Precipitation

The regionally averaged precipitation changes in the projection data with A1B scenario are presented in Figure 3.6. The mean precipitation shows decreases in MAM and increases in SON. It means that the region will have 2 mm/day more precipitation in temperate season. However, it will be experienced less precipitation in MAM. The difference of rainfall is between 1 mm/day both sides inclusive in DJF and MAM.

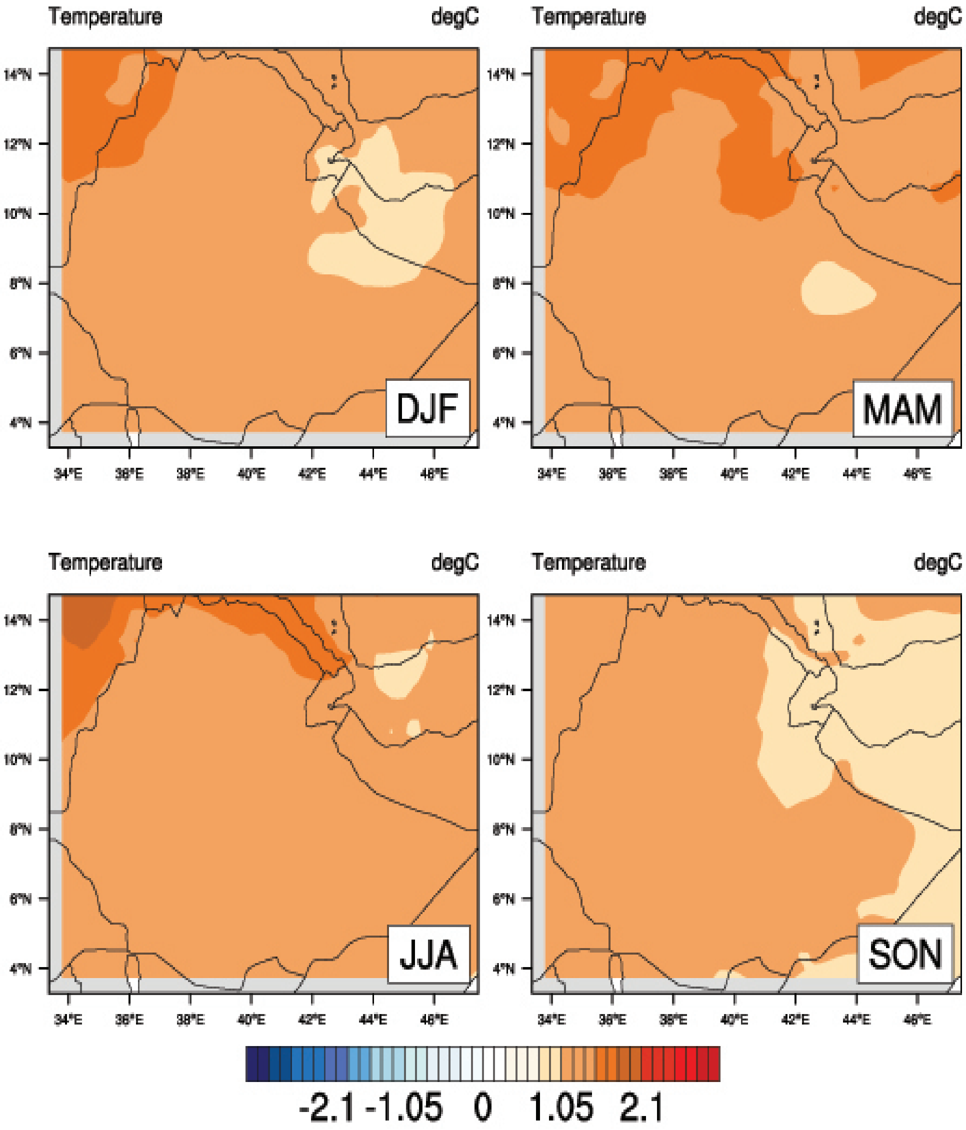

Figure 3.5. Seasonal Average Surface Air Temperature projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Ethiopia.

3.1.3.2. Projection of Monthly Changes. In this section, we examined monthly changes for the period 1970-2000 with respect to the period 2020-2050.

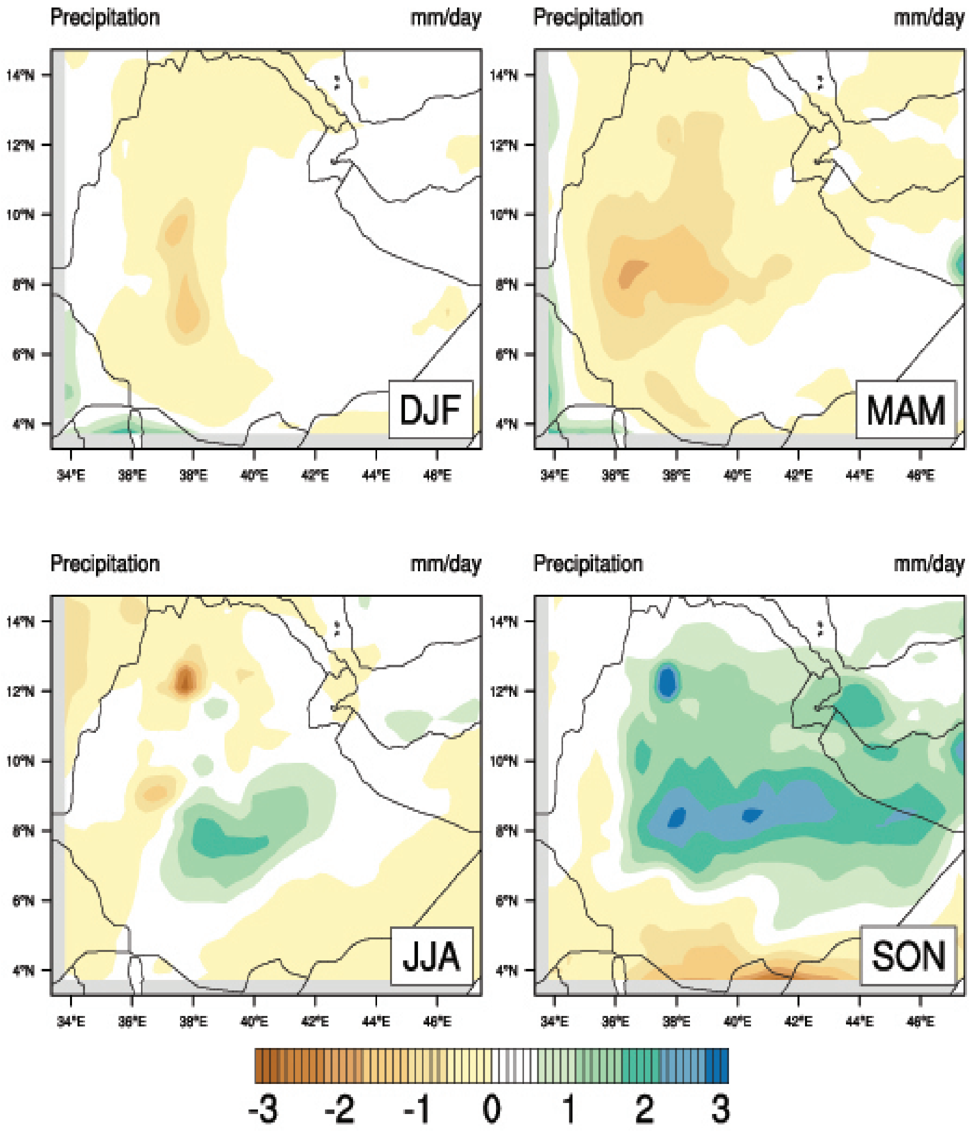

Figure 3.6. Seasonal Average Precipitation projection from RegCM 4.3.5.5 forced by forcing ECHAM5-A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Ethiopia.

Changes in Temperature

As we see in the Figure 3.7, the average surface air temperature will likely increase over the region in all months by taking into account the comparison of the station data and simulation for the period 1970-2000. The minimum increase in the mean surface air temperature is more than 2 °C, it will leads more precipitation over the region. It indicates that greenhouse gases affect the region significantly for the period 2020-2050.

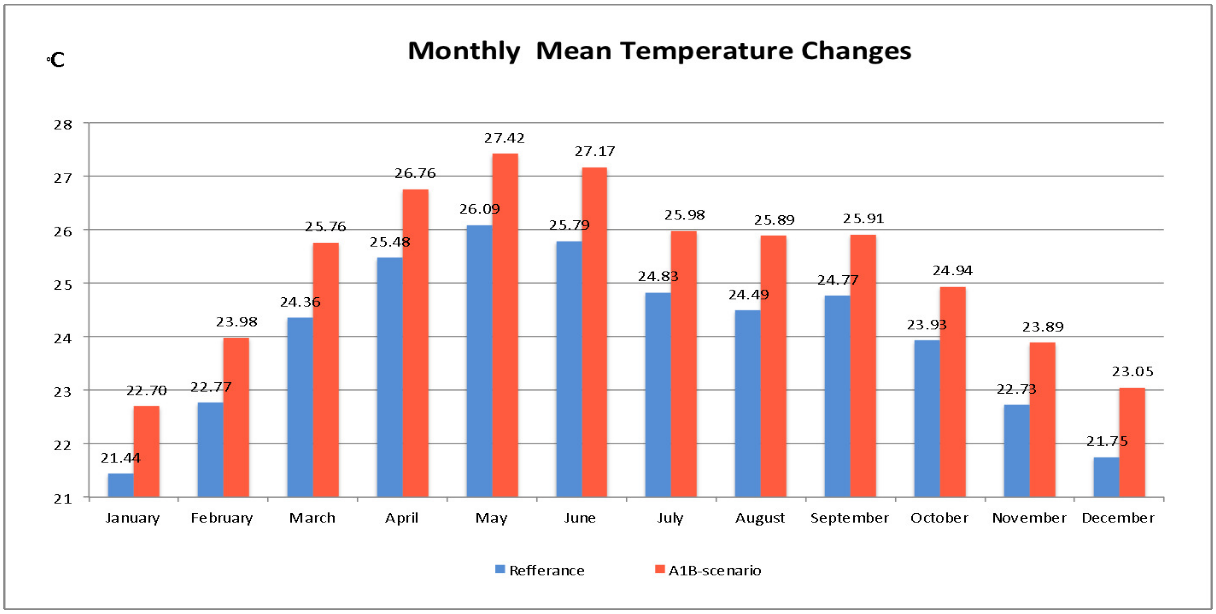

Figure 3.7. Monthly Average Surface Air Temperature projection from RegCM 4.3.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Ethiopia.

Changes in Precipitation

Figure 3.8 shows that the mean precipitation will decrease slightly in January, April, May, June, and August, and increase the rest of the months. Maximum changes will have been experienced in October.

<u>3.1.3.3. Interannual Variability and Trend in a Regional Climate Models.</u> In this section, we examined interannual change trends for the future.

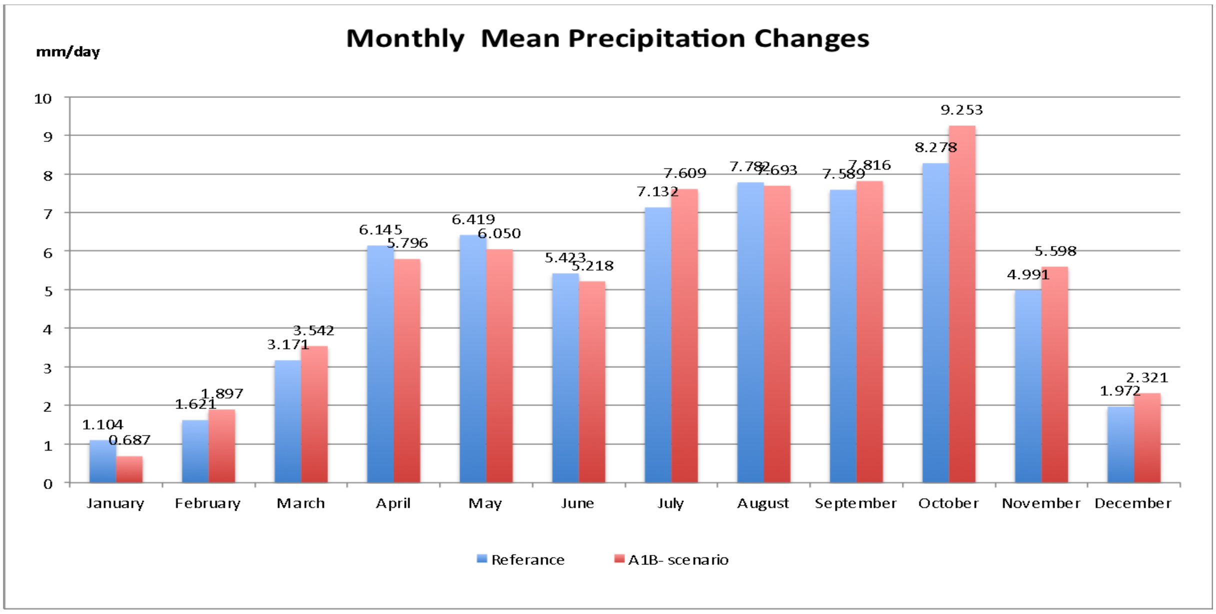

Figure 3.8. Monthly Average Precipitation projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Ethiopia.

Trends in Temperature

The mean surface air temperature trend over the region will raise significantly (Figure 3.9), almost till 27 °C. In 2046 and 2047 the level of the surface air temperature will be above 26 °C. On of the reason of that, GHGs will affect the domain adversely, because the region is placed in the tropics and is receiving a lot of sunlight.

Trends in Precipitation

The mean precipitation of the domain is at a high level, and in the future the course of the mean precipitation will continue (Figure 3.10), and slightly increases. In 2022, 2030, 2035, 2039 and 2050, the mean precipitation will be observed over the normal level.

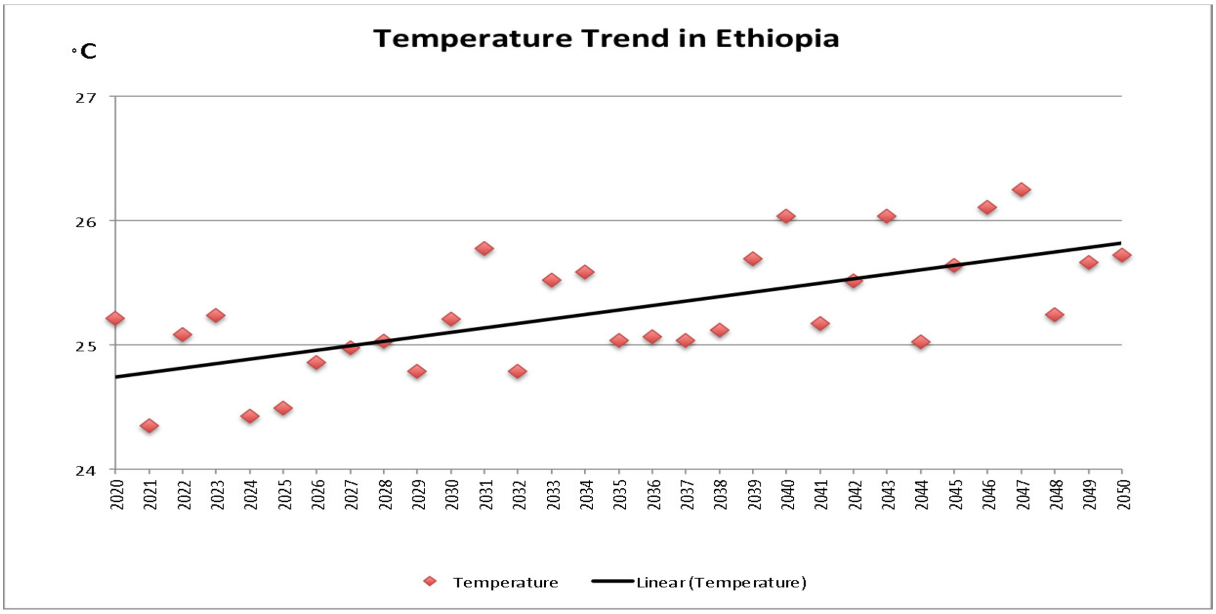

Figure 3.9. Inter-annual mean surface air temperature variable and its trend in the model using RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data as the input for the period 2020-2050 for Ethiopia.

3.2. Bangladesh

Bangladesh has tropical monsoon climate. Winters are mild and summers are humid. The rainy seasons have come throughout June, July and August. Dry periods are between December and February. After dry periods pre-monsoon season starts that drives a lot of rainfall during the next 3 months [49].

Bangladesh was run with RegCM 4.3.5.5, using Emanuel Scheme for cumulus convection and Arakawa & Schubert Scheme for cumulus closure,and Normal Mercator (NORMER) for cartographic projection.

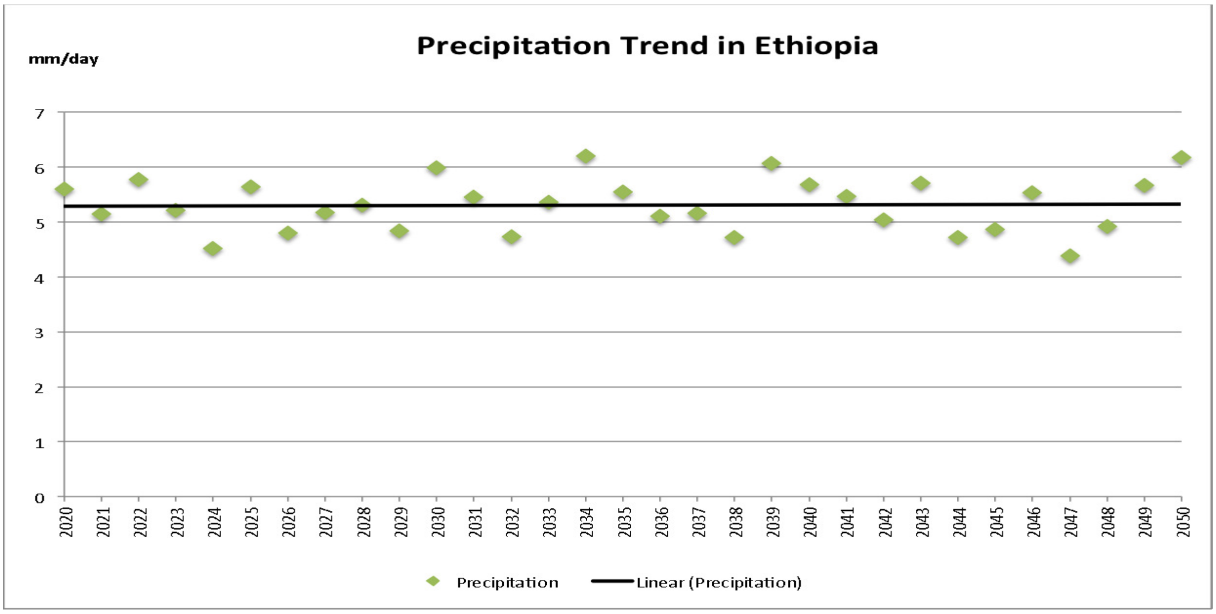

Figure 3.10. Inter-annual mean precipitation variable and its trend in the model using RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data as the input for the period 2020-2050 for Ethiopia.

3.2.1. Seasonal Climate Analysis

3.2.1.1. Average Surface Air Temperature. The seasonal cycle of surface air temperature over the domain is generally in line with the observational data (CRU). In the northern part of the domain during the spring season the cold bias has been observed (Figure 3.11). Apart from the spring season, cold bias reveals itself in the winter, summer and autumn seasons. The bias range is around 1 °C both positively and negatively. It is considered that the performance of the model is pretty feasible even though the region in the tropics.

3.2.1.2. Average Precipitation . Seasonal evolution of the mean precipitation is illustrated in Figure 3.12. The precipitation bias is dominantly negative over the region in the all seasons. One of the reason of these changes is large scale circulation and water vapour loading in the tropics. Other reason why the bias signal is underestimated, is related with

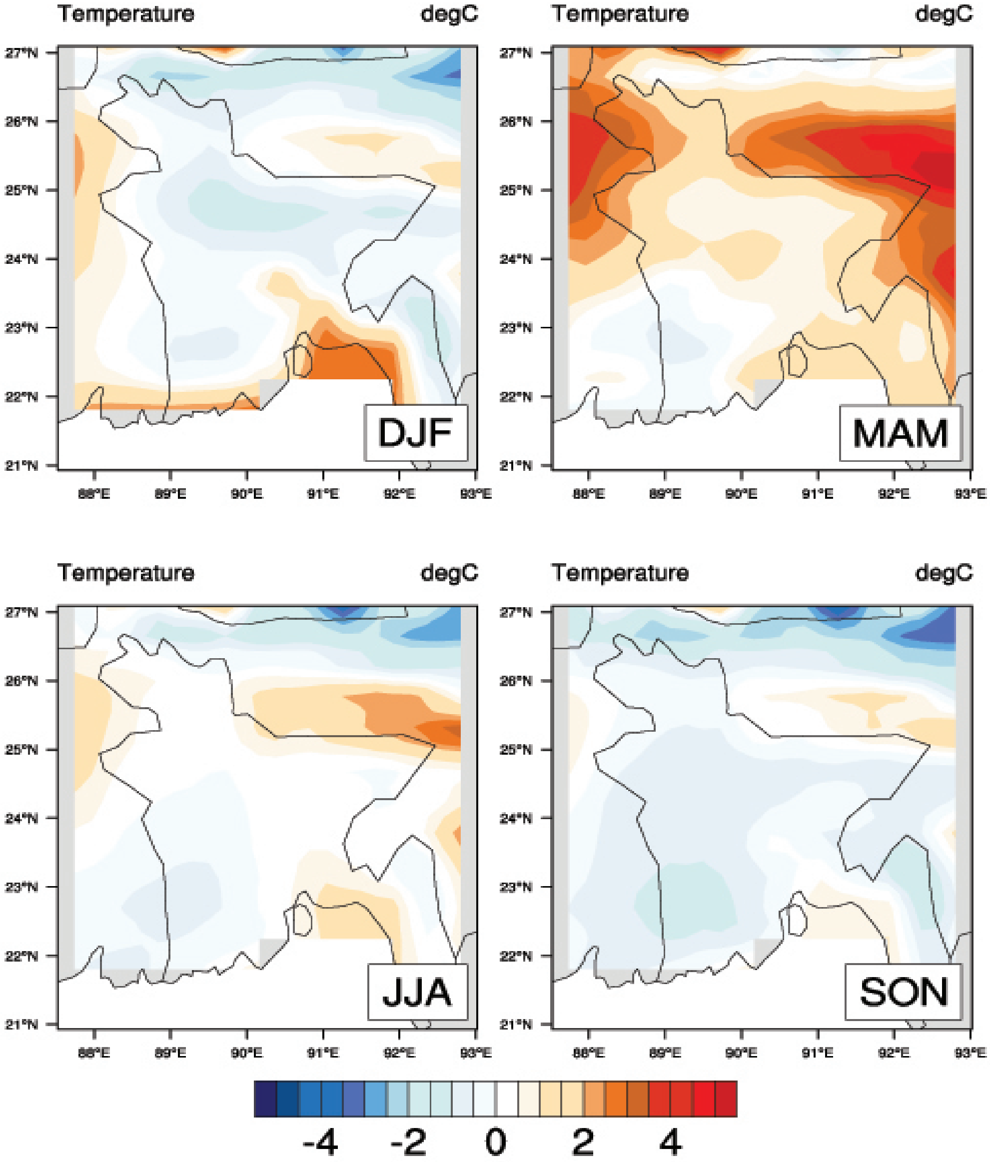

Figure 3.11. Bias of the Seasonal Mean Surface Air Temperature over Bangladesh.

the topography, and insufficiency of the station data over the region.

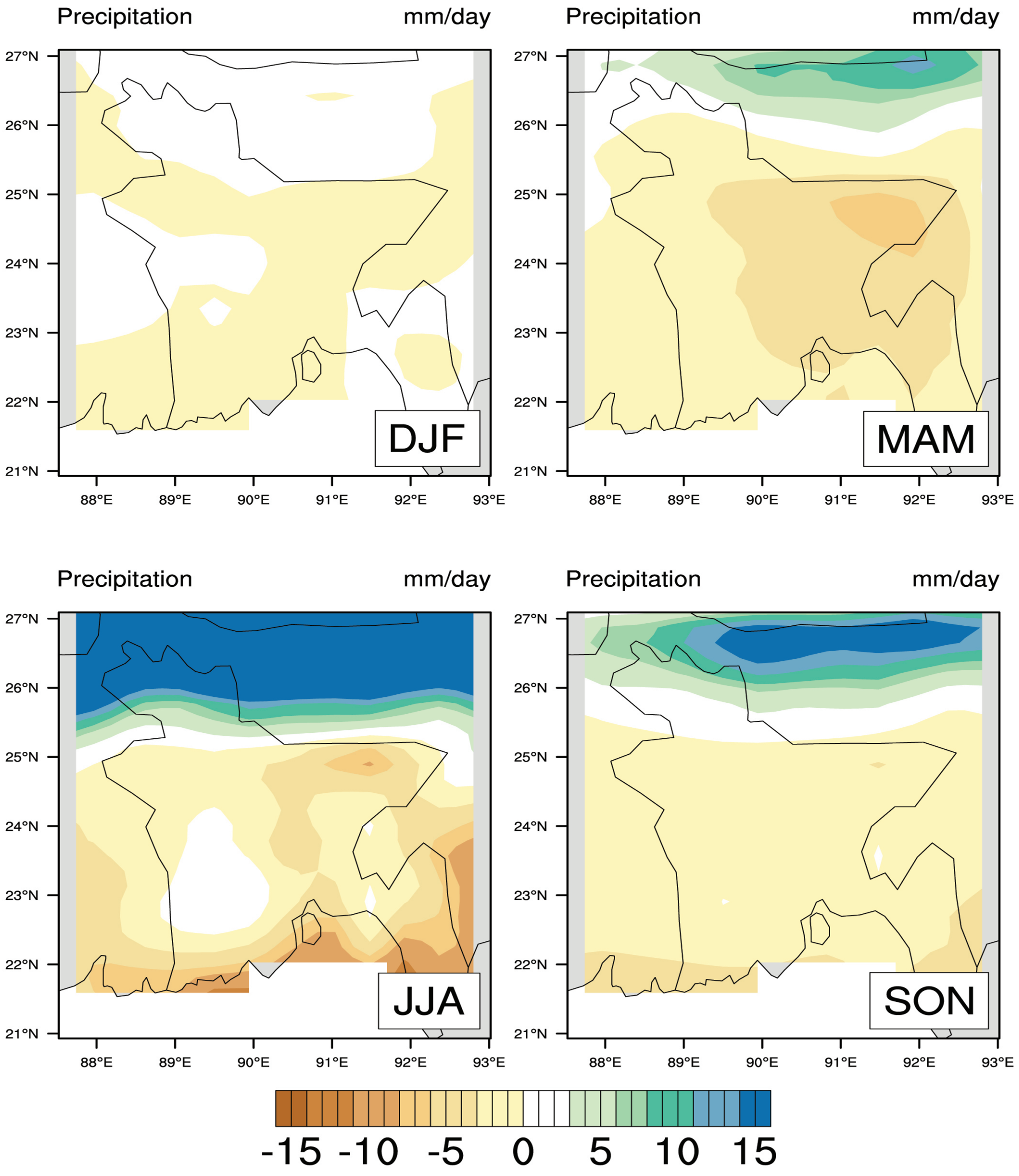

Figure 3.12. Bias of the Seasonal Mean Precipitation over Bangladesh.

3.2.2. Monthly Climate Analysis

3.2.2.1. Mean Surface Air Temperature . Illustration of bias for mean surface air temperature is oddly enough fine over the region (Figure 3.13). Temperature is always high during the year. April and May, the months of monsoon seasons, are the warmest months.

Coolest months are January and February. However, the mean surface air temperature is above the 15 °C. Most sensitive the mean surface air temperature has been observed from June to December.

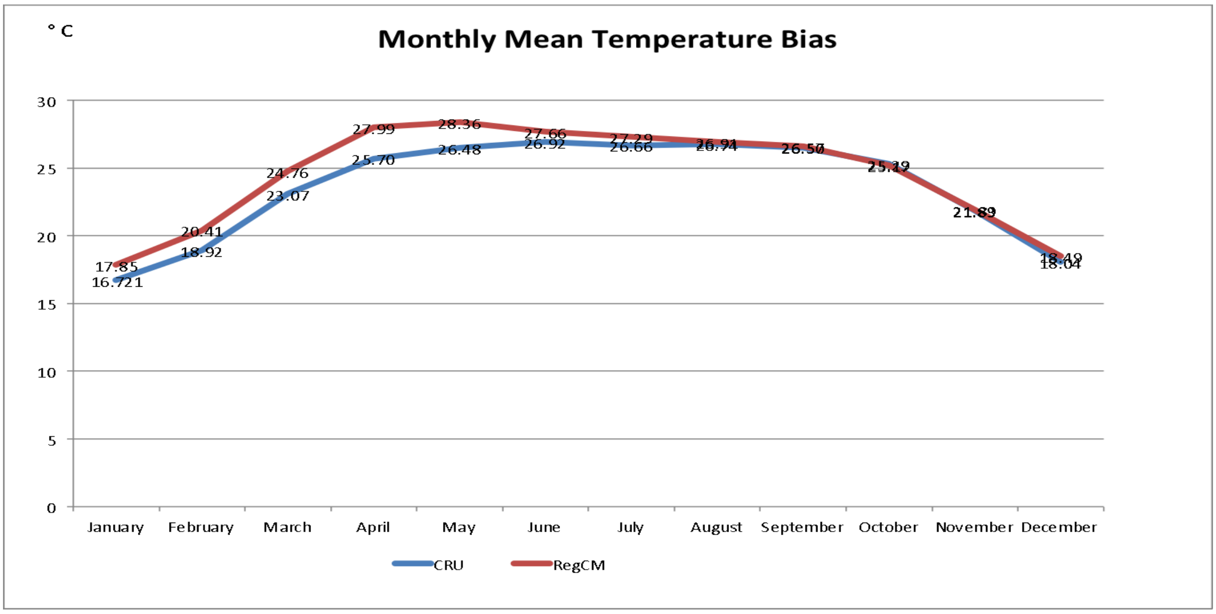

Figure 3.13. Monthly Mean Surface Air Temperature data which is simulated by forcing ECHAM5 using RegCM 4.3.5.5 compared with observations CRU dataset for the period 1970-2000 for Bangladesh.

<u>3.2.2.2. Mean Precipitation .</u> Seasonal evaluation of the mean precipitation over the domain is presented in Figure 3.14 The wettest days are experienced during this monsoon season, in June, July, and August. Monsoon season is warm, cloudy, and wet. The direst months is beginning with November and ending with March. The monthly mean precipitation is overestimated through both pre-monsoon and monsoon seasons, because of the systematic main error.

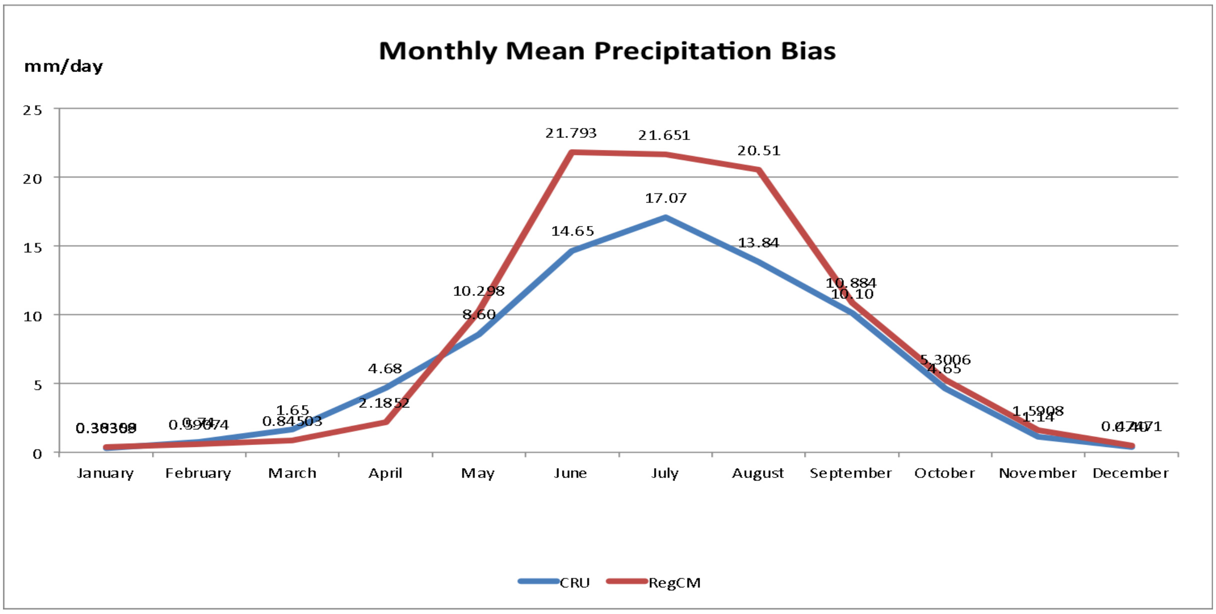

Figure 3.14. Monthly Mean Precipitation data which is simulated by forcing ECHAM5 using RegCM 4.3.5.5 compared with observations CRU dataset for the period 1970-2000 for Bangladesh.

3.2.3. Projection of Climatology for the Future

<u>3.2.3.1. Projection of Seasonal Changes.</u> In this section, we examined seasonal changes for the period 1970-2000 with respect to the period 2020-2050.

Difference in Temperature

In all season , the domain undergoes substantial warming according to the A1B scenario. Some noticeable warming will occur during DJF over the region (almost above 2 °C).

Difference in Precipitation

The illustrated domain tends to consistently produce a greater decrease in precipita-

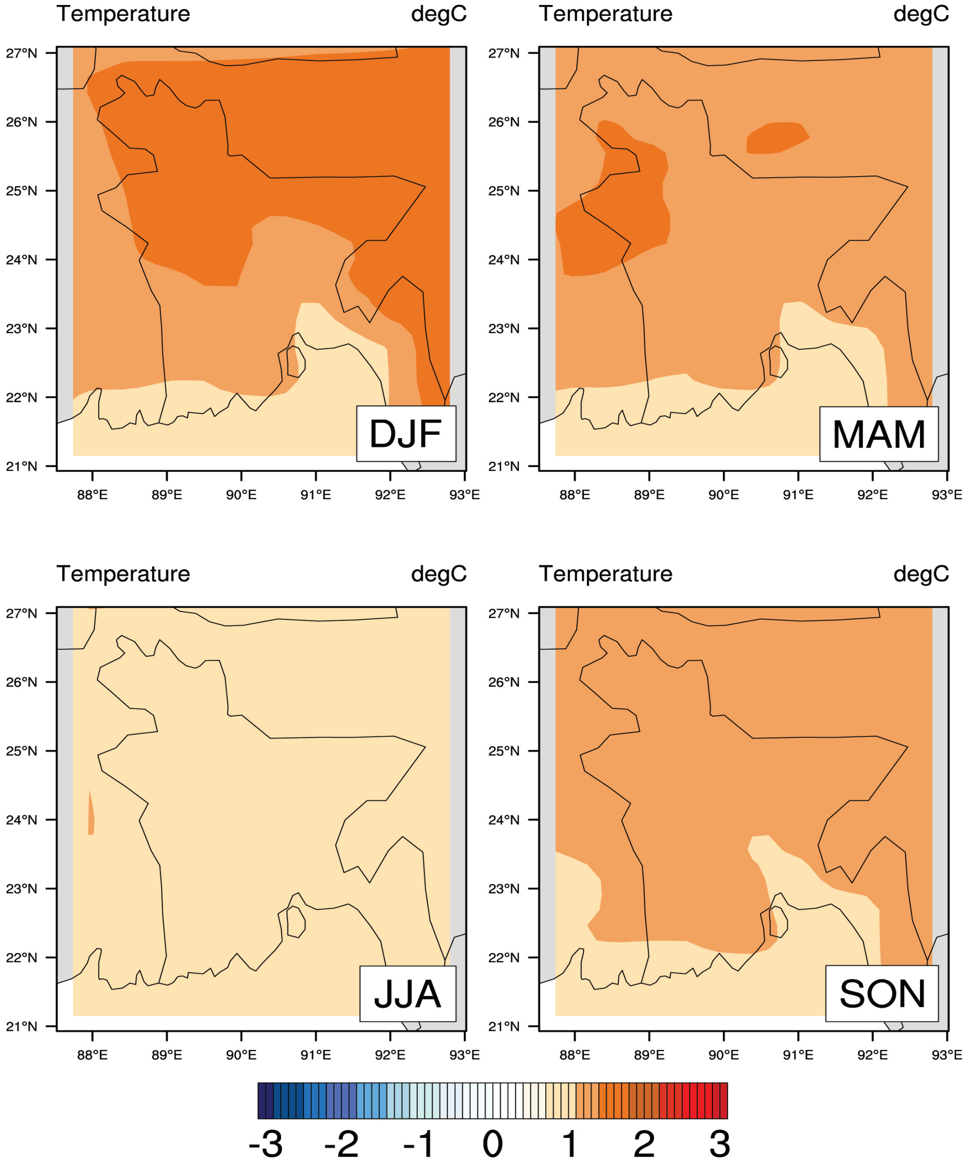

Figure 3.15. Seasonal Average Surface Air Temperature projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Bangladesh.

tion than the past 30-years period. The precipitation change exhibits a distinct north and south gradient in Figure 3.16.

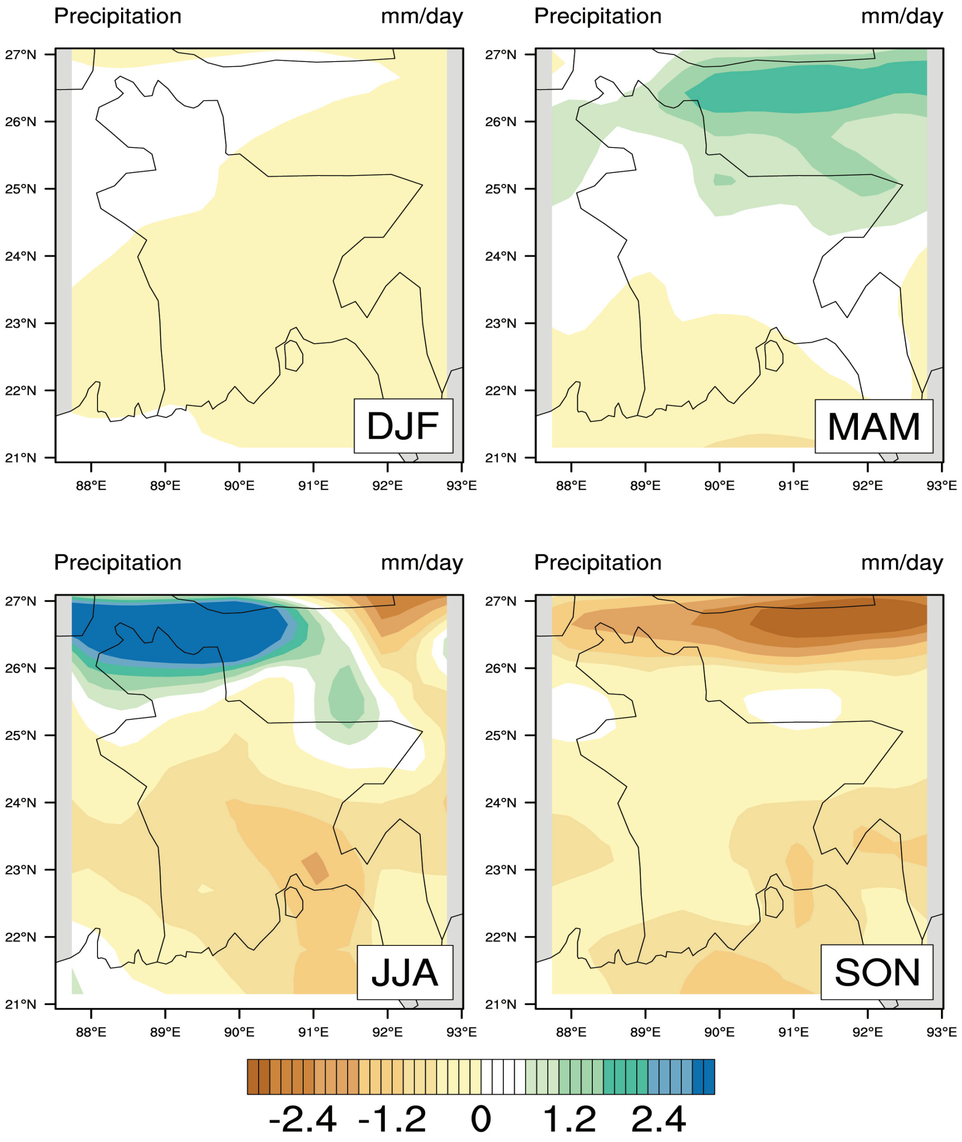

Figure 3.16. Seasonal Average Precipitation projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Bangladesh.

3.2.3.2. Projection of Monthly Changes. In this section, we examined monthly changes for the period 1970-2000 with respect to the period 2020-2050.

Changes in Temperature

Figure 3.17 shows that the surface air temperature will increase more than 1 °C, particularly in November and December. Because of the high temperature over the domain, 1 °C increasing will affect the domain substantially, and the monsoon rainfall will be more intensely.

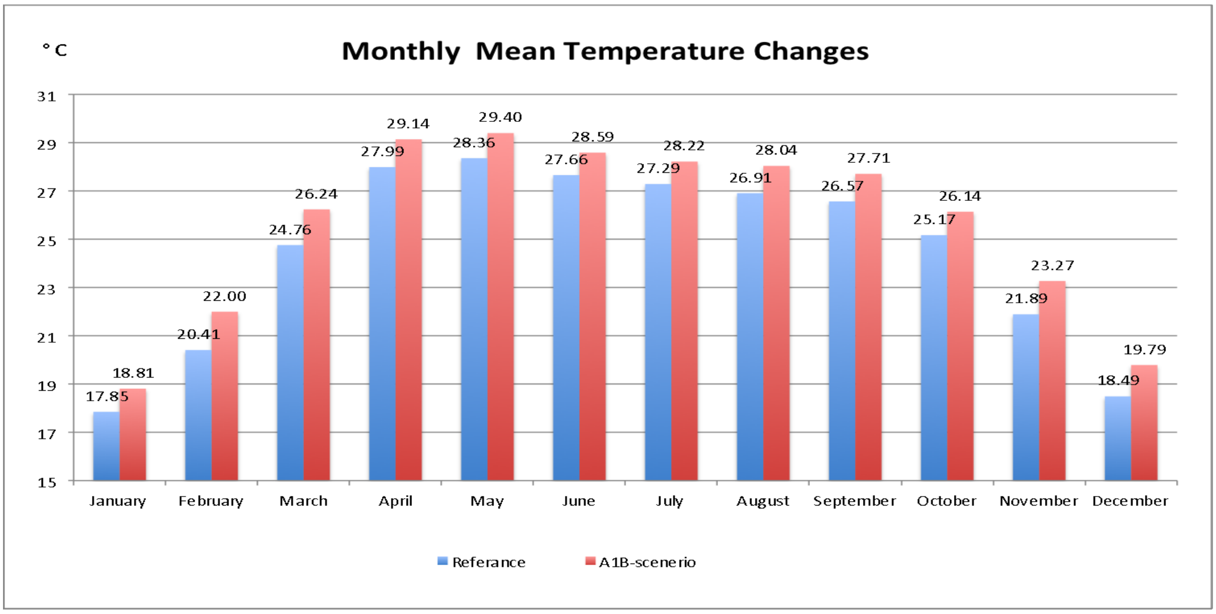

Figure 3.17. Monthly Average Surface Air Temperature projection from RegCM by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Bangladesh.

Changes in Precipitation

The projection of mean precipitation is illustrated in Figure 3.18. The pre-monsoon and monsoon seasons will be wetter during the period 2020-2050. After the monsoon seasons, the precipitation will reduce notably.

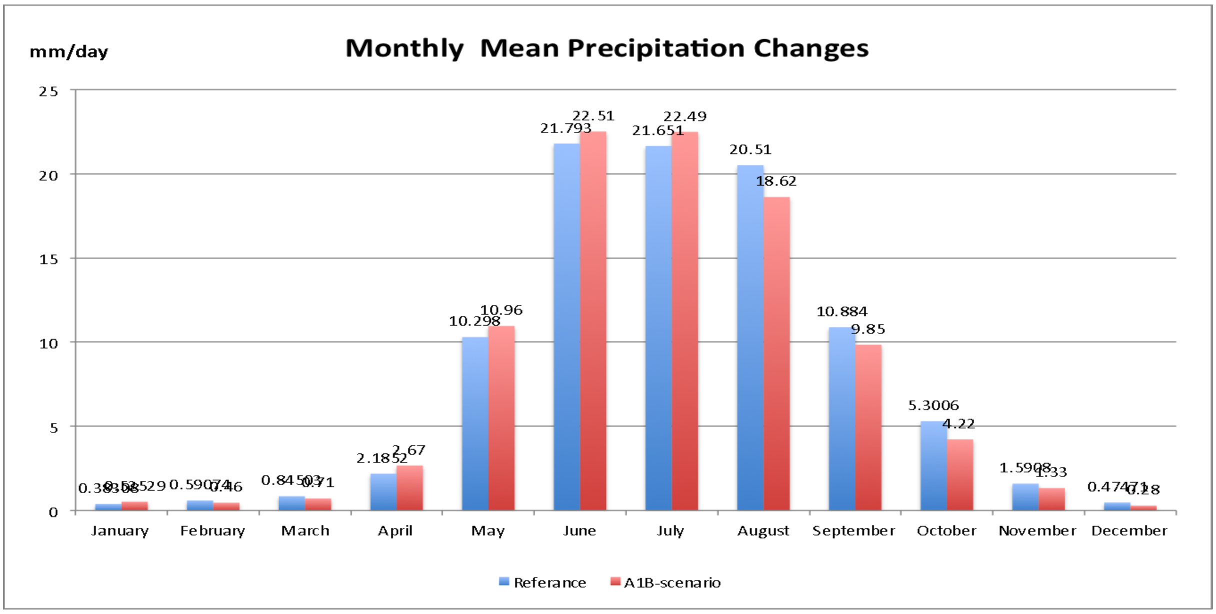

Figure 3.18. Monthly Average Precipitation projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Bangladesh.

<u>3.2.3.3. Interannual Variability and Trend in a Regional Climate .</u> In this section, we examined interannual change trends for the future.

Trends inTemperature

In Figure 3.19, the trend of annual mean surface air temperature is displayed. The increment of the surface air temperature is apparent, and in 2031 and 2043, the warming will be over 1 °C over the region.

Trends in Precipitation

The trend of the annual cycle of the mean precipitation is not changing importantly, however some of the years will be experiencing maximum differences, such as from 2044 to 2045, the level of the precipitation will increase to 2mm/day versus from 2022 to 2023,

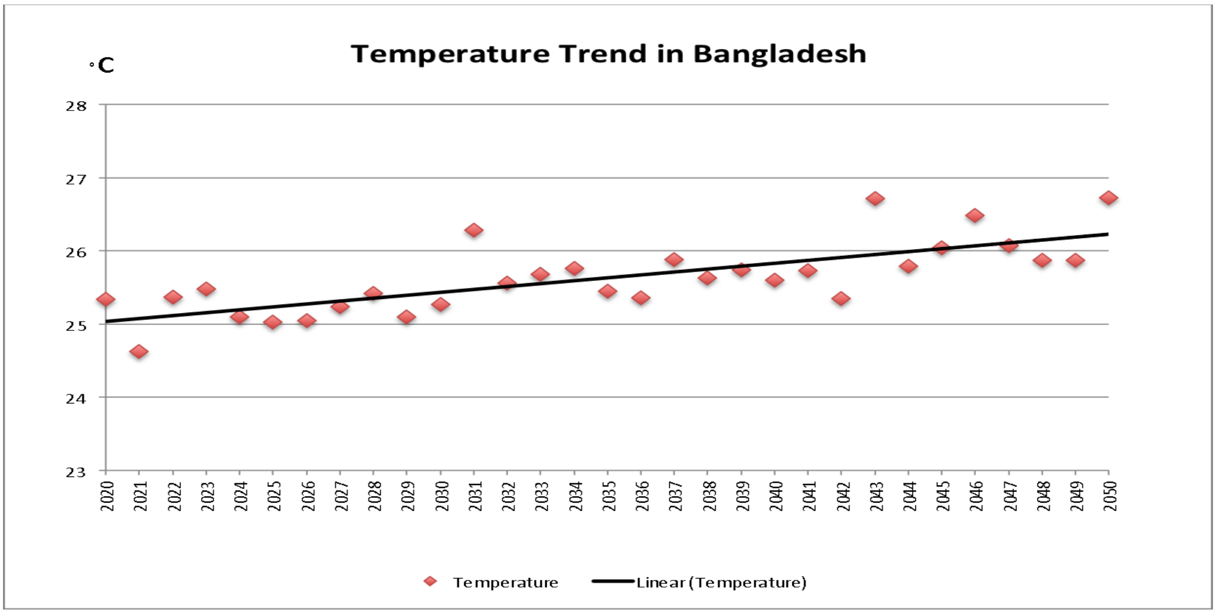

Figure 3.19. Inter-annual mean surface air temperature variable and its trend in the model using RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data as the input for the period 2020-2050 for Bangladesh.

this level will decrease 3 mm/day. These peaks will result from global warming over the region.

3.3. Netherlands

3.3.1. Seasonal Climate Analysis

Atlantic Ocean has an impact on weather condition, therefore Netherlands has maritime climate due to the nearness of North Atlantic Ocean. Summers are warm and winters are quite cold. Excessive hot weather is experienced rarely. Rain always falls throughout the year. The minimum average temperature is 2 °C in January, and the maximum mean temperature is 19 °C in July. The average yearly total precipitation is 750 mm, which is a lot.

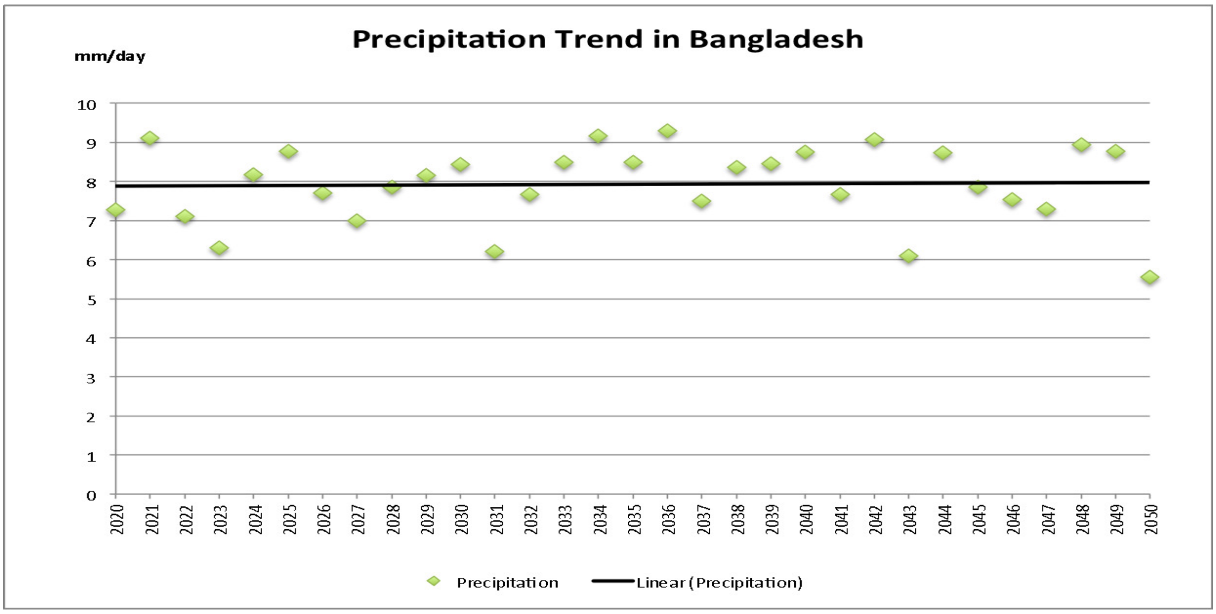

Figure 3.20. Inter-annual mean precipitation variable and its trend in the model using RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data as the input for the period 2020-2050 for Bangladesh.

Netherlands was run with RegCM 4.3.5.5, using Grell Scheme for cumulus convection and Fritsh & Chappell Scheme for cumulus closure,and Rotated Mercator (ROTMER) for cartographic projection.

3.3.1.1. Average Surface Air Temperature. The surface air temperature found in the simulation exhibits qualitatively consistent results with CRU data (Figure 3.21). The region has negative bias up to 1 °C is observed in MAM and JJA which are warm weather season. Conversely, positive bias up to 1 °C is seen in DJF and SON, which is cold weather season. These signify that the regional climate model has different influences during different seasons.

3.3.1.2. Average Precipitation . In Figure 3.22, some noticeable bias around 5 mm/day between simulation data and Station data CRU occurs in JJA over the domain. This

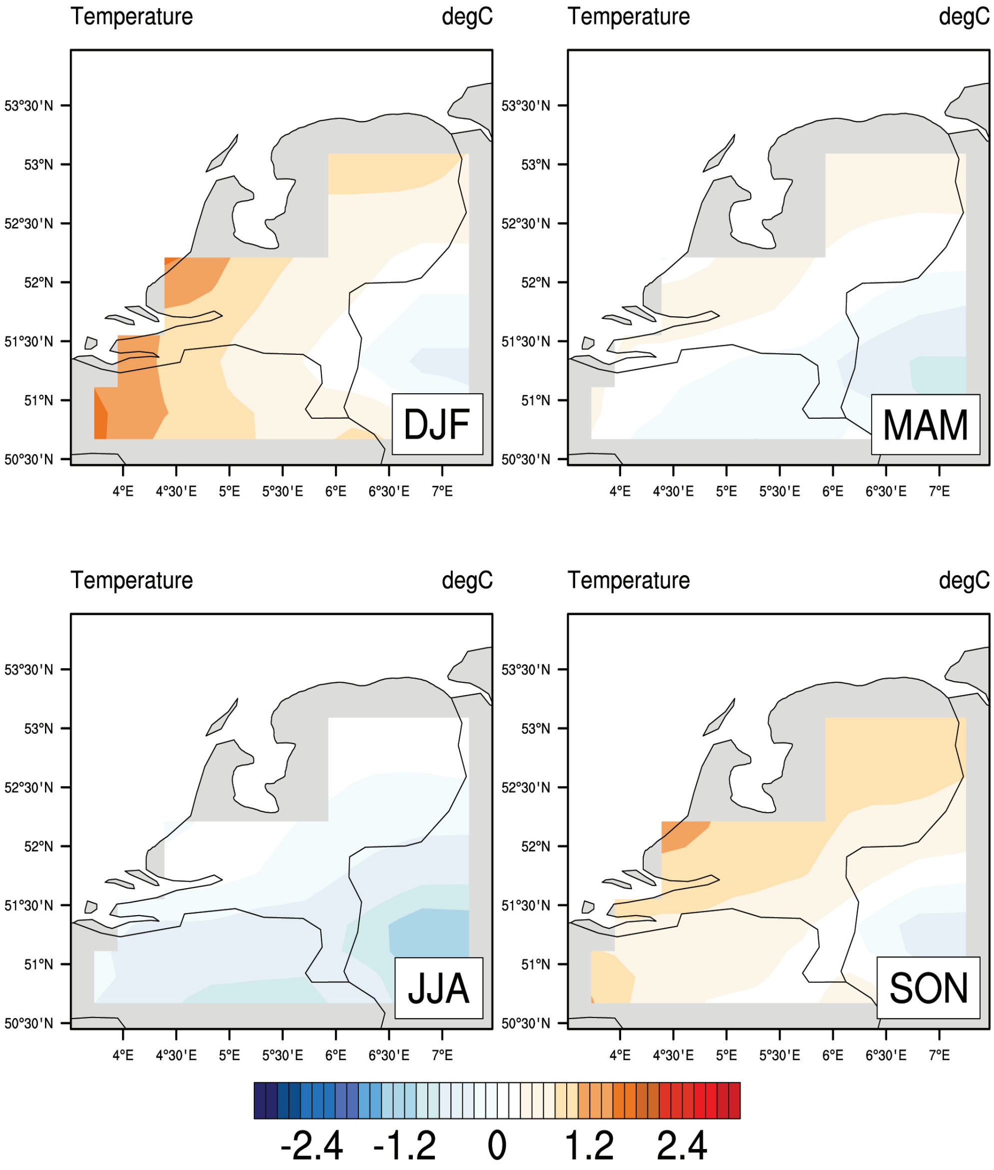

Figure 3.21. Bias of the Seasonal Mean Surface Air Temperature over Netherlands.

bias is evidently due to the effects of Atlantic Ocean coastline forcing as well as the model description of physical process. Small precipitation bias is found in the south of the domain during the months September, October, and November.

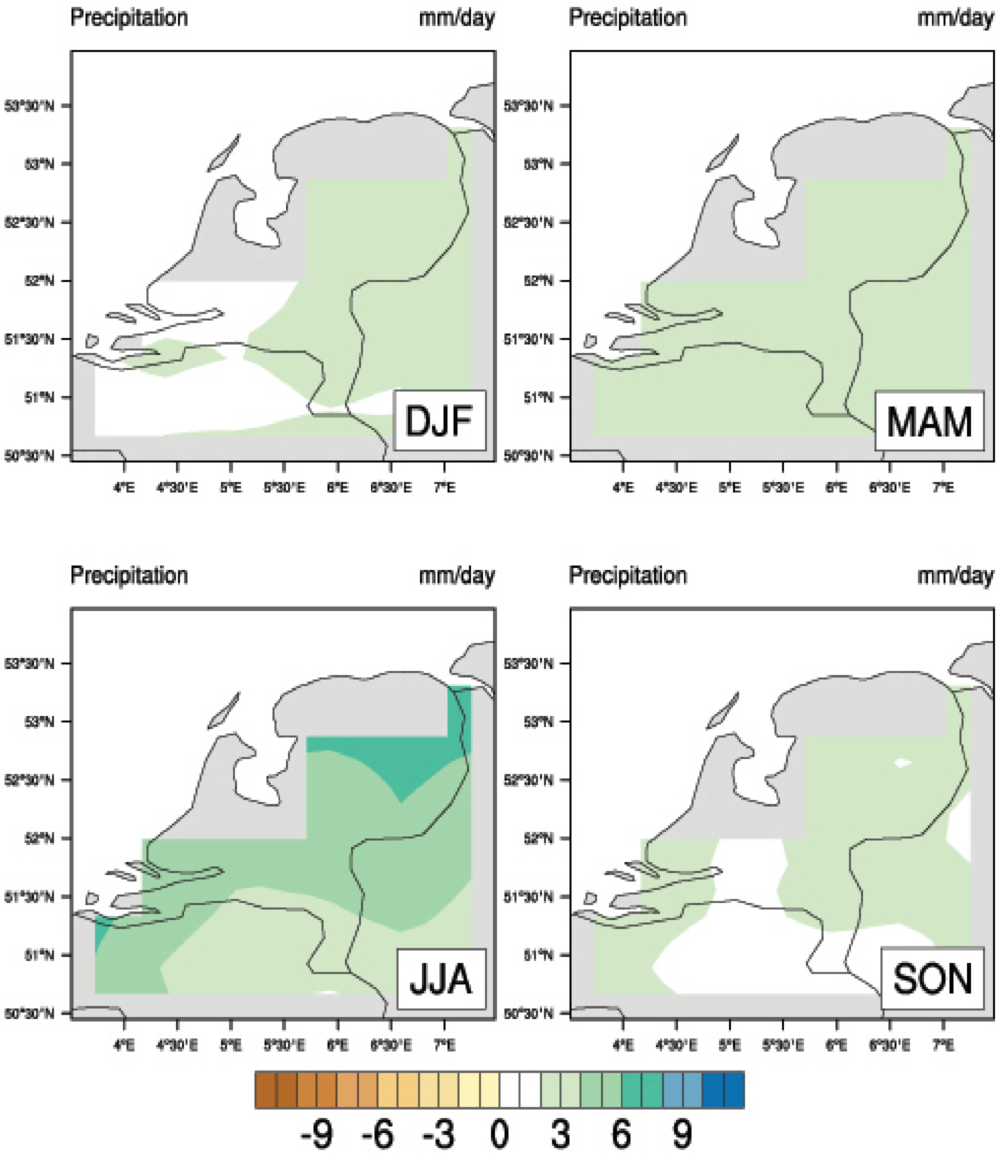

Figure 3.22. Bias of the Seasonal Mean Precipitation over Netherlands.

3.3.2. Monthly Climate Analysis

3.3.2.1. Mean Surface Air Temperature . Both data shows that the surface air temperature bias is generally close to each other during all months (Figure 3.23. Most sensitivity experiments underestimate temperature from March to July, which actually shows a good agreement with observations data, but a significant underestimate in August for the summer season, and December, and January for the winter season. They are the warmest and the coolest months at the same time, respectively.

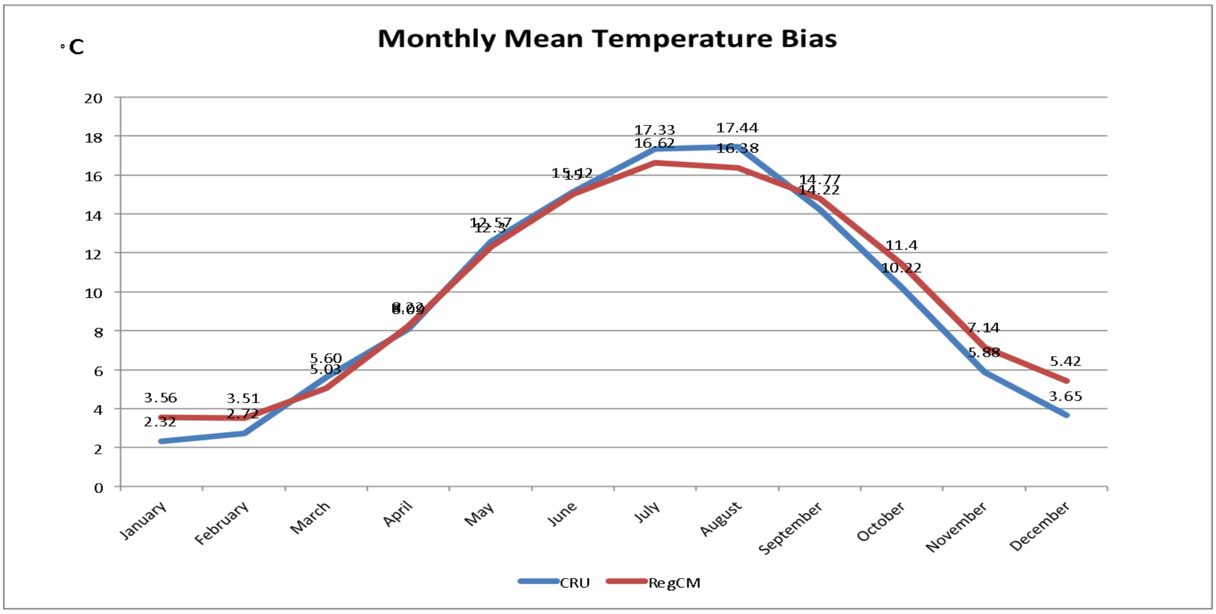

Figure 3.23. Monthly Mean Surface Air Temperature data which is simulated by ECHAM5 using RegCM 4.3.5.5 that is compared with observations CRU dataset for the period 1970-2000 for Netherlands.

3.3.2.2. Mean Precipitation . In Figure 3.24, crucial discrepancy was found in the scenario simulation with the station data over the region, most noticeably in October. In the cold months, December, January, and February, it is seen relatively lower bias rather than other months. It can be said that the wettest month is July and the driest month is January according to the Figure 3.24.

3.3.3. Projection of Climatology for the Future

3.3.3.1. Projection of Seasonal Changes. In this section, we examined seasonal changes for the period 1970-2000 with respect to the period 2020-2050.

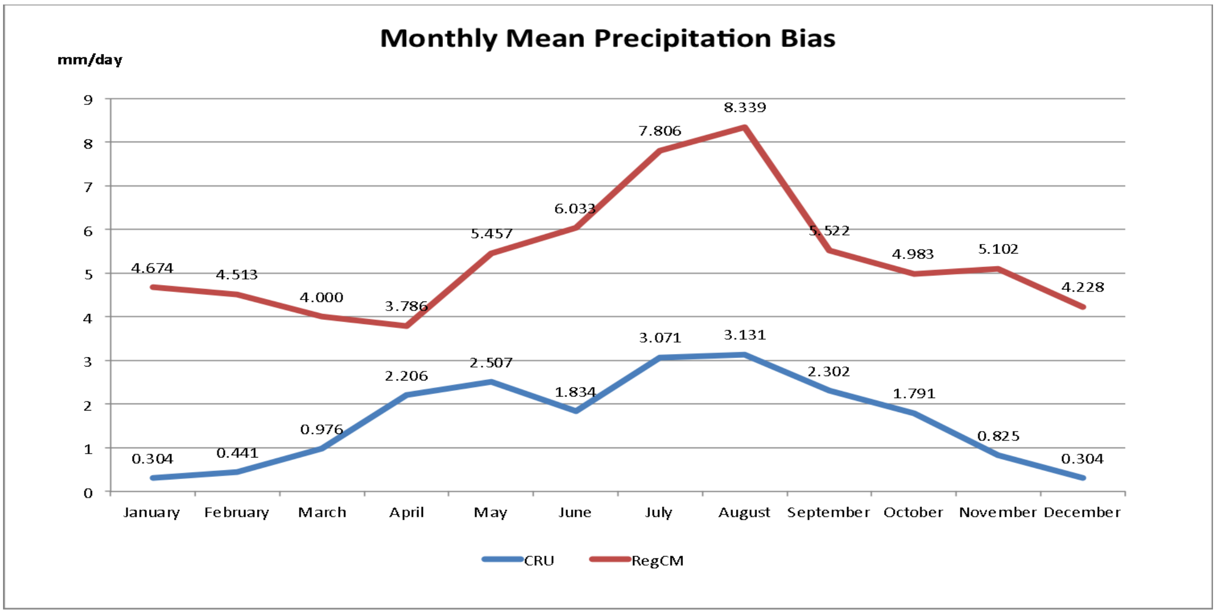

Figure 3.24. Monthly Mean Precipitation data which is simulated by ECHAM5 using RegCM 4.3.5.5 that is compared with observations CRU dataset for the period 1970-2000 for Netherlands.

Difference in Temperature

The warming is dominantly positive in all season over the area (Figure 3.25).The range of the raise is between $0.5 - 1\,^{\circ}$C. It means that this region will be affected by greenhouse gases much less due to the awareness, related to development of the country, of global warming.

Difference in Precipitation

According to projection data shown in Figure 3.26, there will be no changes in DJF and SON, but 1 mm/day decreases are observed in MAM, and JJA which are warm seasons in the interest area. It is thought that warm season will have less precipitation with respect to past 30-years period. The blocking-type summer anticyclonic structure deflects the Atlantic storm track northward and causes a widespread reduction of precipitation over

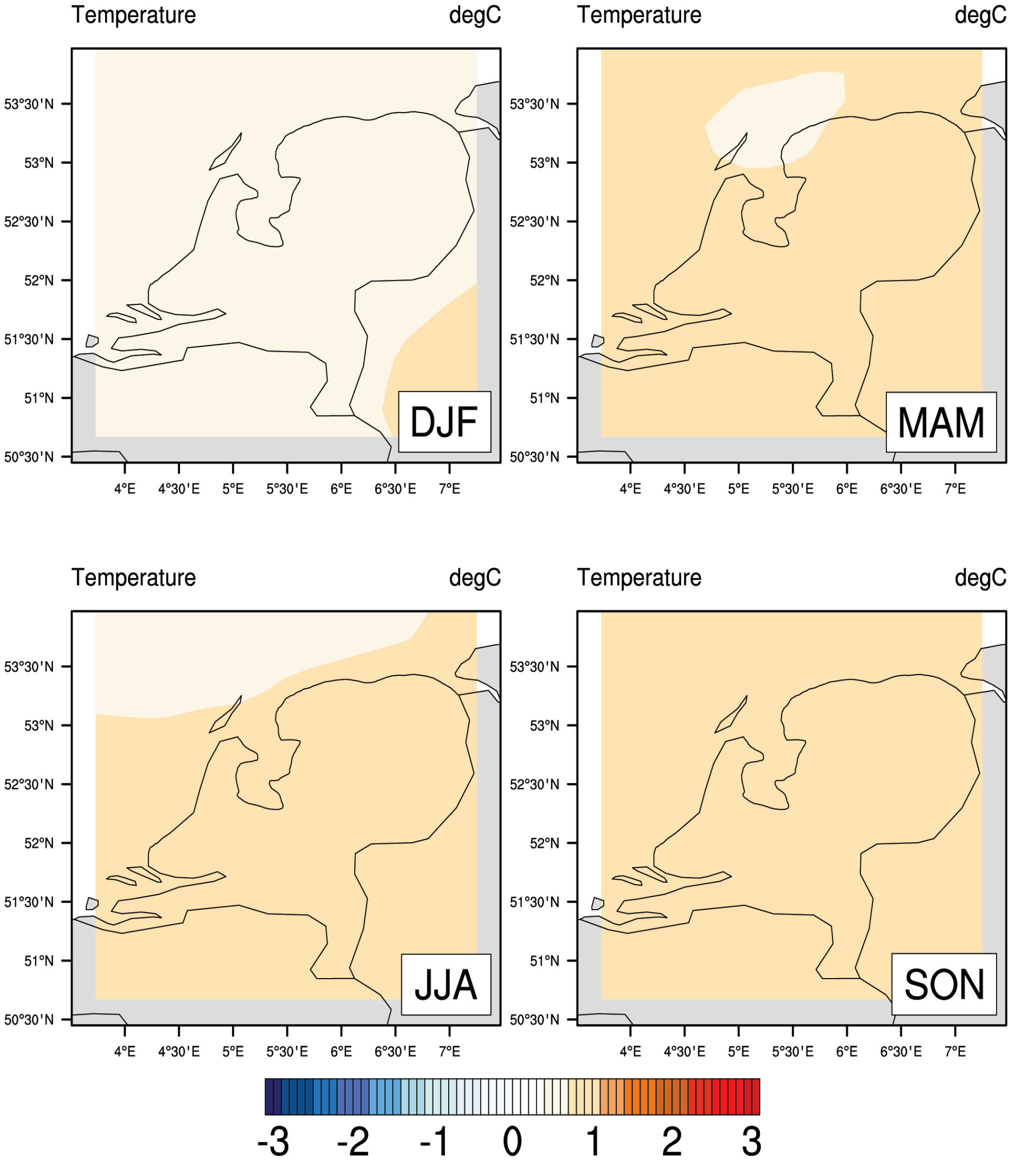

Figure 3.25. Seasonal Average Surface Air Temperature projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Netherlands.

the western part of the domain. [48]

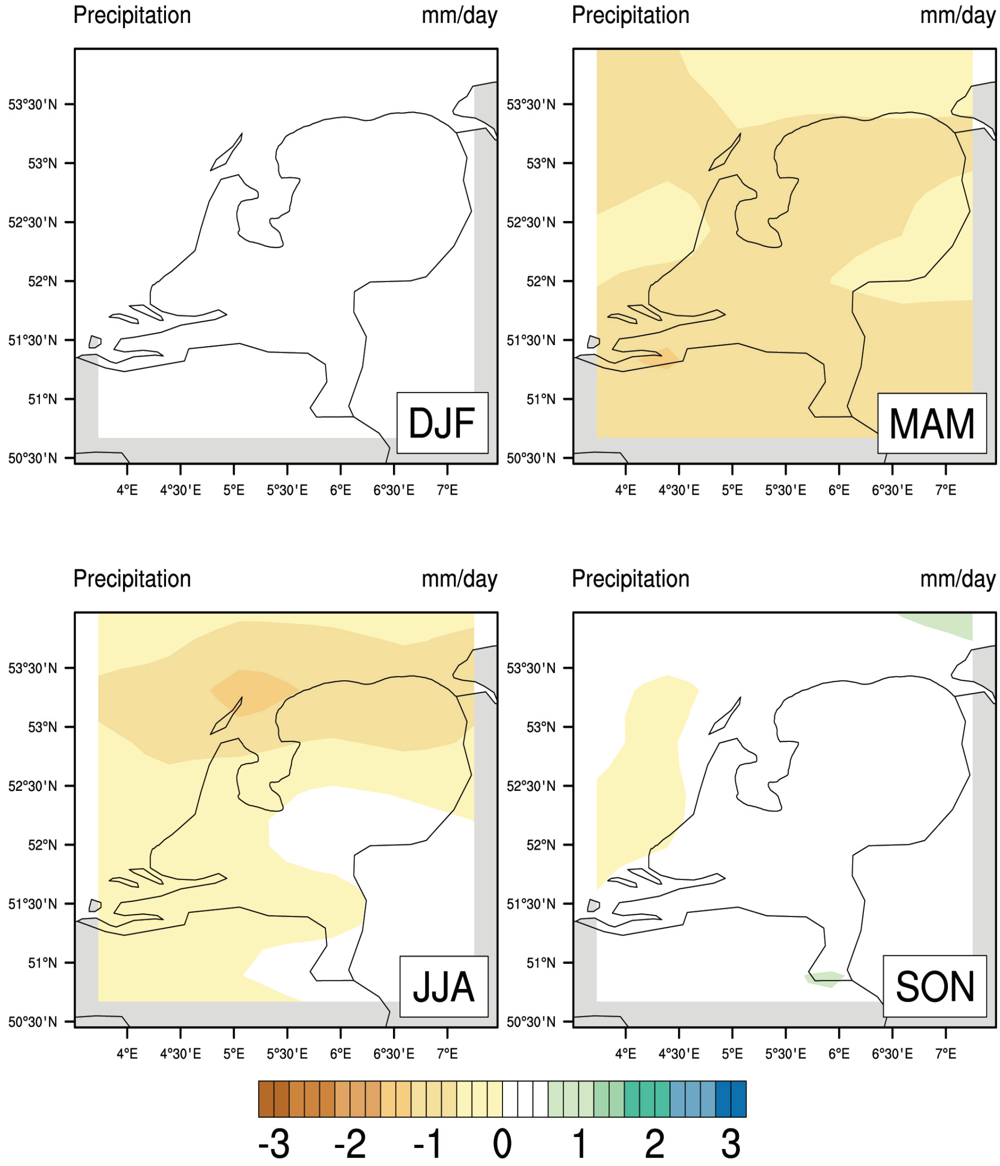

Figure 3.26. Seasonal Average Precipitation projection from RegCM 4.3.5.5 by forcing ECHAM5-A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Netherlands.

3.3.3.2. Projection of Monthly Changes. In this section, we examined monthly changes for the period 1970-2000 with respect to the period 2020-2050.

Changes in Temperature

The bias of the surface air temperature between CRU and simulation model for the period 1970-2000 shows that they overlap (Figure 3.27). Therefore, it is considered that the surface air temperature is warming up to 1 °C almost in all months over the domain

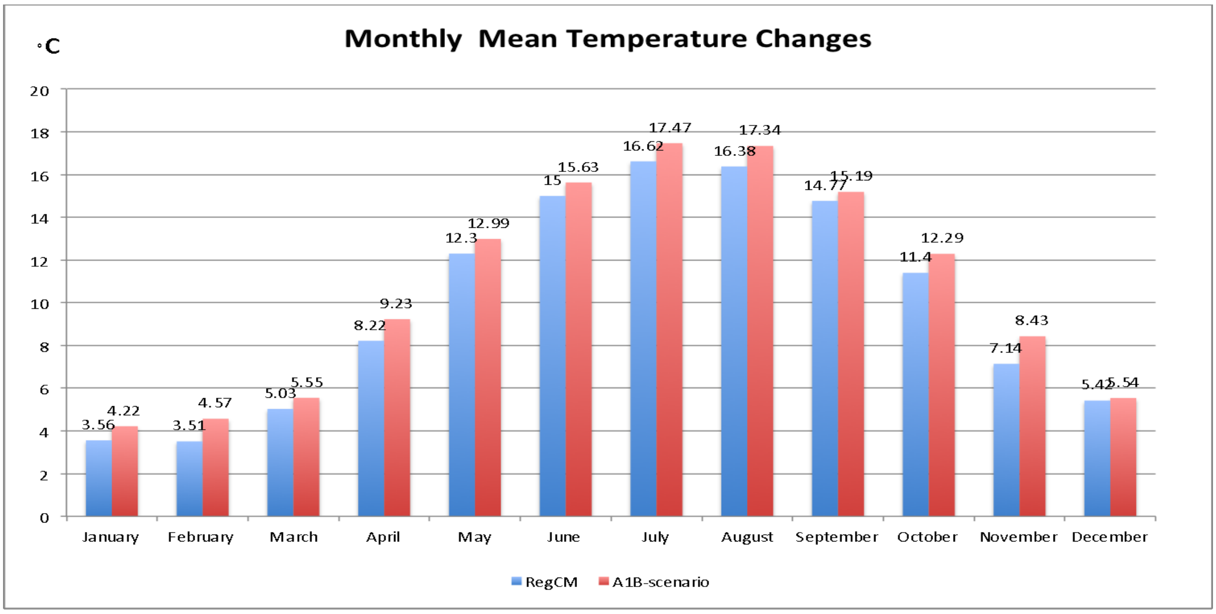

Figure 3.27. Monthly Average Surface Air Temperature projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Netherlands.

Changes in Precipitation

In Figure 3.28, the average precipitation will decrease from March to August. In the cold season will receive more rainfall. The most important changes will be observed in September. Figure 3.28 shows a strong contrast in projected precipitation changes, with large decreases in the summers, and large increases in winters.

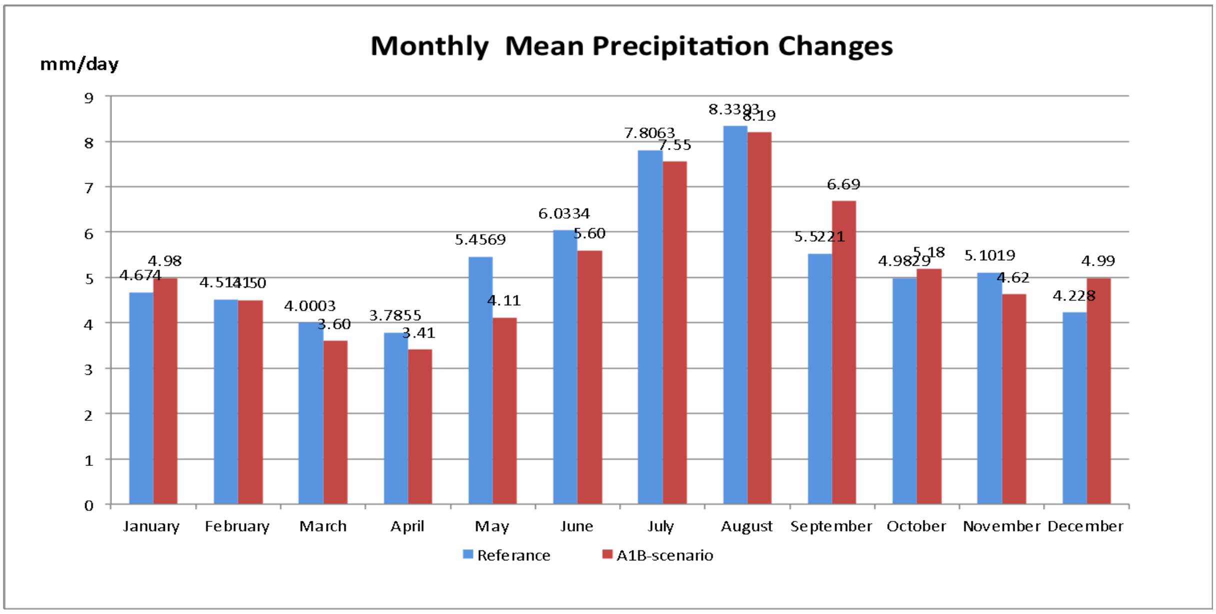

Figure 3.28. Monthly Average Precipitation projection from RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data for the period 2020-2050, with respect to reference simulation model ECHAM5 for the period 1970-2000 in Netherlands.

3.3.3.3. Interannual Variability and Trend in a Regional Climate . In this section, we examined interannual change trends for the future.

Trends in Temperature

The annual cycle of the mean surface air temperature is displayed in Figure 3.29. Trend of annual cycle is going up till 2050. The mean surface air temperature is significantly raise in the 30-years period. Particularly, the range of the difference will be more than 2 °C between 2021-2022, 2036-2038, and 2047-2048.

Trends in Precipitation:

Annual cycles of the mean precipitation over the domain are shown in Figure 3.30. The annual precipitation will increase at a very few level. In 2029, 2037, 2045 and 2047, the

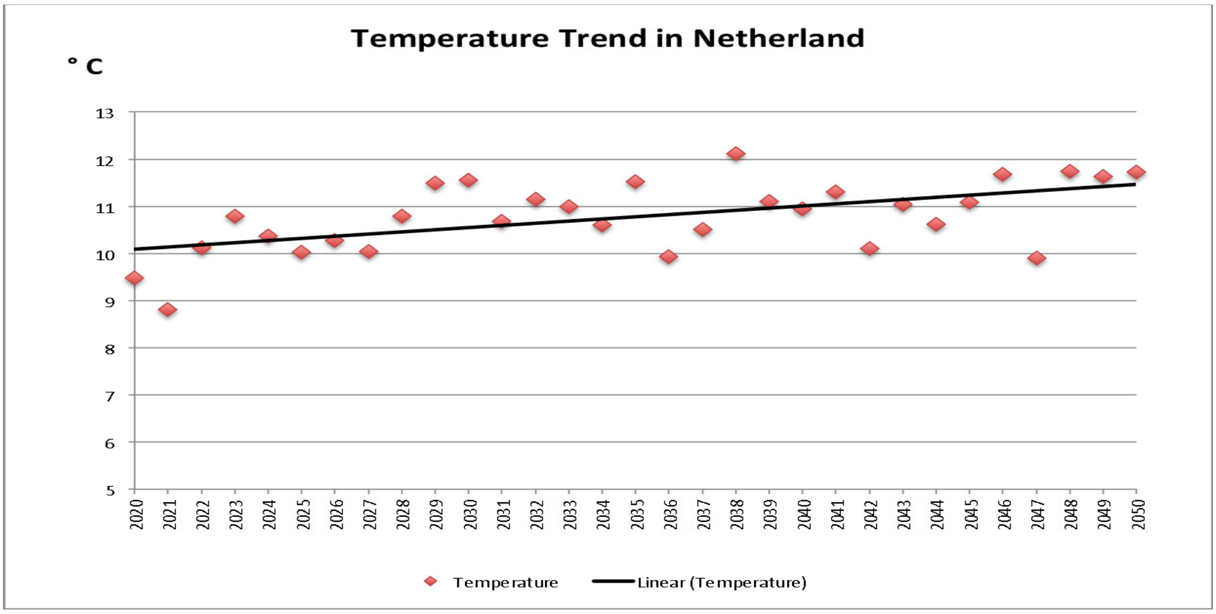

Figure 3.29. Inter-annual mean surface air temperature variable and its trend in the model using RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data as the input for the period 2020-2050 for Netherlands.

mean precipitation is overestimated, and in 2032 and 2040, this value is underestimated.

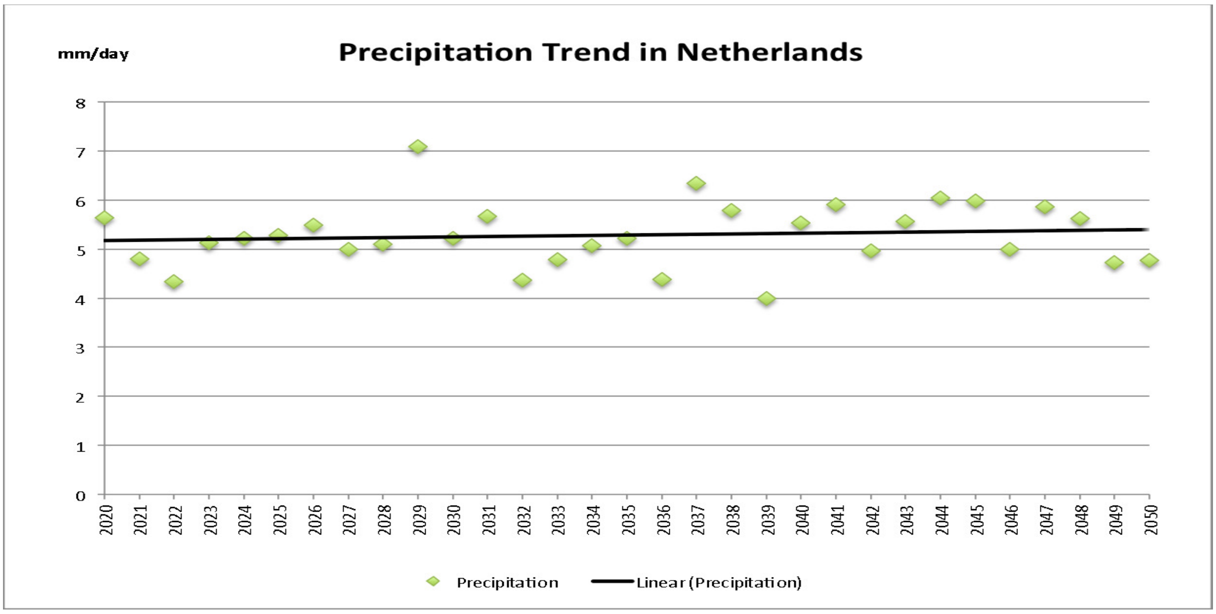

Figure 3.30. Inter-annual mean precipitation variable and its trend in the model using RegCM 4.3.5.5 by forcing ECHAM5 A1B scenario data as the input for the period 2020-2050 for Netherlands.

4. CONCLUSION

We have examined the comparison between the output simulated data using RegCM 4.3.5.5 by forcing ECHAM5 and observations CRU dataset for the period $1970 - 2000$ over vulnerable regions. Bias in mean precipitation is very high, that mean precipitation in simulated data is more than observation dataset in all regions. However bias in mean precipitation is very high, in monthly mean precipitation peaks occur at the same months. We have comprehended that natural climatic events and geographical locations is very important in this model. Unlike mean precipitation, mean surface air temperature is very similar in simulated data with observation CRU dataset. We can say that mean surface air temperature analysis is very accurate in all domains.

We have shown seasonal outcomes for the period $2020 - 2050$ from future simulation and backtesting simulation of the regional climate model in terms of mean precipitation and surface air temperature. Changes in mean precipitation and surface air temperature differs from domain to domain because of the their topographical features, geographical locations, and climatic properties.

Even though it is not very proper to make rigorous generalizations in climate projection, the future projection figures show that all simulated regions will lose precipitation more or less, except Ethiopia of interest region in the fall. The difference of mean surface air temperature in our regions of interest are illustrated in Figures 3.25, 3.28 and 3.27, which show the warming for A1B RegCM simulations compared to the past period simulation of the regional climate model.

Following the global warming due to the increased greenhouse gases concentration, in all regions outstanding warming at least $1\,^{\circ}\mathrm{C}$ in each seasons occurs throughout the selected region. The lowest increase will seen in Netherlands. On the other side, the regions, Ethiopia and Bangladesh, having monsoon climate will display warmer seasons at the range of $1 - 2\,^{\circ}\mathrm{C}$.

Trends in average precipitation produced by RegCM 4.3.5.5 is increasing in low intensity in all domains. Even though both Ethiopia and Bangladesh are in the tropics, the more precipitation anomalies and magnitude in precipitation have been found during the 30-years period. Trends in average surface air temperature produced by RegCM 4.3.5.5 is increasing gradually year by year in all regions.

APPENDIX A: CODES THAT WERE USED IN THE THESIS

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kz = 18,
nsg = 1,
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ptop = 5.0,
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clon = 90.23,
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iband = 0,
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lakedpth = .false.,
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fudge lnd s = .false.,
fudge tex = .false.,
fudge tex s = .false.,
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inpter = '/DATA', (ECHAM5)
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&boundaryparam
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atmfrq = 6.,

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radfrq = 6.,

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&physicsparam

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lakemod = 0,

ichem = 0,

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idcsst = 0,

iseaice = 0,
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iconvlwp = 1,
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&emanparam
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coeffr = 1.0D0,
&clmparam
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imask = 1,
clmfrq = 12.,
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REFERENCES

1. Houghton J., *Global Warming: The Complete Briefing*, Cambridge University Press., Cambridge, 2004.
2. Jacobson, M.Z., *Fundamentals of Atmospheric Modeling*, Cambridge University Press., Cambridge, 2005.
3. Taylor F.W., *Elementary Climate Physics*, Oxford University Press., Oxford, 2006.
4. Goosse, H., P.Y. Barriat, W. Lefebvre, M.F. Loutre, and V. Zunz, *Introduction to Climate Dynamics and Climate Modeling.*, 2011.
5. Holton, J.R., *An Introduction to Dynamic Meteorology*, Elsevier Academic Press., Massachusetts, 2004.
6. IPCC Fourth Assessment Report: Climate Change 2007 *Synthesis Report*, 2011.
7. *Climate Change*, Education Center Arctic Climatology and Meteorology, 2001.
8. Thornthwaite C.W., "An Approach Toward a Rational Classification of Climate", *Geographical Review*, 1948.
9. Shrivastava, A.K., *Global Warming*, 2007.
10. Kelly M., "The Causes of Climatic Change", Climatic Research Unit, Information sheets, 2000.
11. Missouri Department of Natural Resources, "Global Climate Change: Effect of the Earth's Orbit", 2011, `http://www.dnr.mo.gov/energy/cc/cc7.htm`, accessed at May

2013.

12. *Milankovitch Cycle*, 2010, `http://www.indiana.edu/ geol105/images/gaia/chapter4/milankovitch.htm`, accessed at May 2013.

13. *Ozone Destruction*, 2011, `http://www.theozonehole.com/cfc.htm`, May 2013.

14. Charney, J.G., "On a Physical Basis for Numerical Prediction of Large-Scale Motions in the Atmosphere" *Journal of Meteorology*, 1949.

15. Smagorinsky, J.,"General Circulation Experiments with the Primitive Equations" *Montly Weather Review.*, Vol. 91, pp. 99-164 , 1963.

16. Gramelsberger, G.,"Conceiving Meteorology as the Exact Science of the Atmosphere: Vilhelm Bjerknes's Paper of 1904 as a Milestone" *Meteorologische Zeitschrift*, Vol.18, No.6 , pp. 669-673, 2009.

17. Richardson, L.F., *Weather Prediction by Numerical Process*, Cambridge University Press., Cambridge, 2007.

18. Lynch, P.,"The Origins of Computer Weather Prediction and Climate Modeling" *Journal of Computational Physics*, Vol. 227, pp. 3431-3444, 2007.

19. Charney, J.G., Numerical Prediction of Cyclogenesis *Geophysics*, Vol. 40, pp. 99-110, 1954.

20. Charney, J.G., "The Use of the Primitive Equations of Motion in Numerical Prediction", *Tellus*, Vol. 7, pp. 22-26, 1955.

21. Jule G., *Charney Papers* MC 184, Box X. Massachusetts Institute of Technology, Institute Archives and Special Collections, Cambridge, Massachusetts, 2009.

22. Pearce, R.P.,“Meteorology at the Millennium” *International Geophysics Series*, Vol.83, Academic Press., 2002.

23. Lewis, J.M., “Clarifying the Dynamics of the General Circulation: Phillips’s 1956 Experiment” *Bulletin of the American Meteorological Society*, Vol. 79, No.1, pp. 39-60 , 1998.

24. Phillips, A.N.,“On the Problem of Initial Data for the Primitive Equations” *Tellus* , Vol.12, pp. 121-126, 1960.

25. Manabe, S., J. Smagorinsky, and R.F. Strickler, “Simulated Climatology of a General Circulation Model with a Hydrologic Cycle”, *Montly Weather Review*, Vol. 93, pp. 769-798 ,1965.

26. Randall, D.A., “General Circulation Model Development: Past, Present, and Future”, *International Geophysics Series*, Vol.70 , Academic Press., 2000.

27. Climate Models, March, 2012, `http://www.mpimet.mpg.de/en/science/models/echam.html`, accessed at April 2013.

28. Roeckner E., “The atmospheric general circulation model ECHAM- 4: model description and simulation of present-day climate”, *Max-Planck-Institute for Meteorology Rep.*, Vol. 218 , Hamburg, Germany,1996.

29. Buting, E.L.,“GCM vs. RegCM: A Case Study of the Southeastern U.S” *Climate Change Seminar*, 2009.

30. Giorgi, F., “Introduction to the TAC Special Issue: The RegCNET Network”, *Theor. Appl. Climato*, Vol. 86, pp. 1-4, 2006.

31. Dickinson, R.E., “A Regional Climate Model for the Western United States”, *Climatic Change*, Vol.15, pp. 383-422, 1989.

32. Giorgi, F., M.R. Marinucci, and G.T. Bates, “Development of a Second Generation Regional Climate Model (RegCM2). Part I: Boundary-Layer and Radiative Transfer Processes”, *Montly Weather Review*, Vol. 121, pp. 2794 – 2813, 1993a.

33. Giorgi, F., M.R. Marinucci, G.T. Bates, and G. De Canio,“Development of a Second Generation Regional Climate Model (RegCM2). Part II: Convective Processes and Assimilation of Lateral Boundary Conditions”, *Montly Weather Review*, Vol. 1, 1993b.

34. Giorgi, F., and L.O. Mearns, “Regional Climate Modeling Revisited”, *An Introduction to the Special Issue*, Vol. 1, 1998.

35. Kiehl, J.T., “The National Center for Atmospheric Research Community Climate Model:CCM3”, *Journal of Climate* Vol. 11, pp. 1131 – 1149, 1998.

36. Elguindi, N. and F. Giorgi, “Simulating Multi-Decadal Variability of Caspian Sea Level Changes Using Regional Climate Model Outputs”, *Climate Dynamics*, Vol. 26, pp. 167 – 181, 2006.

37. Francisco, R.V., “Regional Model Simulation of Summer Rainfall over the Philippines: Effect of Choice of Driving Fields and Ocean Flux Schemes”, *Theor. Appl. Climatol.*, Vol. 86, pp. 215 – 227, 2006.

38. Giorgi, F., “Regional Climatic Model RegCM User Manual Version 4.1”, *The Abdus Salam International Centre for Theoretical Physics, Earth System Physics Section.*, 2011.

39. Purser, R. J. and L. M. Leslie,“A Semi-Implicit, Semi-Lagrangian Finite Difference

Scheme Using High-Order Spatial Differencing on a Non-staggered Grid", *Montly Weather Review*, Vol. 116, pp. 2069-2080, 1998.

40. Collins, W. D., "The Community Climate System Model version 3 (CCSM3)", *Journal of Climate* Vol. 9, pp. 2122 – 2143, 2006.

41. Grell, G.A., "Prognostic Evaluation of Assumptions Used by Cumulus Parameterizations" *Montly Weather Review*, Vol. 121, pp. 764-787, 1993.

42. Dickinson, R. E., A. Henderson-Sellers, and P.J. Kennedy, "Biosphere-atmosphere transfer scheme (bats) version 1e as coupled to the ncar community climate model, Tech. rep.", *National Center for Atmospheric Research* Vol. 116, pp. 2069 – 2080, 1993.

43. Holtslag, A. A. M., E. I. F. de Bruijn, and H.-L. Pan, "A high resolution air mass transformation model for short- range weather forecasting" *Montly Weather Review*, 2012.

44. Emanuel, K. A., "A scheme for representing cumulus convection in large-scale models" *J. Atmospheric Science*, Vol. 48(21), pp. 2313 – 2335, 1991.

45. Emanuel K. A., and M. Z. Rothman, "Development and evaluation of a convection scheme for use in climate models", *J. Atmospheric Science*, Vol. 56, pp. 1766 – 1782, 1999.

46. Giorgi F., "Indirect vs. Direct Effects of Anthropogenic Sulfate on the Climate of East Asia as Simulated with a Regional Coupled Climate-Chemistry/Aerosol Model", *Climatic Change* Vol. 58, pp. 345 – 376, 2003.

47. Country Weather Profile, 2011, `http://www.weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine-in-Ethiopia`, accessed at May 2013.

48. Giorgi F.,“Mean Interannual variability and trends in a regional climate change experiment over Europe. II: climate change scenarios $(2071 - 2100)$”, *Climate Dynamics*, 2004.

49. Country Weather Profile, 2010, `http://www.weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine-in-Bangladesh`, accessed at April 2013.