IMPACT OF SULPHATE AEROSOLS ON REGIONAL CLIMATE: A REGIONAL CLIMATE MODEL STUDY OVER SOUTH ASIA FOCUSING PAKISTAN

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Submitted in partial fulfillment of the requirements for the MS degree in discipline of **Environmental Science** With specialization in **climate change science** at the faculty of **Basic and Applied sciences,** International Islamic University, Islamabad.

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Month, Year
December, 2010

Dedicated to My lovely Parents,
Sisters and Brothers

DECLARATION

I hereby declare that the work presented in the following thesis is my own effort, expect where otherwise acknowledge, and thesis is my own composition. No part of the thesis has been previously presented for any other degree.

Tahira Munir

FORWARDING SHEET

The thesis entitled **IMPACT OF SULPHATE AEROSOLS ON REGIONAL CLIMATE: A REGIONAL CLIMATE MODEL STUDY OVER SOUTH ASIA FOCUSING PAKISTAN** submitted by **Tahira Munir** in partial fulfillment of MS degree in discipline of **Environmental Science** with specialization in **Climate Change Science** has been completed under my guidance and supervision. I am satisfied with the quality of student's research work and allow her to submit this thesis for further process as per IIUI rules and regulations.

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TABLE OF CONTENTS

CHAPTER 1 .... **1**

INTRODUCTION 1

1.1 Background 1

1.1.1 Description of Scenarios 3

1.1.2 Climate Model 7

1.1.3 Climate Modeling 8

1.1.4 Global Climate Model (GCM) 8

1.1.5 Regional Climate Model (RCM) 10

1.1.6 Atmospheric Aerosols 11

1.1.7 Sulphate Aerosols 12

1.2 Objectives of the research 15

1.3 Significance of Research 16

CHAPTER 2 .... **18**

LITERATURE REVIEW 18

CHAPTER 3 .... **31**

MATERIALS AND METHODS 31

3.1 General 31

3.2 Study Area 32

3.2.1 General Profile of Study Area 32

3.3 Climatic Regions of Pakistan 34

3.4 Model Description and Data 35

3.4.1 Description of the PRECIS 35

3.4.2 Data sets used with PRECIS 37

3.5 Experimental Design 38

3.5.1 The SRES A2-emission scenario 39

3.5.2 The Sulphur Cycle Scheme in PRECIS 40

3.6 Model Domain and Configuration 41

Chapter 4 43

RESULTS AND DISCUSSION 43

4.1 General 43

4.2 Validation of Model 44

4.2.1 Validation of Downscaled HadAM3P-PRECIS Data 44

4.3 Base Period (1961-70) climatology 51

4.3.1 Baseline Climatology for Climatic Regions 55

4.4 Future Period (2071-2080) climatology 59

4. 4. 1 Future Projections for Climatic Regions 61

CHAPTER 5 68

CONCLUSIONS AND RECOMMENDATIONS 68

5.1 Conclusions 68

5.2 Recommendations 70

REFERENCES 71

LIST OF TABLES

Table 1. Overview of greenhouse gases (GHGs), ozone precursors, and and sulfur emissions for the SRES scenario groups..6

Table 2. Climatic Regions of Pakistan... 35

Table 3: RMSE and correlation for temperature and precipitation.................................. 50

Table 4. Projected temperature changes (^{o}C) over climatic regions 62

Table 5. Projected precipitation changes (%) over climatic regions 64

LIST OF FIGURES

Figure 1. Total CO2 emissions by Region 3

Figure 2. Schematic illustration of SRES scenarios 5

Figure 3. Natural processes included in Climate Model 7

Figure 4. Population in millions and Range of annual average SO2 concentration during 1880-84 in ug/m3 13

Figure 5. Estimated man-made SO2 emissions 14

Figure 6. Location Map of Pakistan 33

Figure 7. Climatic Regions of Pakistan 34

Figure 8. Model Domain (a) South Asia (b) Pakistan 41

Figure 9. Schematic Diagram showing Experimental design of Study 42

Figure 10. 10-years (1961-1970) annual mean temperature of (a) CRU data, (b) HadAM3P downscaled data (c) their differences 46

Figure 11. 10-years (1961-1970) annual mean precipitation of (a) CRU data, (b) HadAM3P downscaled data (c) their differences (%) 47

Figure 12. Annual cycle of mean temperature (^{0}C) and precipitation (mm/day) for model and CRU climatology for 1961-1970 over Pakistan 48

Figure 13. Difference (base with sulphur-base without sulphur) in base line climatology for annual, summer and winter means temperature (^{0}C) (Left Column) and precipitation (%) (Right Column) over South Asia (1961-1970) 52

Figure 14. Difference (base with sulphur-base without sulphur) in base line climatology for annual, summer and winter means temperature (^{0}C) (Left Column) and precipitation (%) (Right Column) over Pakistan (1961 - 1970) 54

Figure 15. Annual cycles of mean temperature (^{0}C) and precipitation (mm/day) for the time period 1961-1970 over Pakistan 55

Figure 16 (a). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the time period 1961-1970 over different climatic regions of Pakistan 57

Figure 16 (b). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the time period 1961-1970 over different climatic regions of Pakistan 58

Figure 17. Projected future changes (future with sulphur-future without sulphur) in mean annual, summer and winter temperature (^{0}C) (Left Column) and Precipitation (%) (Right Column) over Pakistan (2071-2080) 60

Figure 18. Annual cycles of mean temperature (^{0}C) and precipitation (mm/day) for the time period 2071-2080 over Pakistan 61

Figure 19. Sulphur Dioxide emissions in Punjab for the time period of 1990-2000 63

Figure 20 (a). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the period of 2071-2080 over different climatic region of Pakistan 66

Figure 20 (b). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the period of 2071-2080 over different climatic region of Pakistan 67

ABSTRACT

Sulphate aerosols are capable of modifying the climate not only by reflecting incoming sunlight back to the space (direct effect) but also by indirectly altering the properties of clouds. The objective of this study was to analyze the impact of sulphate aerosols on the climatology of South Asia with main focus on Pakistan. In this study, PRECIS; a Regional Climate Model developed by the Hadley centre UK was used. High resolution climate change scenarios were developed for South Asia region focusing Pakistan. Newly developed interactive sulphur cycle scheme and a new microphysics scheme of PRECIS was used to estimate the impacts of the direct and indirect effect of sulphate aerosols. The variables for study included temperature and precipitation. Two time periods were used in this study termed as Baseline (1961-1970) and Future (2071-2080) and for each time period, PRECIS is forced by the Global Climate Model data set of HadAM3P for IPCC SRES A2-emission scenario. RMSE and correlation between Model and CRU was calculated.

For South Asia, direct and indirect impact of sulphate aerosol showed no significant changes supporting the view that impact of sulphate aerosol was spatially localized and for few days. Study was further reinforced by taking the detailed analysis of Pakistan and its different climatic regions. Results showed that there was significant reduction in temperature in Northern parts (Region (I (a, b) and II) and Central and Southern Punjab (Region (III) with the inclusion of sulphur scheme in future projections. In Region (III) the sulphur dioxide emissions which resulted in sulphate aerosol formation were high due

to industrial activity and transportation when compared with other regions. In case of precipitation, after inclusion of sulphur cycle, there was prominent reduction in precipitation in almost all regions expect region I (a) for projected change with sulphur.

CHAPTER 1

CHAPTER 1

INTRODUCTION

1.1 Background

Climate change has recently become a global concern though the impacts on the Earth's climate were initiated by man during ancient times when forests were burned and cleared for agricultural production and animal husbandry. Increasing human population and desire for luxurious life style made these interferences more significant in comparison to the magnitude of natural fluctuations in global climate. According to a recent report of Intergovernmental Panel on Climate Change (IPCC) (IPCC; 2007), and scientists, anthropogenic forcing has a significant impact on global climate, biodiversity and this impact is evident. Since the start of the industrial revolution (1860), and especially over the previous half-century, modern human population impacts on climate are much more severe as compared to the past records. It is also encountered that for the first time in the history of our planet due to modern human life trends and economic growth, emissions of trace gasses from human activities equal or even exceed emissions from natural sources (Henderson and McGuffeie, 2001).

Climatic region shift, the rise in sea levels, more frequent storms, droughts and floods as well as other unprecedented environmental changes are subject due to greenhouse effect and climate change. Challenges to new societies and threat to sustainable utilization of natural resources are ahead because of climate change phenomenon. In real it has the potential to influence every sphere of life if neglected. Point of importance is that developing countries are contributing insignificantly to anthropogenic gas releases; but their inhabitants are found to be more vulnerable to calamities brought by climate change. Need of the time is to reduce risk due to environmental hazards, and in particular against extreme events such as drought and floods as vulnerable populations have limited capacity to protect themselves against such adversities (Jones *et al.* 2003).

Developing countries of the world; with 5.7 billion population contributes 54% of the world emissions; and the developed world with 1 billion populations contributes about 46% of the world emissions. Along with vulnerability to threats such as floods and droughts, developing countries are trying to extend the industrialize sector, hence, contributing more towards emissions. Since 1990, the developing countries have been growing faster than developed countries. This is true for two reasons – one, more population and two, higher economic growth.

Figure 1 provides a projection for future greenhouse gas emissions of developed and developing countries. Total emissions from the developing world are expected to exceed those from the developed world by 2015 (Anantula, 2009)

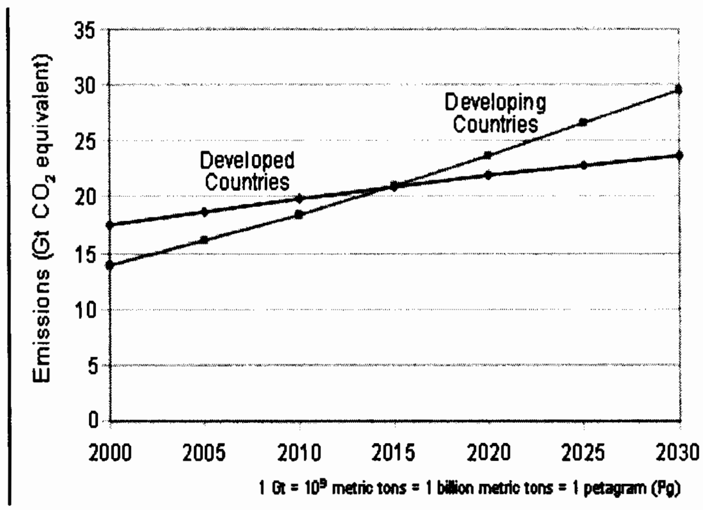


Figure 1. Total CO2 emissions by Region
(Source: http://www.epa.gov/climatechange/science/futureac.html)

1.1.1 Description of Scenarios

Emission scenarios are a central component of any assessment of climate change. Scenarios facilitate the assessment of future developments in complex systems that are either inherently unpredictable or have high scientific uncertainties, and the assessment of future emissions is an essential component of the overall assessment of global climate change by the IPCC (Nakicenovic, et al., 2000).

The IPCC decided at its September 1996 plenary session in Mexico City to develop a new set of emissions scenarios. This Special Report on Emission Scenarios (SRES) describes the new scenarios and how they were developed. The SRES scenarios cover a finite, albeit a very wide, range of future emissions. These are as follow:

The A1 storyline and scenario family describes a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological changes are more fragmented and slower than in other storylines. The B1 storyline and scenario family describes a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels (Figure 2) (Nakicenovic, et al., 2000).

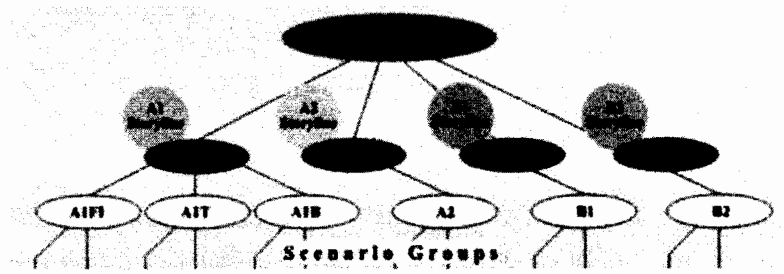


Figure 2. Schematic illustration of SRES scenarios
(Source: http://www.grida.no/climate/ipcc/emission/index.htm)

Emission estimates for radiatively important gases generated in 40 Special Report on Emission Scenarios (SRES) scenarios is exbhited in Table 1. These gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2), chloro fluoro-carbons (CFCs) and hydro chlorofluorocarbons (HCFCs), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs), and sulfur hexafluoride (SF_6). In addition, sulfur emission estimates are presented in the regional gridded format to assist in quantifying the effects at the local level (Nakicenovic, et al., 2000).

Table 1. Overview of greenhouse gases (GHGs), ozone precursors, and sulfur emissions for the SRES scenario groups

	CO_2 (GtC)	CH_4 ($MtCH_4$)	N_2O (MtN)	HFC, PFC, SF_6 (MtC equiv.)	CO (Mt CO)	NMVOCs (Mt)	NO_x (MtN)	[redacted]
A1B	13.5 (13.5-17.9)	289 (289-640)	7.0 (5.8-17.2)	324 combined	1663 (1080-2532)	193 (133-552)	40.2 (40.2-77.0)	27.6 (27.6-71.2)
A1C	(25.9-36.7)	(392-693)	(6.1-16.2)	same as in A1	(2298-3766)	(167-373)	(63.3-151.4)	(26.9-83.3)
A1G	(28.2-30.8)	(289-735)	(5.9-16.6)	same as in A1	(3260-3666)	(192-484)	(39.9-132.7)	(27.4-40.3)
A1T	(4.3-9.1)	(274-291)	(4.8-5.4)	same as in A1	(1520-2077)	(114-128)	(28.1-39.9)	(20.2-27.4)
[redacted]	29.1 (19.6-34.5)	889 (549-1069)	16.5 (8.1-19.3)	1096 combined	2325 (776-2646)	342 (169-342)	109.2 (71.0-110.0)	[redacted]
B1	4.2 (2.7-10.4)	236 (236-579)	5.7 (5.3-20.2)	386 combined	363 (363-1871)	87 (58-349)	18.7 (16.0-35.0)	24.9 (11.4-24.9)
B2	13.3 (10.8-21.8)	597 (465-613)	6.9 (6.9-18.1)	139 combined	2002 (661-2002)	170 (150-304)	61.2 (34.5-76.5)	47.9 (33.3-47.9)

(Source: IPCC Emission Scenarios, 2001)

Emissions of GHGs and SO_2 are the basic input for determining future climate patterns with simple climate models, as well as with complex general circulation models (GCMs). Possible climate changes together with the major driving forces of future emissions, such as demographic patterns, economic development and environmental conditions, provide the basis for the assessment of vulnerability, possible adverse impacts and adaptation strategies and policies to climate change. The major driving forces of future emissions also provide the basis for the assessment of possible mitigation strategies and policies designed to avoid climate change (IPCC, 2007).

1.1.2 Climate Model

Climate models use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. They are used for a variety of purposes from study of the dynamics of the climate system to projections of future climate (Wikipedia, 2010)[1].

Thousands of climate researchers use global climate models to better understand how global changes such as increasing greenhouses gases or decreasing Arctic sea ice will affect the Earth (Figure 3). The models are used to look hundreds of years into the future, so that we can predict how our planet's climate will likely change (NESTA, 2007)[2].

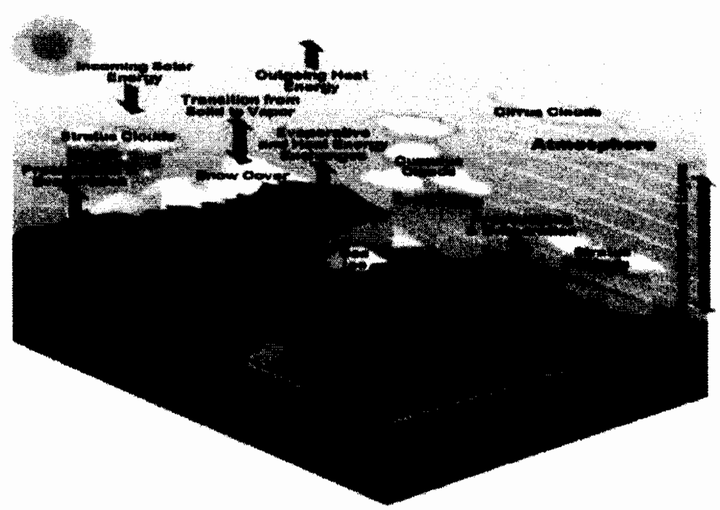


Figure 3. Natural processes included in Climate Model
([2]Source: NESTA, 2007)

[1]http://en.wikipedia.org/wiki/Climate_model
[2]http://www.windows2universe.org/earth/climate/cli_models3.html

1.1.3 Climate Modeling:

Assessment of the vulnerability to greenhouse warming induced climate change is mostly based upon scenarios of future climate. These scenarios are generally derived from projections of climate change undertaken by climate modeling. Mathematical representation of climate system is termed as climate modeling which is then expressed through computer codes and then run on powerful computers. These climate models are reliable because one source of confidence in models comes from that these models fundamentals are based on established physical laws, such as conservation of mass, energy and momentum including observations. Climate models provide believable quantitative confidence and estimates that what will happen in future. Confidence about model generated data is based on the foundation of climate model accepted physical principles and also there capability of producing current and future climate changes. Increasing level of greenhouse gases and its significant role in global warming and climate change has been pasteurized by climate models after passing through a phase of development. These results are now unambiguous and significant (IPCC, 2007).

1.1.4 Global Climate Model (GCM)

A global climate model or general circulation models (GCMs) are a class of computer-driven models for weather forecasting, understanding climate and projecting climate change, where they are commonly called Global Climate

Models. A global climate model or general circulation model aims to describe climate behavior by integrating a variety of fluid-dynamical, chemical, or even biological equations that are either derived directly from physical laws (e.g. Newton's law) or constructed by more empirical means. There are both atmospheric GCMs (AGCMs) and ocean GCMs (OGCMs).An AGCM and an OGCM can be coupled together to form an atmosphere-ocean coupled general circulation model (AOGCM).With the addition of other components (such as a sea ice model or a land model), the AOGCM becomes the basis for a full climate model[3].

With GCM's there is significant problem for decision making process arising from the weak link between climate change information based on global climate models and impact studies that are necessarily based on real local conditions. Global Circulation Models (GCMs) can reproduce reasonably well climate features on large scales (global and continental), but their accuracy decreases when proceeding from continental to regional and local scales because of the lack of resolution. This is especially true for surface fields, such as precipitation, surface air temperature and their extremes. They are critically affected by topography and land use. However, in many applications, particularly related to the assessment of climate-change impacts, the information on surface climate change at regional to local scale is fundamental. To bridge the gap between the climate information provided by GCMs and that needed in impact studies, especially when aiming the interactions of climate and air-quality issues,

[3]Source:http://en.wikipedia.org/wiki/Global_climate_model

dynamical downscaling, i.e., nesting of a fine scale limited area model (or Regional Climate Model, RCM) within the GCM is the most expedient tool (Halenka *et al.*, 2008).

1.1.5 Regional Climate Model (RCM)

A Regional Climate Model (RCM) is a tool to add small-scale detailed information of future climate change to the large-scale projections of a GCM. RCMs are full climate models and as such are physically based and represent most or all of the processes, interactions and feedbacks among different components of the climate system that are represented by GCMs. They take coarse resolution information from a GCM and then develop fine-scale information (both temporally and spatially) using their higher resolution representation of the climate system. The typical horizontal resolution of an RCM is about 50 km. It covers an area (domain) of typically 5000 m x 5000 m, over a particular region of interest. It is a comprehensive physical model, usually of the atmosphere and land surface, containing representations of the important processes in the climate system (e. g. clouds, radiation, rainfall, soil hydrology) as are found in a GCM. An RCM does not generally include an ocean component; as this can increase complexity and would need more computing power (Jones *et al.*, 2004).

1.1.6 Atmospheric Aerosols

Atmospheric aerosols have counteracted the warming effects of greenhouse gases over the past century. This has provided some "climate protection", but also prevented the true magnitude of the problem from becoming evident. Over the coming century, the role of aerosols in opposing global warming will wane, since their lifetime is short, and because there are powerful policy reasons to reduce their emissions. They will, on the other hand, continue to play a role in regional climate change, especially with regard to the water cycle. In contrast to the GHG, aerosol pollution has severe health impacts that affect most strongly the populations in the regions where emissions take place (Andreae, 2007).

Among anthropogenic perturbations of the Earth's atmosphere, aerosols are also considered to have a major impact on the energy budget through their impact on radiative fluxes. Anthropogenic aerosols are considered to be important contributors to observed changes in surface radiation and temperature over the last decades. Only the combined consideration of the radiative impacts of anthropogenic greenhouse gases (GHGs) and aerosol emissions allows global general circulation models (GCMs) to simulate realistically the observed increasing temperature trend over the last century. Therefore, future climate change will be controlled combination with changes in variety of adverse health impacts (Kloster *et al.*, 2009).

The aerosol effects on climate can be large and complex due to the fact that aerosols chemical composition, abundance and size distribution are highly variable, both spatially and temporally. Most of the earliest investigations on direct aerosol forcing have focused on sulphate aerosols because of their importance as an anthropogenic aerosol component (Streets, 2007).

1.1.7 Sulphate Aerosols

Sulphate aerosols are capable of modifying the climate not only by reflecting incoming sunlight back to space (direct effect) but also by altering the properties of clouds (indirect effect). Direct effects are induced by the radiative forcing associated with the sulphate aerosols reflecting and absorbing the of solar radiation; indirect effects are related to the role of sulphate aerosol particles as Cloud Condensation Nuclei (CCN),since the CCN population determines the microphysical properties of clouds and thus affects the cloud optical properties and atmospheric residence time (Giorgi, 2002).

Looking back at the twentieth century, and more precisely, at the 1930–1989 period, the observed warming on the global scale has been less than expected due to the anthropogenic greenhouse gases. Additional anthropogenic forcing by sulfate aerosols has been proposed as a negative forcing which partially counterbalanced the warming effect of greenhouse gases. A number of studies have shown that aerosols of anthropogenic origin can have significant climatic impacts, especially at the regional scale (Quass *et al.*, 2004).

The effects of anthropogenic aerosols on the climate constitute one of the largest sources of uncertainty in quantifying climate change. The anthropogenic aerosols released from South Asia region are projected to become the dominant component of anthropogenic aerosols worldwide in the next 25 years (Nakicenovic and Swart, 2001).

The South Asian Region includes the Indian subcontinent (India, Pakistan, Bangladesh, Nepal and Bhutan) as well as Sri Lanka, and Maldives. The region is one of the most densely populated in the world, with present population densities of 100-500 persons/km^2. Several of the world's most polluted cities are found in South Asia (Figure 4): Calcutta, Delhi, Mumbai, Karachi, and Dhaka are examples of megacities that produce unacceptably high emissions of health endangering gaseous and particulate matter (UNEP, 2001).

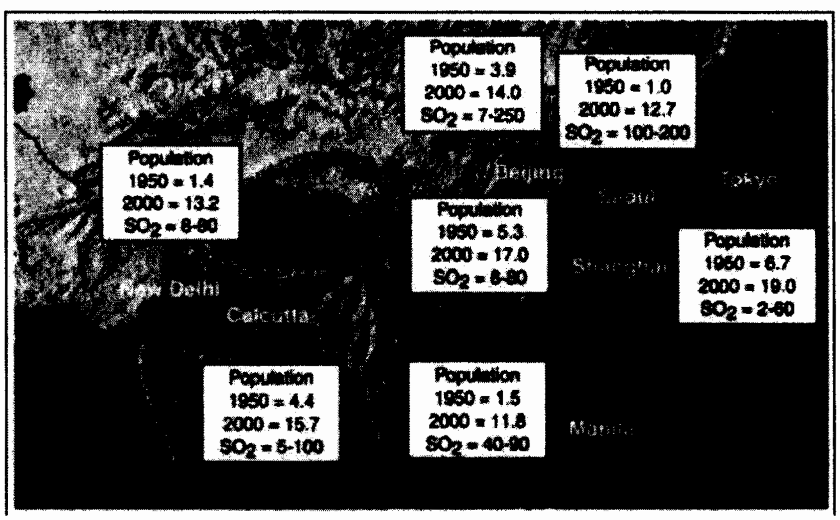


Figure 4. Population in millions and Range of annual average SO2 concentration during 1880-84 in ug/m3
(Source: Mega-city Growth and Future)

Part of the emissions occurs as microscopic particles (aerosols) or in particular as gaseous precursors of aerosols. A main example is the release of sulfur dioxide (SO_2) from fossil fuel combustion. Emission estimates are shown in Figure 5 indicating a particularly significant Asian contribution by China due to heavy use of sulfur-rich coal. In the atmosphere, SO_2 is converted into particulate sulfate, which are referred to as sulphate aerosols (UNEP, 2001).

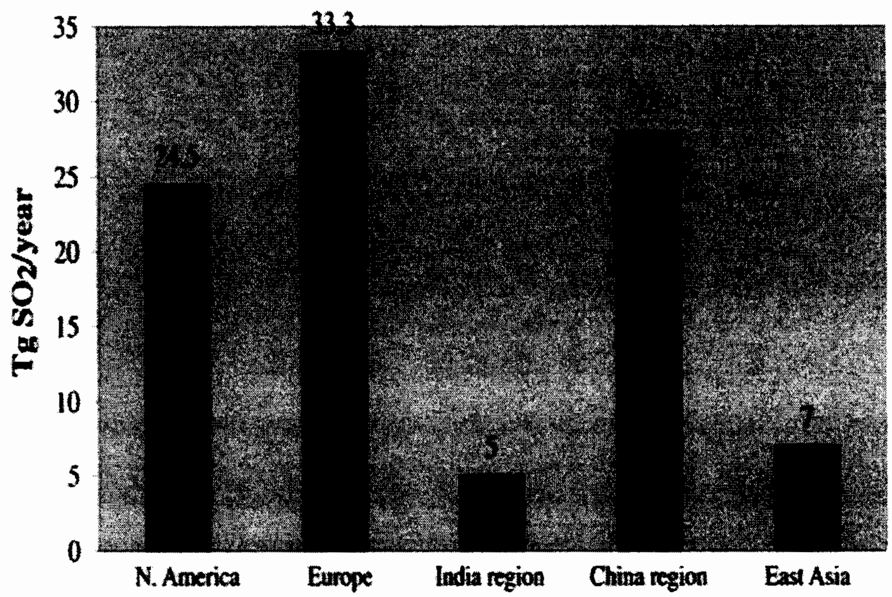


Figure 5. Estimated man-made SO2 emissions
(Source: UNEP Assessment Report. 1990).

Pakistan is ranked among the most urbanized countries in South Asia, with a 33.5% urban population. The country is witnessing substantial increases in urban population, along with excessive release of air pollutants especially through vehicular emissions, industrial pollution and burning of municipal waste.

Although Pakistan contributes least to global warming by emitting only 1/35th of the world's average of carbon dioxide emissions, temperatures in the country's coastal areas have risen since the 1900s from 0.6 to 1 degree centigrade. Precipitation has decreased 10 to 15 per cent in the coastal belt and hyper arid plains over last 40 years while there is an increase in summer and winter rains in northern Pakistan. Although Pakistan produces minimal chlorofluorocarbons and a little sulphur dioxide emissions, thus making a negligible contribution to ozone depletion and acid rain, it will suffer disproportionately from climate change and other global environmental problems (Khaliq, 2009).

1.2 Objectives of the research

The core objective of the current research was to introduce a RCM facility that will facilitate the simulation of present and possible future climate patterns over South Asia focusing Pakistan. This is achieved through the following sub-objectives:

1. To use the RCM in order to perform high resolution climate change scenarios for South Asia region focusing Pakistan by dynamic downscaling of the GCM (Global Climate Models) data based on selected SRES scenarios.

2. To determine possible future climate response to different future scenarios for sulphur dioxide emission and to work out the impact of sulphate aerosols on both variables: (i) Temperature and (ii) Precipitation.

1.3 Significance of research

The effect on temperature involves the direct scattering or absorption of incoming solar radiation by the aerosol particles. The direct effect has been estimated to exert a negative (cooling) radiative forcing on the climate system.

The indirect effect of aerosols depends on increasing the concentration of cloud condensation nuclei (CCN), so increasing the concentration of cloud droplets and thereby (assuming constant cloud water content) reducing the mean size of cloud droplets (Williams *et al.*, 2001).

This reduction in cloud droplet size has two further effects: Firstly, clouds with smaller droplets reflect more solar radiation back to space; this first indirect effect is sometimes known as the 'albedo' effect. Secondly, the reduction in cloud droplet size also affects the efficiency with which clouds form precipitation, tending to increase the amount of water in clouds and also affecting their persistence. Consequently, this second indirect effect (sometimes known as the 'lifetime' effect), as well as having a cooling effect in the shortwave due to the clouds being brighter, could also exert a long wave warming influence due to the increase in cloud water (Jones *et al.*, 2001)

This study will provide an overview of the current scientific understanding of the subject and lead to some quantitative estimates of the influence of aerosols on regional climate change of South Asia focusing Pakistan.

CHAPTER 2

CHAPTER 2

LITERATURE REVIEW

(Rangwala, *et al*,. 2009). Our analysis suggests that the Tibetan Plateau will warm during the twenty-first century under the SRES A1B scenario. This warming is likely to be more pronounced at higher elevations in the plateau due to (a) increases in DLR caused by surface humidity increases during cold seasons, (b) increases in ASR caused by decreases in the snow cover extent during spring and summer and (c) larger aerosol concentrations at lower elevations. The elevation-based changes in surface energy balance affected by changes in surface humidity, snow cover and atmospheric aerosol will also tend to produce an EDW trend over the plateau during the twenty-first century.

(Fronzek, et *al*., 2009). During the past two decades there has been a large effort in Europe to determine the likely impacts of anthropogenic climate change for natural systems and human activities. Methods of applying climate scenarios to investigate uncertainties in future impacts have been refined over time, but the basic approach has changed little since impact studies were first conducted.

(Füssel, 2009). The IPCC Fourth Assessment Report (AR4) published in 2007 (IPCC 2007) presents the most complete and authoritative assessment of the scientific knowledge on anthropogenic climate change, on associated impacts and vulnerabilities, and on options for reducing climatic risks through mitigation and adaptation.

(Rasch, *et al.*, 2008). The studies reviewed here suggest that sulphate aerosols can counteract the globally averaged temperature increase associated with increasing greenhouse gases, and reduce changes to some other components of the Earth system. The aerosols also serve as surfaces for heterogeneous chemistry resulting in increased ozone depletion. In this study two simple delivery scenarios are explored, but similar exercises will be needed for other suggested delivery mechanisms. While the introduction of the geoengineering source of sulphate aerosol will perturb the sulphur cycle of the stratosphere significantly.

(XiaoHui, *et al.*, 2008). At present, it is convinced that human activities are contributing to climate change, in which atmospheric aerosols are playing an important role have suggested that anthropogenic aerosol is likely a mechanism that affects the precipitation in the Sahel region in Africa. They have used different GCM models (CSIRO and ECHAM4GCM) coupled with a respective mixed layer ocean model to conduct equilibrium tests in response to increased anthropogenic aerosol concentration

(Rinaldi, *et al.*, 2007). Atmospheric aerosol particles exhibit a wide range of sizes, from nanometer to micrometer range, while the chemical composition differs greatly among the size ranges, and even among individual particles within a given size interval. Particle size is essential for describing the interaction between aerosol and solar radiation (radiative effects), as well as the aerosol uptake of water vapor (effects on visibility and cloud formation). However, aerosol properties are also a function of chemical composition, because the chemical constituents of aerosol particles can exhibit very different optical and hygroscopic properties. For this reason, the concurrent characterization of particle size and chemical composition is necessary to predict the climate-relevant properties of atmospheric aerosols.

(Park and Chang, 2007). Atmospheric aerosols play a major role in the global climate system. Many researchers have conducted studies on the radiative forcing of aerosols for recent years. Aerosol particles are known to cool or warm the atmosphere directly by absorption, scattering and emission of solar and terrestrial radiation and indirectly by changing the albedo and the life time of clouds by acting as cloud condensation nuclei. The uncertainties are due in part to the limited data on aerosol climatology, and in part to the lack of our understanding on the processes responsible for the production, transport, physical and chemical evolution and the removal of aerosols at various spatial and time scales.

(Iversen, *et al.*, 2007). Depending on their chemical composition, sizes and shapes, aerosol particles may scatter and absorb solar radiation and act as nuclei for condensation of water vapor and for freezing of water droplets. Availability of cloud condensation (CCN) and ice nuclei (IN) is responsible for the realized water vapour super-saturations in the troposphere. Human activity inadvertently produces aerosol particles. Production mechanisms include combustion of fossil fuels and biomass, leading to submicron particles containing sulphate, nitrate, black carbon and particulate organic matter.

(Göttel, *et al.,* 2007). The global near surface temperature increased since the beginning of the industrialization. For the twentieth century an increase of about 0.6±0. 2°C was quantified (Houghton et al. 2001). The warming was non-uniform over the globe and is expected to be larger in the Arctic than in other regions of the world. For the last 40 years an increase of 1.5°C is documented in the Arctic (ACIA 2004), a region which is extremely vulnerable to climate change. With increasing temperature and precipitation and a corresponding decrease of sea ice, permafrost and snow cover, severe impacts on the ecosystems are expected. The societal and economic welfare of the Barents Sea Region is closely connected to the natural environment. The economy is mostly based on fishery, forestry and reindeer herding.

(Popovicheva and Starik, 2007). Aircraft is one of the sources of man's impact on the atmosphere. The annually increasing amounts of carbon dioxide, water, and methane emitted by the engines of commercial aircraft are considered to alter both the chemical and radiation balances of the atmosphere, a circumstance that, in parallel with the emission of sulfate aerosols, may affect climate. Such particles dominate in the composition of atmospheric aerosols mixed with organic substances, soil minerals, and metallic additives. Formerly, when the climatic effects of emissions of soot aerosols were estimated; the main emphasis was on variations in the atmospheric composition owing to heterogeneous chemical reactions occurring on the surface of soot particles. At present, the influence of the emission of soot particles on climate is considered to be caused mainly by the formation of long-lived contrails (direct effect) and by the initiation of cirrus clouds (indirect effect).

(Lili, *et al.,* 2007). The ambient aerosols effect on climatic change has become an important area of atmospheric science research. Tropospheric aerosol has a substantial climatic influence through direct and indirect radioactive forcing and taking part in cloud processes, and aerosol also plays a most important role in environmental change. However, climatic and environment influence of aerosol is still uncertain due to the incomplete knowledge of the microphysical and optical properties of aerosols and their extreme heterogeneous spatial distribution.

(Abdalmogith, *et al.*, 2006). Secondary aerosols are attracting the interest of many researchers because of their link to adverse health effects, climate change, acidification, and visibility problems. Epidemiological studies provide strong evidence associating serious health outcomes with both short-term exposures to elevated PM2.5 and and PM10 levels and long-term exposures. The atmospheric residence time of SO_2 and NO_x and their secondary products are of the order of several days, implying a travel distance of hundreds or thousands of kilometers from their sources.

(Dyson, 2006). This paper comments on the issue of global warming and climate change, in an attempt to provide fresh perspective. Essentially, five main arguments are made. First, that the process of modern economic development has been based on the burning of fossil fuels, and that this will continue to apply for the foreseeable future. Second, that in large part due to momentum in economic and demographic processes, it is inevitable that there will be a major rise in atmospheric CO_2 during the present century. Third, that available data on global temperatures suggest strongly that the coming warming will be appreciably faster than anything that humanity has experienced during historical times. Moreover, especially in a system that is being forced, the chance of an abrupt change in climate happening must be rated as fair.

(Huang, *et al.*, 2006). A regional coupled climate–chemistry–aerosol model is developed to examine the impacts of anthropogenic aerosols on surface temperature and precipitation over East Asia. Besides their direct and indirect reduction of short-wave solar radiation, the increased cloudiness and cloud liquid water generate a substantial downward positive long-wave surface forcing;

consequently, nighttime temperature in winter increases by +0.7°C and the diurnal temperature range decreases by −0.7°C averaged over the industrialized parts of China. Confidence in the simulated results is limited by uncertainties in model cloud physics. However, they are broadly consistent with the observed diurnal temperature range decrease as reported in China, suggesting that changes in downward long-wave radiation at the surface are important in understanding temperature changes from aerosols.

(Lohmann, 2006). Aerosols affect the climate system by changing cloud characteristics in many ways. They act as cloud condensation and ice nuclei, they may inhibit freezing and they could have an influence on the hydrological cycle. While the cloud albedo enhancement (Twomey effect) of warm clouds received most attention so far and traditionally is the only indirect aerosol forcing considered in transient climate simulations.

(Tsutsui, 2006). Stabilization of greenhouse gas concentrations in the atmosphere at a certain level may be needed to prevent dangerous anthropogenic interference with the climate system. Since the climate system includes much slower processes like ocean heat uptake than atmospheric responses to radiative forcing changes, attention has been turned to long-term climate responses after the stabilization as well as different stabilization levels and profiles.

(Swart, *et al.,* 2004). Climate change and air pollution are also interrelated through aerosols (particulate matter). Particles in the atmosphere have an important radiative effect. At the same time, these particles cause serious health impacts, including significant increases in mortality from cardio-vascular and cardio-pulmonary diseases as well as cancer. Particles resulting from fossil fuel and other burning accumulate in the size range below 1 micrometer.

(Shine, 2004). The effects of increases in the so-called well-mixed greenhouse gases, and in particular carbon dioxide, appear to be the dominant mechanism. However in this study , there are considerable uncertainties in estimates of many other forcing mechanisms; those associated with the so-called indirect aerosol forcing (whereby changes in aerosols can impact on cloud properties) may be the most serious, as its climatic effect may be of a similar size as, but opposite sign to, that due to carbon dioxide. The possible role of volcanic eruptions as a natural climate change mechanism is also highlighted.

(Quaas, *et al.,* 2004). Among anthropogenic perturbations of the Earth's atmosphere, greenhouse gases and aerosols are considered to have a major impact on the energy budget through their impact on radiative fluxes. Three ensembles of simulations with the LMDZ general circulation model to investigate the radiative impacts of five species of greenhouse gases (CO_2, CH_4, N_2O, CFC-11 and CFC-12) and sulfate aerosols for the period 1930–1989 were used in this study. Focus is on the atmospheric changes in clouds and radiation from greenhouse gases and aerosols, sea-surface temperatures in these simulations was prescribed.

(Hulme and Viner, 2004). Future greenhouse gas induced climate change will have implications for global mean climate and sea level but, more importantly, will have contrasting regional manifestations. For example, in some regions temperatures may not raise for several decades, rainfall seasonality may change, and tropical cyclone activity may be altered. Changes in climate variability are also likely, although even harder to specify. Regional climate change prediction, in the sense of being able to attach probabilities to the outcomes of climate model experiments, is not yet possible.

(Alleni, et *al.,* 2001). Aerosol particles present in the atmosphere affect the radiative balance of the Earth, directly by scattering or absorbing light and indirectly by acting as cloud condensation nuclei (CCN), thereby influencing the albedo and lifetime of clouds. Anthropogenic activity has perturbed the natural aerosol by increasing sulphate, nitrate and soot concentrations as well as those of organic condensates. The role of aerosols in tropospheric chemistry and the contribution of aerosols to global climate models are poorly characterised due to both the lack of a comprehensive global data set as well as a clear understanding of the processes linking aerosol precursors, particles and radiative effects.

(Weaver and Zwiers 2000). Climate modeling has produced varying projections of possible global rises in temperature. A simple statistical method brings several such projections into closer agreement and includes an indication of potential accuracy. Governments around the world are investing heavily in coupled-climate models to project future climate change. Such models have interacting atmosphere, ocean, land and sea-ice components, and serve as laboratories for studying the effects of natural and human influences on the climate system.

(Haywood, *et al.,* 1999). Tropospheric aerosols affect the radiative forcing of Earth's climate, but their variable concentrations complicate an understanding of their global influence. Model-based estimates of aerosol distributions helped reveal spatial patterns indicative of the presence of tropospheric aerosols in the satellite-observed clear-sky solar radiation budget over the world's oceans. The results show that, although geographical signatures due to both natural and anthropogenic aerosols are manifest in the satellite observations, the naturally occurring sea-salt is the leading aerosol contributor to the global-mean clear-sky radiation balance over oceans.

(Buseck and Pósfai, 1999). Aerosol particles are ubiquitous in the troposphere and exert an important influence on global climate and the environment. They affect climate through scattering, transmission, and absorption of radiation as well as by acting as nuclei for cloud formation. Sulfate particles are the main cooling agents among aerosols; we found that in the remote oceanic atmosphere a significant fraction is aggregated with soot, a material that can diminish the cooling effect of sulfate.

(Reader and Boer, 1998). The Canadian Centre for Climate Modeling and Analysis (CCCMA) second generation climate model (GCMII) consists of an atmospheric GCM coupled to mixed layer ocean. It is used to investigate the climate response to a doubling of the CO_2 concentration together with the direct effect of scattering by sulphate aerosols. As expected, the aerosols offset some of the greenhouse gas (GHG) warming; the global annual mean screen temperature change due to doubled CO_2 is 3.4 °C in this model and this is reduced to 2.7 °C when an estimate of the direct effect of anthropogenic sulphate aerosols is included.

(Lohmann and Feichter, 1997). A coupled sulfur chemistry-cloud microphysics scheme (COUPL) is used to study the impact of sulfate aerosols on cloud lifetime and albedo. The cloud microphysics scheme includes precipitation formation, which depends on the cloud droplet number concentration (CDNC) and on the liquid water content. On the basis of different observational data sets, CDNC is proportional to the sulfate aerosol mass, which is calculated by the model. For each experiment, two simulations, one using present-day and one using pre industrial sulfur emissions are carried out.

(Mitchell, *et al.*, 1995). Climate models suggest that increases in greenhouse-gas concentrations in the atmosphere should have produced a larger global mean warming than has been observed in recent decades, unless the climate is less sensitive than is predicted by the present generation of coupled general circulation models. After greenhouse gases, sulphate aerosols probably exert the next largest anthropogenic radiative forcing of the atmosphere, but their influence on global mean warming has not been assessed using such models. Model results suggest that global warming could accelerate as greenhouse-gas forcing begins to dominate over sulphate aerosol forcing.

(Wright and Schindler, 1995). In the atmosphere sulphate aerosols tend to increase haze, altering the global radiation balance. Increased nitrogen deposition to N-limited systems such as boreal forests results in increased growth and increased sequestration of atmospheric CO_2, slowing the increase in CO_2 levels in the atmosphere. Future reduction in S and N emissions may result in a trade-off -- better with respect to some effects of acid deposition and greenhouse warming, but worse with respect to others. Global warming may cause the incidence and severity of drought to increase.

(Kiehl and Briegleb, 1993). Calculations of the effects of both natural and anthropogenic tropospheric sulfate aerosols indicate that the aerosol climate forcing is sufficiently large in a number of regions of the Northern Hemisphere to reduce significantly the positive forcing from increased greenhouse gases.

Summer sulfate aerosol forcing in the Northern Hemisphere completely offsets the greenhouse forcing over the eastern United States and central Europe. Anthropogenic sulfate aerosols contribute a globally averaged annual forcing of -0.3 watt per square meter as compared with +2.1 watts per square meter for greenhouse gases.

(Balling, *et al.*, 1991) Sulfate aerosols in the stratosphere are generally believed to have a cooling effect on surface air temperature, due to their attenuation of incoming solar radiation. Sulfate aerosols in the troposphere are also believed to cool the earth's surface via enhanced backscatter of solar radiation. Hence, before surface air temperature trends can be used to infer anything about possible greenhouse warming over the past century, it is necessary to first evaluate the possible effects of historical trends in these two aerosol populations on surface air temperature.

CHAPTER 3

CHAPTER 3

MATERIALS AND METHODS

3.1 General

Aerosols are thought to have a cooling effect on the atmosphere and therefore have mitigated some of the expected global warming. On the other hand, due to the increase in atmospheric concentrations of man-made aerosols from different sources, such as transportation, industry, agriculture, and urban land use, not only poses serious problems to human health, but also has an effect on weather and climate. There is general observation that increased aerosol loading may have changed the energy balance in the atmosphere and at the Earth's surface, and it may alter the global water cycle in ways that make the climate system more prone to precipitation extremes. Therefore, aerosols, clouds and their interaction with climate are still the most uncertain areas of climate change and require multidisciplinary coordinated research efforts (Pilewskie, 2007).

3.2 Study Area

Although impact of sulphate aerosols is localized, in this study South Asia and particularly Pakistan is study area to analyze the role and impact of sulphate aerosols on regional climate and its change.

Pakistan is among the countries that are hit hardest by the effect of climate change even though it contributes only a fraction to global warming (Shahid, 2009).

3.2.1 General Profile of Study Area

Study region includes South Asia (India, Pakistan, Bangladesh, Bhutan, Nepal, Maldives, Afghanistan, Iran and Sri Lanka) and particularly Pakistan. Pakistan is situated in the north west of South Asia. On the globe, it is located between the latitudes 23.45-degree and 36.75-degree north and between longitudes 61 degree and 75.5 degree east. In the north- west lies Afghanistan. In the west of Baluchistan province, Iran is situated. In the east of Pakistan lies India and It is bordered by China in the north, (Figure 6) [4].

There is an extreme variation in the temperature of Pakistan depending on the topography. Pakistan's major part experiences dry climate. Northern Sindh, southern Punjab, north-western Baluchistan and the central parts of Northern Areas receive less than 125 mm of rainfall but humid conditions prevail over a small area in the north. True humid conditions appear when rainfall

[4]Source: Central Intelligence Agency-The World Fact Book at
https://www.cia.gov/library/publications/the-world-factbook/geos/pk.html

increases to 750 mm in plains and 625 mm in highlands. There are two sources of rainfall in Pakistan: the Monsoon and the Western Depression. The former takes place from July to September and the latter from December to March (UNEP, 1998).

The estimated population of Pakistan in 2008 is 162.37 million making it the world's sixth most-populous country, behind Brazil and ahead of Russia. Around 67.5 per cent of its total population and 80 per cent of the poor live in rural space[5].

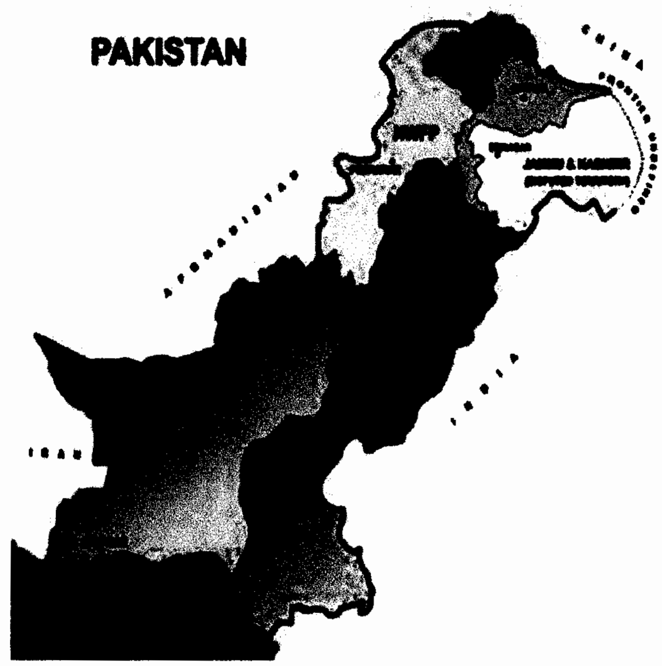


Figure 6. Location Map of Pakistan
(Source: CIA-The World Fact Book)

[5]Source: Economic survey of Pakistan 2008-09, Gov. of Pakistan at
http://www.pro-pakistan.com/2009/06/11/download-economic-survey-of-pakistan-2008-09/

3.3 Climatic Regions of Pakistan

Pakistan lies in sub-tropics and partly in the temperate region. A large part of Pakistan is arid to semi-arid with some areas as hyper-arid in the lower southern half of the country. The coastal climate is confined to a narrow strip along the coast in the south and south east and a humid belt along the sub-montane regions of Himalayas.

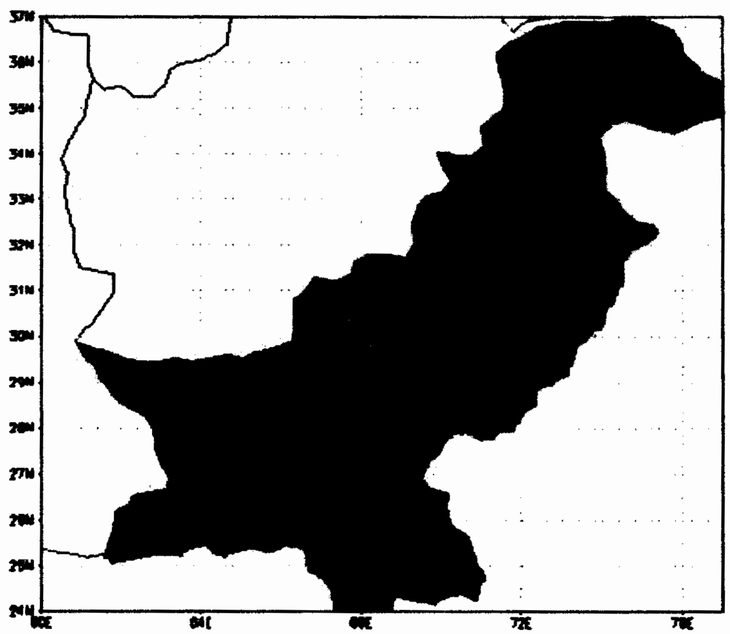


Figure 7. Climatic Regions of Pakistan
(Source: Research Report GCISC–RR–6)

Based on these physiographic and climatic features of the country, Pakistan is divided, climatically into eight major climatic regions as shown in Figure 7 and the data taken for characterizing these different regions is gathered from all available meteorological stations in Pakistan. Each region compromises stations as listed in the Table 2 (Islam, et al., 2009).

Table 2. Climatic Regions of Pakistan

Regions	Meteorological stations in the Regions
Region I(a): Greater Himalayas (Winter dominated)	Astor, Bunji, Chilas, Chitral, Dir, Drosh, Gilgit, Gupis, Skardu
Region I(b): Sub-montane region And Monsoon dominated	Balakot, Garhi Dupatta, Islamabad, Jhelum, Kakul, Kotli, Lahore, Murree, Muzaffarabad, Saidu Sharif, Sialkot
Region II: Western Highlands	Cherat, D. I. Khan, Kohat, Parachinar, Peshawar, Risalpur
Region III: Central & Southern Punjab	Bahawalnagar, Bahawalpur, Faisalabad, Khanpur, Mianwali, Multan, Raffique, Sargodha
Region IV: Lower Indus Plains	Chhor, Hyderabad, Jacobabad, Nawabshah, Padidan, Rohri
Region V(a) : Balochistan Plateau (Northern) (Sulaiman & Kirthar Ranges)	Barkhan, Kalat, Khuzdar, Lasbela, Quetta, Sibbi, Zhob
Region V(b): Balochistan Plateau (Western)	Dalbandin, Nokkundi, Panjgur
Region VI: Coastal Belt	Badin, Jiwani, Karachi, Pasni

(Source: Islam, et al., 2009)

3.4 Model Description and Data

3.4.1 Description of the PRECIS

The third-generation Hadley Centre RCM (PRECIS) is based on the latest GCM, HadCM3 (Gordon *et al.*, 2000). It has a horizontal resolution of 50 resolutions, namely 0.44° and 0.22° (giving grid boxes of approximately 50 km x 50 km and 25 km x 25 km, respectively). Whilst a more realistic land-sea mask and fine scale detail is expected at 25 km resolution, the time to complete such a simulation takes approximately six times longer than the time to complete a 50 km resolution run over the same area (Gregory *et al.*, 1990).

The PRECIS RCM requires prescribed surface and lateral boundary conditions. For present-day simulations, surface boundary conditions are only required over water, where the model needs time series of SSTs and sea-ice. For the lateral boundary conditions different GCMs output data sets are used (Gregory *et al.*, 1990).

3.4.2 Data sets used with PRECIS

The description of driving data set used for simulation by PRECIS is as follows:

3.4.2.1 HadAM3P Data

This boundary data is provided by 10-year integration of HadAM3P (Gordon, C. et al., 2000), a 150 km-resolution version of the Hadley Center's global atmosphere-only model. Observed time series of HadISST sea-surface temperatures and sea-ice for 1961-1970 are used in this integration. PRÉCIS RCM is forced by model-derived boundary conditions output data on an idealized 360-day calendar.

3.4.2.2 CRU (Climate Research Unit) Data

Observed data of Climate Research Unit (CRU), UK (New *et al.* 1999) of 50km resolution is used.

3.5 Experimental Design

High resolution climate change projections were simulated for South Asia region focusing particularly over Pakistan. As the impact of sulphate aerosols is localized having life time of few days, this study was further focused on different climatic regions of Pakistan to enhance the Impacts of sulphate aerosols.

Two time periods were used in this study termed as Base (1961-1970) and Future (2071-2080). For recent period termed as base (1961-1970), the regional climate model PRECIS was nested into HadAM3P GCM data set forced with the SRES A2-emission scenario while 2071-2080 was taken as future scenario period in order to downscale the regional response of the GCM projections over South Asia particularly Pakistan. The above procedure was repeated for the same time period base (1961-1970) and future (2071-2080) but this time using the sulphur cycle scheme in PRECIS. In this study newly developed interactive sulphur cycle scheme and a new microphysics scheme was used to estimate the impacts of first and second indirect effects of sulphate aerosols (Figure: 3.3). Temperature and precipitation changes were analyzed over whole of South Asia, particularly Pakistan.

3.5.1 The SRES A2-emission scenario

The SRES A2 emission scenario was used in this study. This family represents a differentiated world. The A2 world "consolidates" into a series of economic regions. Self-reliance in terms of resources and less emphasis on economic, social, and cultural interactions between regions are characteristic for this future. Economic growth is uneven and the income gap between now-industrialized and developing parts of the world does not narrow, unlike in the A1 and B1 scenario families. The A2 world has less international cooperation than the A1 or B1 worlds. People, ideas, and capital are less mobile so that technology diffuses more slowly than in the other scenario families. International disparities in productivity, and hence income per capita, are largely maintained or increased in absolute terms. With the emphasis on family and community life, fertility rates decline relatively slowly, which makes the A2 population the largest among the storylines (15 billion by 2100). Technological change in the A2 scenario world is also more heterogeneous than that in A1. It is more rapid than average in some regions and slower in others, as industry adjusts to local resource endowments, culture, and education levels. Regions with abundant energy and mineral resources evolve more resource-intensive economies, while those poor in resources place a very high priority on minimizing import dependence through technological innovation to improve resource efficiency and make use of substitute inputs. The fuel mix in different regions is determined primarily by resource availability. High-income but resource-poor regions shift toward advanced post-fossil technologies (renewable or nuclear), while low-income resource-rich regions generally rely on older fossil technologies. Final energy intensities in A2 decline with a pace of 0.5 to 0.7% per year (Nakicenovic, et al., 2000).

3.5.2 The Sulphur Cycle Scheme in PRECIS

Extra prognostic variables are required to simulate the distribution of sulphate aerosol in PRECIS. The present scheme involves few variables representing the mass mixing ratios of sulphur dioxide (SO2), dimethyl sulphide (DMS) and three modes of sulphate. The latter comprise two size modes of free particle, labeled Aitken and accumulation modes, and a third mode representing sulphate dissolved in cloud droplets. The Aitken mode is produced by gas phase oxidation of SO_2, while the accumulation mode is largely the result of loud processing (via the dissolved mode). The conversion of DMS to SO_2, and of SO to sulphate, requires the parameterization of complex chemistry that is not yet completely understood. The approach taken here is fairly simple. Monthly average three dimensional fields of the hydroxyl radial (OH), hydrogen peroxide (H_2 O_2), the per oxide radial (HO_2) and ozone (O_3), produced from simulations using the lagrangian chemistry model STOCHEM , are interpolated in space and time to provide boundary conditions that are used to control the rates of oxidation of DMS and SO_2 (Jones, et al. , 2001).

3.6 Model Domain and Configuration

The horizontal resolution used for the simulation is taken to be 0.44° (~50 km) with the domain covering South Asia from 6° to 39° north and 60° to 93° east, and for Pakistan from 20° to 40° north and 60° to 80° east (Figure:8). The model was driven by input data of HadAM3P. This data set is downscaled for the time periods comprising 1961-1970 in base line and 2071-2080 in future for HadAM3P data set.

(a) (b)

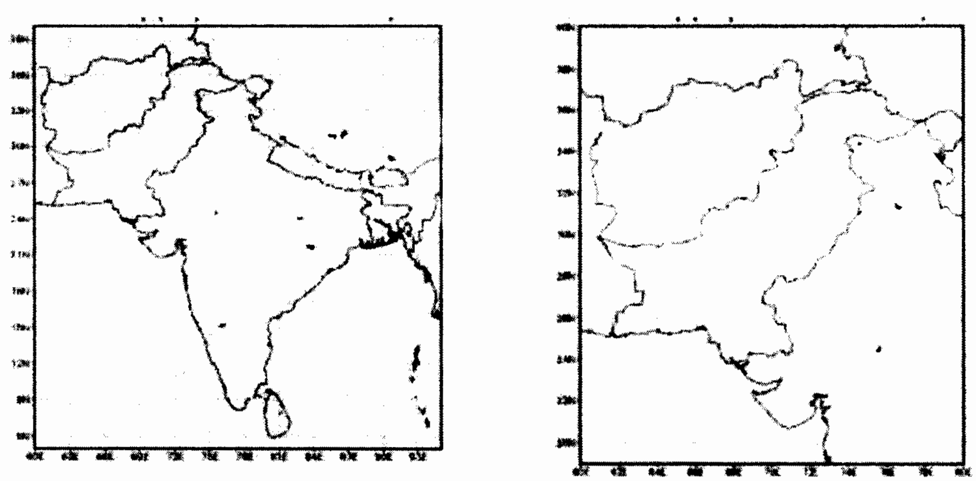


Figure 8. Model Domain (a) South Asia (b) Pakistan

To validate and compare downscaled data, CRU data set (New et al, 1999) of 0.5 degree resolution is used. Model output is first regridded to regular latitude / longitude grids (dx=dy=50km) to make the comparison possible. For model validation, downscaled HadAM3P data is compared with CRU climatology for annual mean precipitation and temperature.

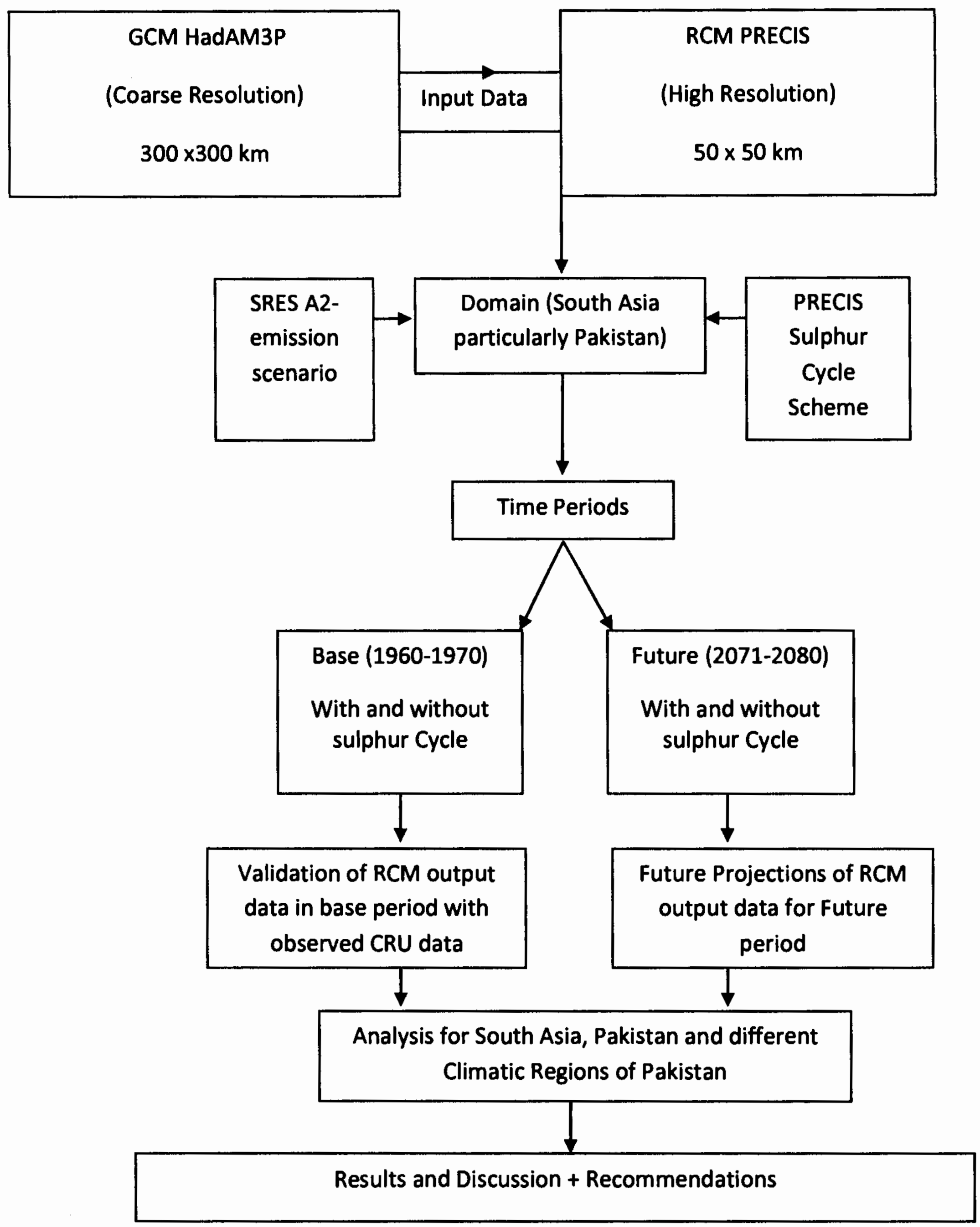


Figure 9. Schematic Diagram showing Experimental design of Study

CHAPTER 4

CHAPTER 4

RESULTS AND DISCUSSION

4.1 General

The applications used for the assessment of climate change impacts, require information at regional to local scales with higher resolution rather than coarse resolution information of GCMs. To bridge this gap RCMs are playing important role by generating detailed information for particular region under study. In this study using built-in sulphur cycle scheme of PRECIS RCM, future climate change scenarios are developed to account and assess the impact of sulphate aerosols on future climate change of South Asia particularly, Pakistan. These aerosols are said to be the masking agent for global warming caused by increased Green House Gases (GHGs). Therefore, along with the CO_2 and SO_2 concentration (As in A2 scenario), this study explored the potential human induced climate change by focusing particularly on the effect of sulphate aerosols.

As discussed in the methodology section. PRECIS RCM was run for the period 1961-1970 and 2071-2080 to get base line and future climatology/climate data respectively. To validate RCM, base line period of model data was used against observed data. Results for validation, by incorporating sulphur scheme of the model, are briefly described in 1st section whereas future climate change scenarios are discussed in 2nd section of this chapter.

4.2 Validation of Model

Validation of RCM is performed to build confidence about its projections of future climate change simulation. This confidence of particular RCM comes in part from its ability to simulate the recent climate by comparing it with observed climate. This validation can be performed on annual as well as seasonal basis.

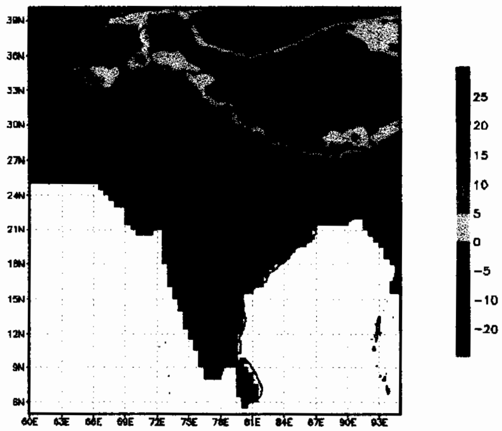
4.2.1 Validation of Downscaled HadAM3P-PRECIS Data

Various numerical and statistical methods were used on annual basis to assess the PRECIS RCM performance over South Asia and Pakistan. To validate and compare HADAM3P-PRECIS output (data downscaled by using PRECIS at 50km resolution) on annual and seasonal basis, the observed data of Climate Research Unit (CRU), UK (New *et al.*, 1999) of 50km resolution was used. Validation was first performed over whole South Asia and then only Pakistan was masked out from the main domain for further validation.

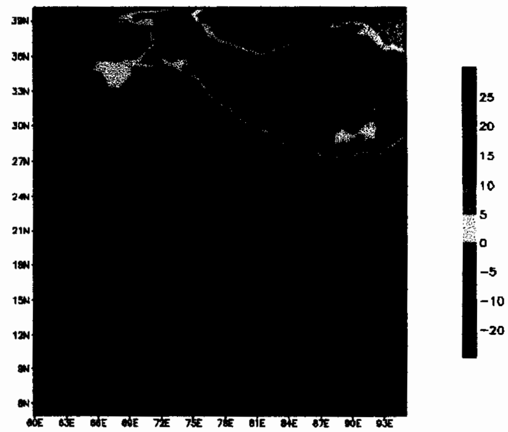
Spatial patterns of annual climatology only over South Asia and annual cycles for Pakistan were developed for model data as well as observed data of CRU, while Root Mean Square Error (RMSE) and Correlation for different climatic regions of Pakistan were calculated between model and CRU data.

In Figure 10 and 11, differences between spatial patterns of 10- years mean temperature and precipitation of Model and observed data are shown, respectively. In case of temperature, model showed a good agreement with CRU over the whole region mainly over Bangladesh and most parts of Pakistan and India whereas small amount of cold bias was observed over Nepal and northern parts of Pakistan. The decrease of 5°C was observed over central part of India for annual temperature.

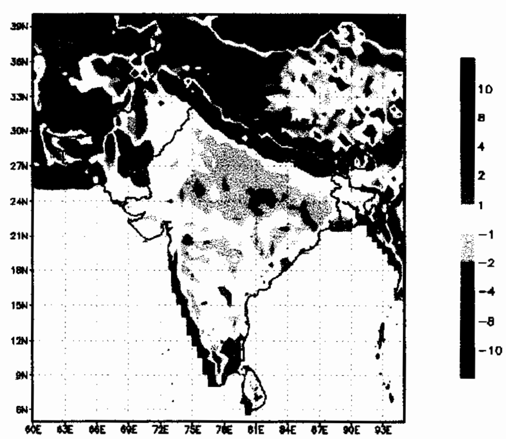
For precipitation, the annual pattern was well captured by the model over most parts of South Asia particularly over plane areas of Pakistan and India whereas over complex topography areas of whole South Asia, there were significant biases as model is overestimating the precipitation over those areas (Figure 10). Monsoon patterns over India and Pakistan were also captured by RCM but with overestimation in precipitation Profile.



(a)

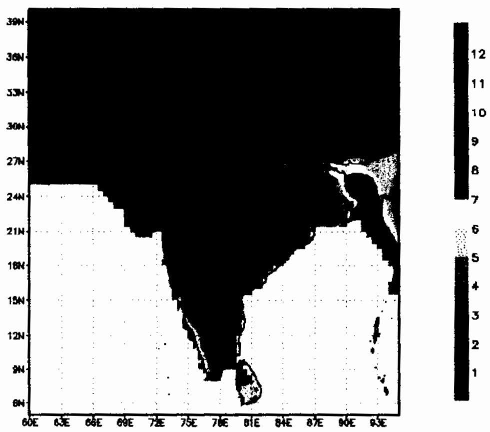


(b)

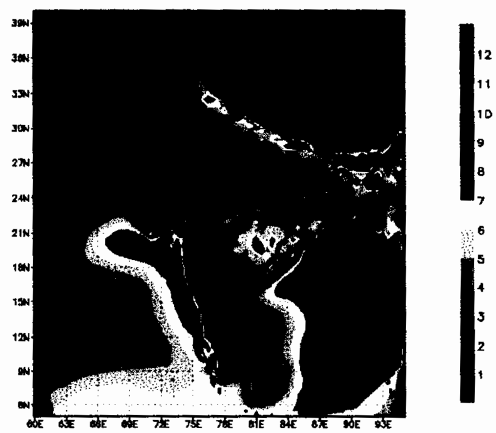


(c)

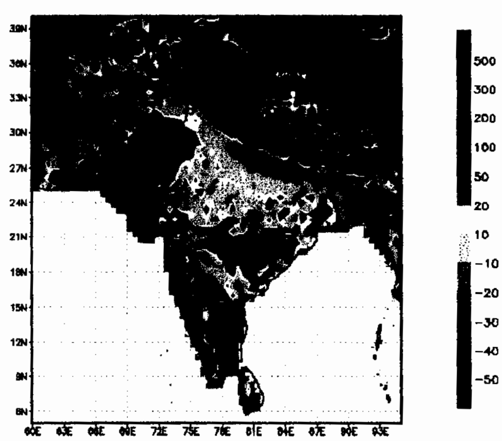
Figure 10. 10-years (1961-1970) annual mean temperature of (a) CRU data, (b) HadAM3P downscaled data (c) their differences



(a)



(b)



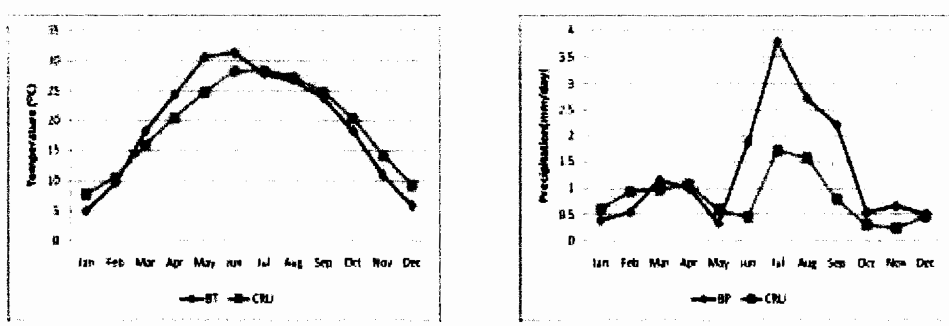
(c)

Figure 11. 10-years (1961-1970) annual mean precipitation of

(a) CRU data, (b) HadAM3P downscaled data (c) their differences (%)

Generally all of the RCMs currently available in the World are not able to simulate precipitation patterns fairly well because complex processes like formation of clouds and other condensation processes have not yet been completely translated into the Model physics. In the case of temperature, models are able to perform well when compared with other variables.

Annual cycles of temperature and precipitation were averaged over Pakistan for the validation of RCM, while RCM and CRU data are compared in the Figure 12. It is apparent from annual pattern that the annual rise and fall in temperature of model and CRU were almost same throughout the year except in April, May and June where warm bias is observed.



(BT=Base temperature, BP=Base precipitation, CRU=Climate Research Unit (Observed temperature and precipitation.)

Figure 12. Annual cycle of mean temperature (^{O}C) and precipitation (mm/day) for model and CRU climatology for 1961-1970 over Pakistan

As a whole, model performance in simulating temperature was good. In case of precipitation, the model overestimated the precipitation in monsoon season (i.e. JJAS) showing that model was not that good in capturing the monsoon climatology of precipitation.

In addition, two statistical methods i-e root mean square error (RMSE) which basically is an accuracy measure expressed in the same unit of measurement as per data, and Correlation were applied to the data to validate the model statistically over Pakistan as well as for different climatic regions of Pakistan.

In Table 3 RMSE and correlation between Model and CRU data is shown. As a whole, over Pakistan, for temperature, RMSE was found to be 2.9 between CRU data and Model base line climatology. In case of precipitation, RMSE values were very small as compared to temperature i.e. 0.92 mm/d, but it is due to averaged precipitation over whole Pakistan. As precipitation is localized phenomenon therefore it is better to validate the precipitation amount over small patches (like climatic regions) instead of whole Pakistan. For different climatic regions in case of temperature RMSE over regions V (a and b) and VI is less as compared to other regions while RMSE showed an overestimation for precipitation in most of regions. But actual annual observed precipitation was very small over region V (a and b). RMSE was quite large over region I (a) in case of temperature.

Table 3: RMSE and correlation for temperature and precipitation

REGION	Temperature (^{o}C)		Precipitation (mm/d)	
	RMSE	Correlation	RMSE	Correlation
Pakistan	2.9	0. 96	0.92	0. 76
I (a): Greater Himalayas (Winter dominated)	4.88	0. 98	1. 80	0. 80
I (b): Sub-montane region and Monsoon dominated	4. 28	0. 94	1. 28	0. 82
II: Western Highlands	4. 16	0. 95	1. 12	0. 59
III: Central & Southern Punjab	4. 22	0. 92	1. 01	0. 86
IV: Lower Indus Plains	3. 21	0. 93	1. 45	0. 92
V (a) : Balochistan Plateau (Northern)	2. 71	0. 96	0. 80	0. 39
V (b): Balochistan Plateau (Western)	2. 44	0. 98	0. 46	-0. 10
VI: Coastal Belt	2. 21	0. 95	1. 18	0. 89

It is clear that for model correlation with observation for temperature over all climatic regions, the correlation was very high which indeed for the case of temperature was true because temperature has large scale spatial variability and the model processes are mostly better for temperature. For precipitation, the correlation was high only over those regions which receive some amount of precipitation throughout the year. Over the dry region like region V (a and b), the correlation seemed to be insignificant.

Although from validation, it can be observed that there were many biases in the simulation results, but in climate modeling biases are acceptable as none of the currently available climate model is perfect for simulation. Further, in case of temperature biases present in the base line period, were automatically cancelled out with the same biases in future simulation. Therefore, after the validation of PRECIS RCM with CRU data, simulation for the base time slice of 1961-1970 was performed with and without sulphur cycle using A2 scenario data of HadAM3P driving GCM. Results corresponding to the base period climatology are discussed in the section below.

4.3 Base Period (1961-70) climatology

To see the effect of sulphur cycle, PRECIS sulphur cycle scheme was incorporated in the simulation for base line time period (1961-1970). Two simulations were performed for the base period, one with sulphur cycle and the other without sulphur cycle. Figure 13 shows the difference (with sulphur-without sulphur) in the base line climatology for two simulations. Spatial patterns of temperature showed some spotted and localized impact of aerosols over many parts of South Asia. But from the magnitude of difference in temperature, many of these spots were insignificant. Same was the case for precipitation where many spotted changes were observed which is due to the inclusion of sulphate aerosols. It is also indirectly linked with the amount of cloud condensation nuclei that play role in the formation of clouds.

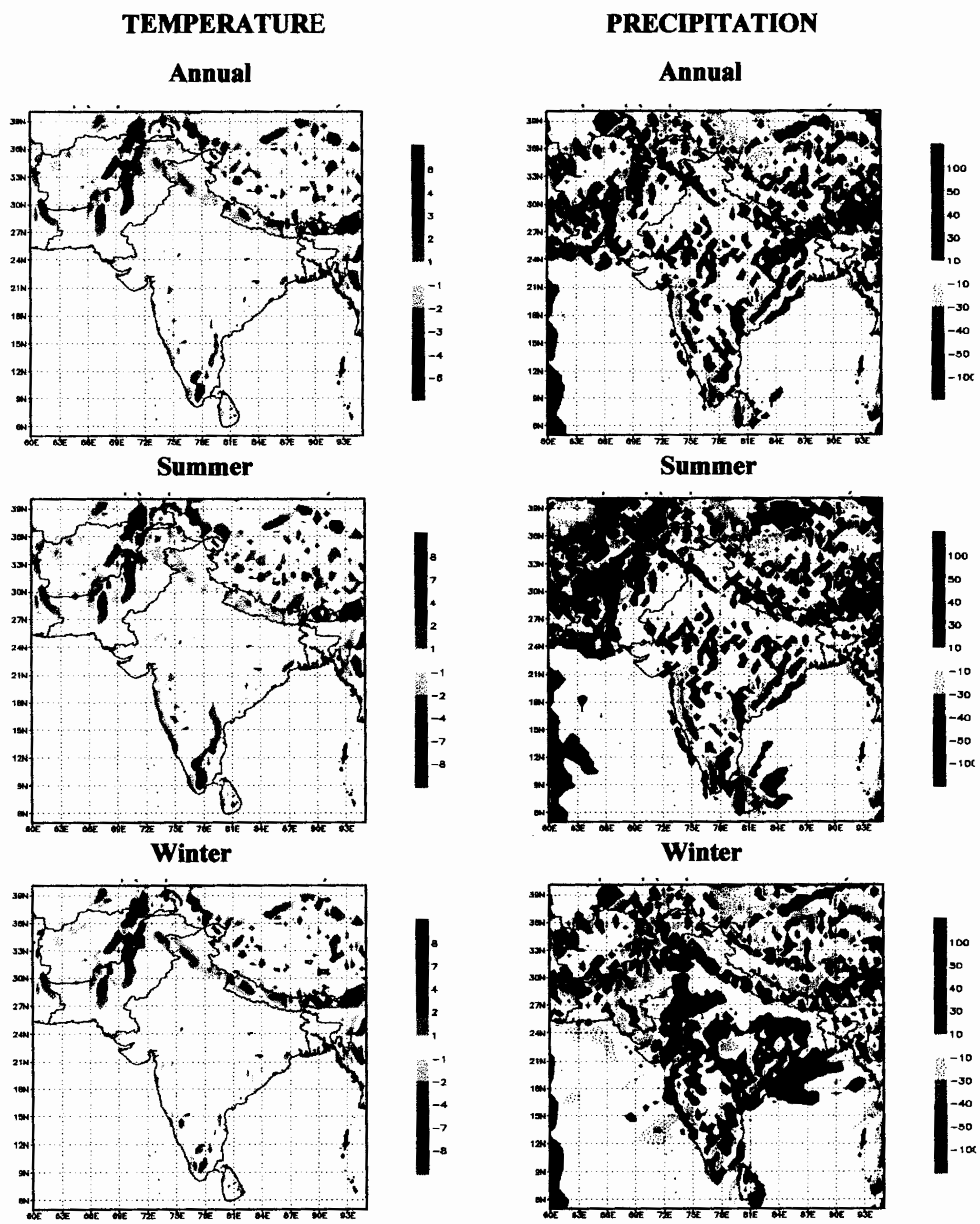


Figure 13. Difference (base with sulphur-base without sulphur) in base line climatology for annual, summer and winter means temperature (^{0}C) (Left Column) and precipitation (%) (Right Column) over South Asia (1961-1970)

With significant observation that there were few changes in climatology over whole South Asia domain by including the sulfate aerosols effect, Pakistan region for further analysis was zoom out. Figure 14 depicts the same differences as shown in the Figure 13 but it is particularly for Pakistan. Impact of sulphate aerosol was not even regular over whole country (Figure 14) and reduction in temperature over few regions in summer was seen particularly over Baluchistan region. In case of precipitation, reduction in the winter precipitation was observed in few regions when compared with summer and annual climatology. In the summer season, the same areas, where some changes in temperature were seen, were showing an increase in precipitation. This may be due to enhanced heating effect which forced model to precipitate more over the same regions.

In this study it is important to mention that for both simulations in base line period (with and without sulphur cycle), initial conditions of the model were kept same. It supported the core purpose that only the effect which was visible in spatial patterns were due to sulphate aerosols so it has nothing to do with any noise effect or randomization of the data.

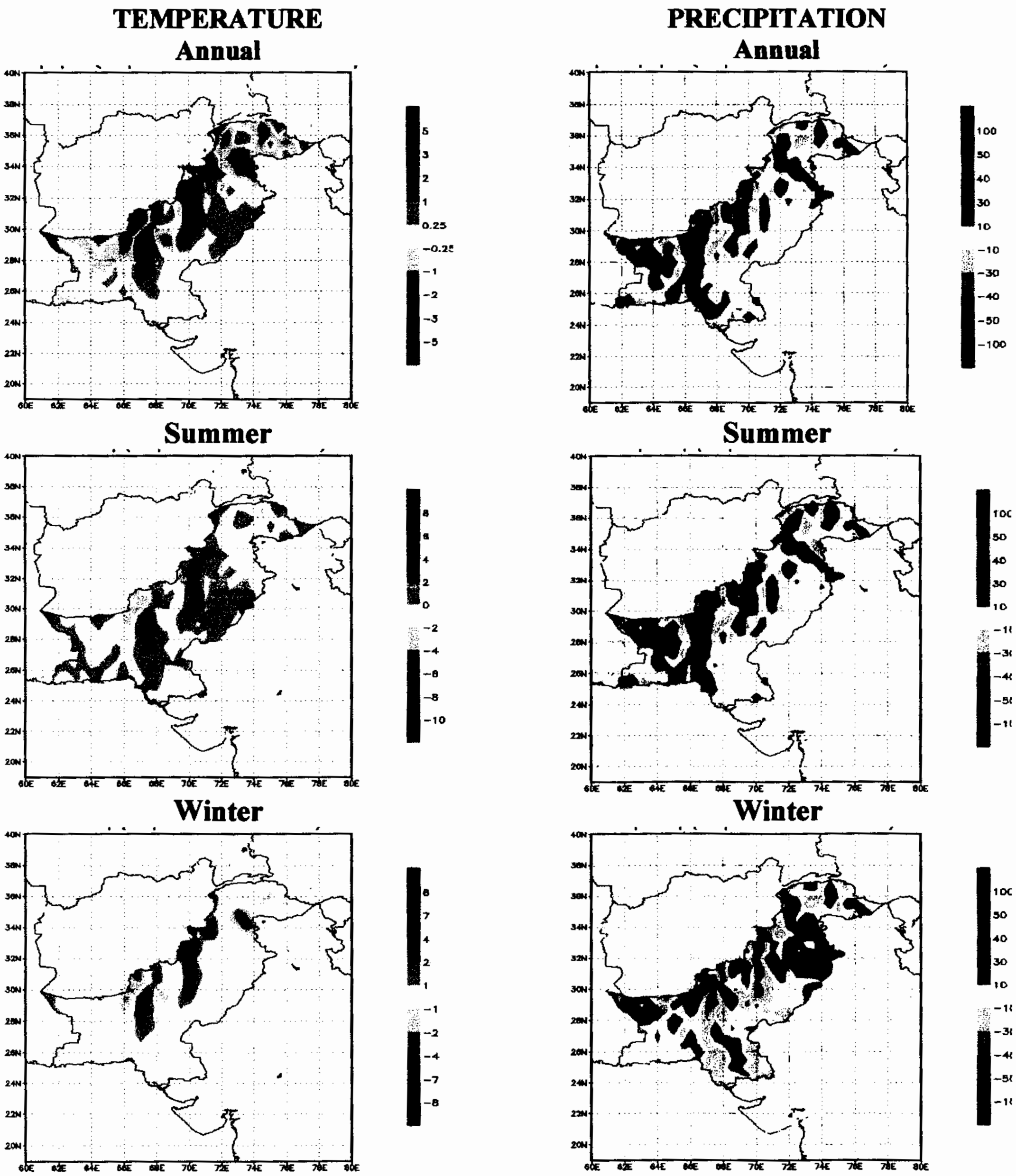
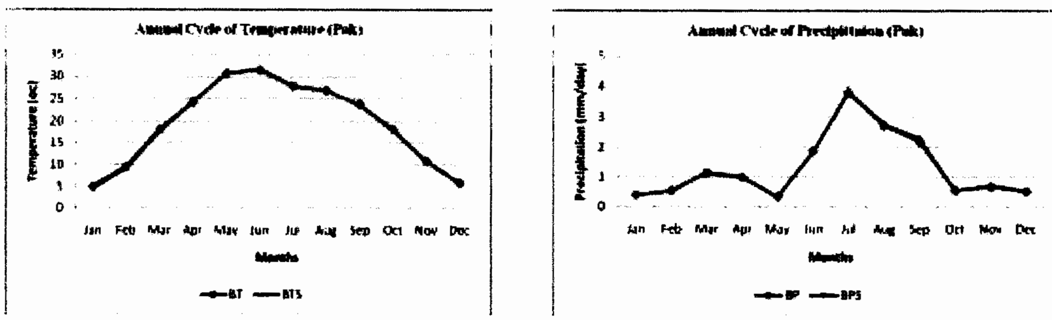


Figure 14. Difference (base with sulphur-base without sulphur) in base line climatology for annual, summer and winter means temperature (^{0}C) (Left Column) and precipitation (%) (Right Column) over Pakistan (1961 - 1970)

For base period (1961-1970), annual cycle of temperature and precipitation over Pakistan was averaged as shown in Figure 15. Both figures show that there is no significant change for temperature and precipitation.



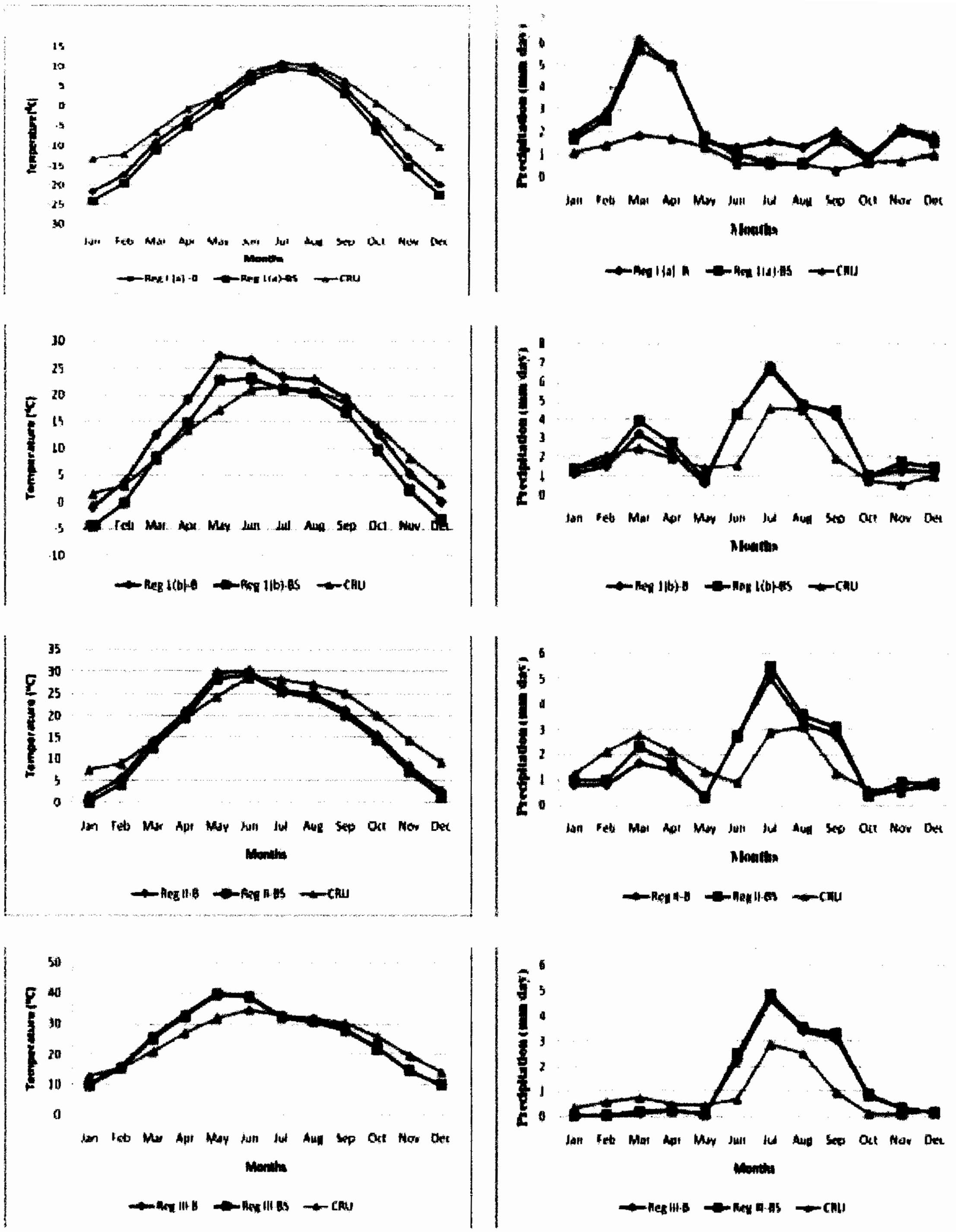
(BT=Base temperature, BTS=Base temperature with sulphur, BP= Base precipitation, BPS= Base precipitation with sulphur)

Figure 15. Annual cycles of mean temperature (^{0}C) and precipitation (mm/day) for the time period 1961-1970 over Pakistan

4.3.1 Baseline Climatology for Climatic Regions

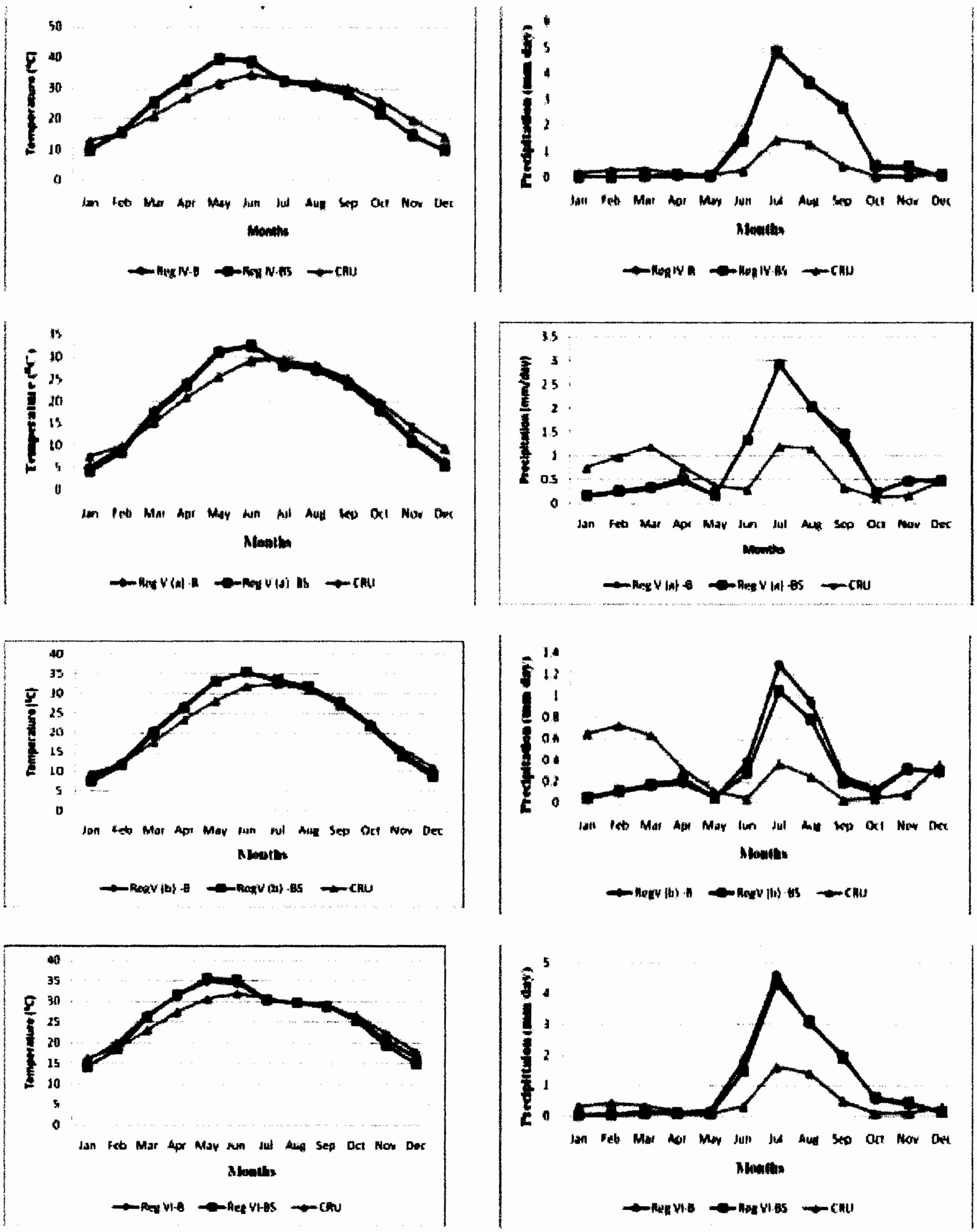
Annual cycle of temperature and precipitation for observed CRU data and model output (influenced by sulfur scheme of the RCM) for the base line period of 1961-1970 were shown on different climatic regions of Pakistan in Figure 16 (a and b). While comparing the base period, it was clear that there were differences in observed and model cycles in some particular months. The patterns of the cycle were almost same when model baseline time period was compared with its sulphur cycle base time period. For temperature, this pattern was same but with the difference in temperature values (temperature change). For precipitation, again in few regions the decrease was prominent as reduction in winter precipitation and weak monsoon in Region I(a) and Region (III) , while again in

Region I(b) the winter precipitation pattern was weak and also showing reduction in monsoon in Region V(b). These reductions in temperature and precipitation pattern enhanced direct and indirect impact of sulphate aerosols in these regions.



(Reg = Region, B= base, BS=.base with sulphur, CRU=Climate Research Unit (Observed temperature and precipitation

Figure 16 (a). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the time period 1961-1970 over different climatic regions of Pakistan



(Reg=.Region, B=.base, BS=.base with sulphur, CRU=Climate Research Unit (Observed temperature and Precipitation.)

Figure 16 (b). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the time period 1961-1970 over different climatic regions of Pakistan

4.4 Future Period (2071-2080) climatology

Figure 17 exhibits the climatology of projected change in temperature and precipitation for future time period (2071-2080) over Pakistan. Changes due to sulphate aerosols on annual as well as seasonal basis are shown. From the climatology, it was significant that reduction in temperature is prominent in winter when compared with summer climatology over Pakistan. On seasonal basis, in summer, reduction in precipitation in few northern areas and in winter, significant reduction, of 20-30% in Gawadar, Bhawlpur, Bella and few regions of Peshawar was observed.

For baseline time period and future time period climatology over Pakistan, reduction in temperature and precipitation was giving support to first direct and second indirect impact of sulphate aerosols.

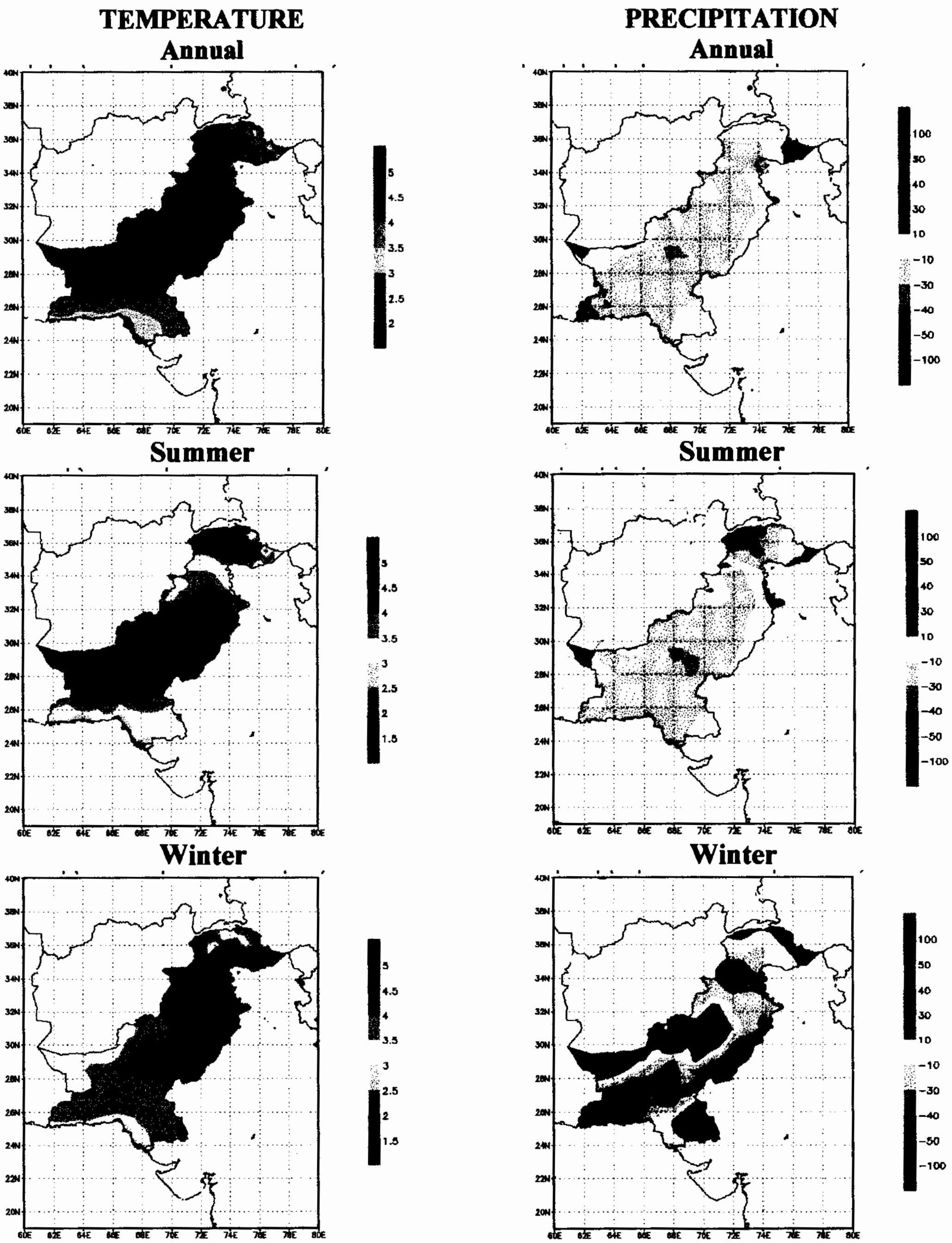
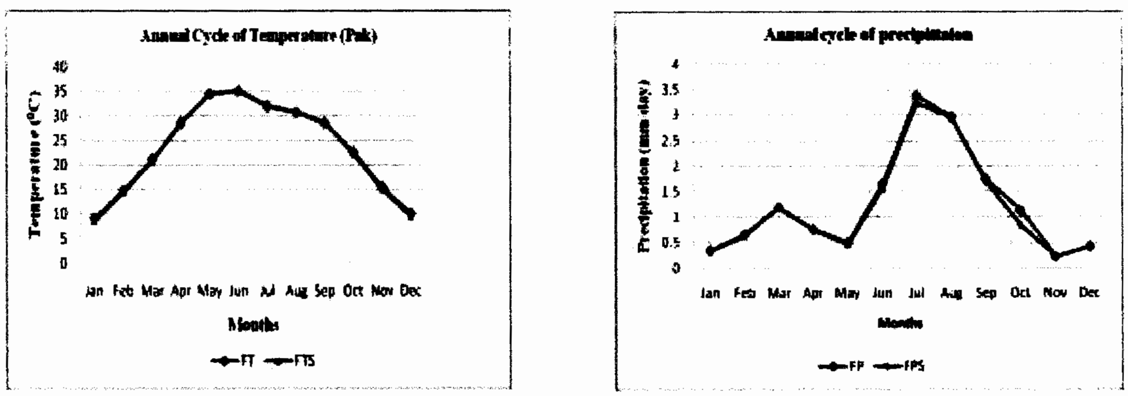


Figure 17. Projected future changes (future with sulphur-base with sulphur) in mean annual, summer and winter temperature (^{0}C) (Left Column) and Precipitation (%) (Right Column) over Pakistan (2071-2080)

Annual cycles of temperature and precipitation over Pakistan for future are also shown in Figure 18. For temperature, the trend was almost same but in case of precipitation, less precipitation was observed for the months of July, September, October and November.



(FT= Future temperature, FTS= Future temperature with sulphur, FP= Future precipitation, FPS= Future precipitation with sulphur)

Figure 18. Annual cycles of mean temperature (^{0}C) and precipitation (mm/day) for the time period 2071-2080 over Pakistan

4. 4. 1 Future Projections for Climatic Regions

In this study Pakistan was focal discussion area, so for that purpose detailed analysis of the impact of aerosols on future temperature and precipitation changes have been worked out on annual basis over different climatic regions of Pakistan. Spatial patterns were analyzed over whole Pakistan domain, where as for different climatic regions, time series analysis of annual cycles was carried out with and without sulphur cycle scheme. The projected temperature and precipitation changes over different climatic regions for the base (1961-1970) and future (2071-2080) time period are shown in Table 4 and 5. From table 4, it is notable that Projected changes for future-base and future sulphur –base sulphur showed that after incorporating sulphur scheme in simple future-base time periods (1961-1970 and 2071-2080), decrease in temperature was prominent in Northern parts of Pakistan (34°N – 37. 2°N) i-e region (I(a,b) and II) and Central parts of Pakistan (30°N – 34°)i-e, region (III) while for Southern parts of Pakistan (24°N – 30°N) i-e, region (IV, V(a,b), VI) (Islam, et al., 2009) there was no significant reduction.

Table 4. Projected temperature changes (^{0} C) over climatic regions

PROJECTED TEMPERATURE ΔT(°C)			
Climatic Regions	**Change (F-B)**	**Change (FS-BS)**	**Difference= (FS-BS)-(F-B)**
I (a): Greater Himalayas (Winter dominated)	4. 15	4. 08	-0.07
I (b): Sub-montane region and Monsoon dominated	4. 36	4. 26	-0.1
II: Western Highlands	4. 34	4. 29	-0.05
III: Central & Southern Punjab	4. 88	4. 69	-0.19
IV: Lower Indus Plains	4. 04	4. 16	0.12
V (a) : Balochistan Plateau (Northern) (Suleman & Kirthar Ranges)	4. 27	4. 28	0.01
V (b): Balochistan Plateau (Western)	4. 14	4. 17	0.03
VI: Coastal Belt	3. 43	3. 72	0.29

It is significant that in these climatic regions the sulphur dioxide emissions which resulted in sulphate aerosol formation were high particularly in region (III) due to industrial activity and transportation when compared with other regions. This could also be verified by using observed data of 10 years (1990-2000) from GAINS Asia model of IIASA (Figure 19). GAINS Asia model take Region (III) under Punjab (http://gains. iiasa. ac. at/gains/IND/index. login?logout=1). An assumption could be developed on the basis of GAINS model results that if sulphur dioxide emissions are high in Punjab from different sectors for the time period of 1990-2000 then this region in the past (1961-1970) would be having more industrial activity at initial stages of development.

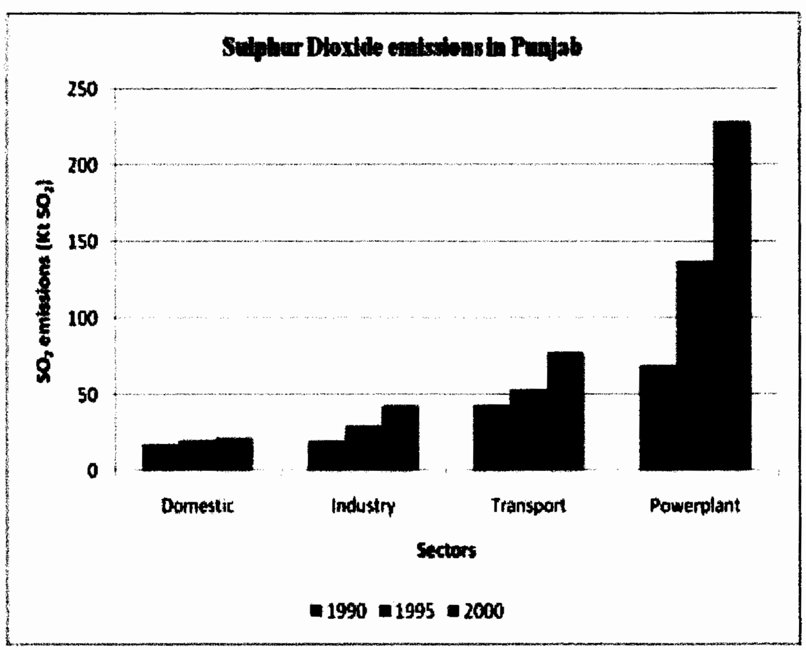


Figure 19. Sulphur Dioxide emissions in Punjab for the time period of 1990-2000

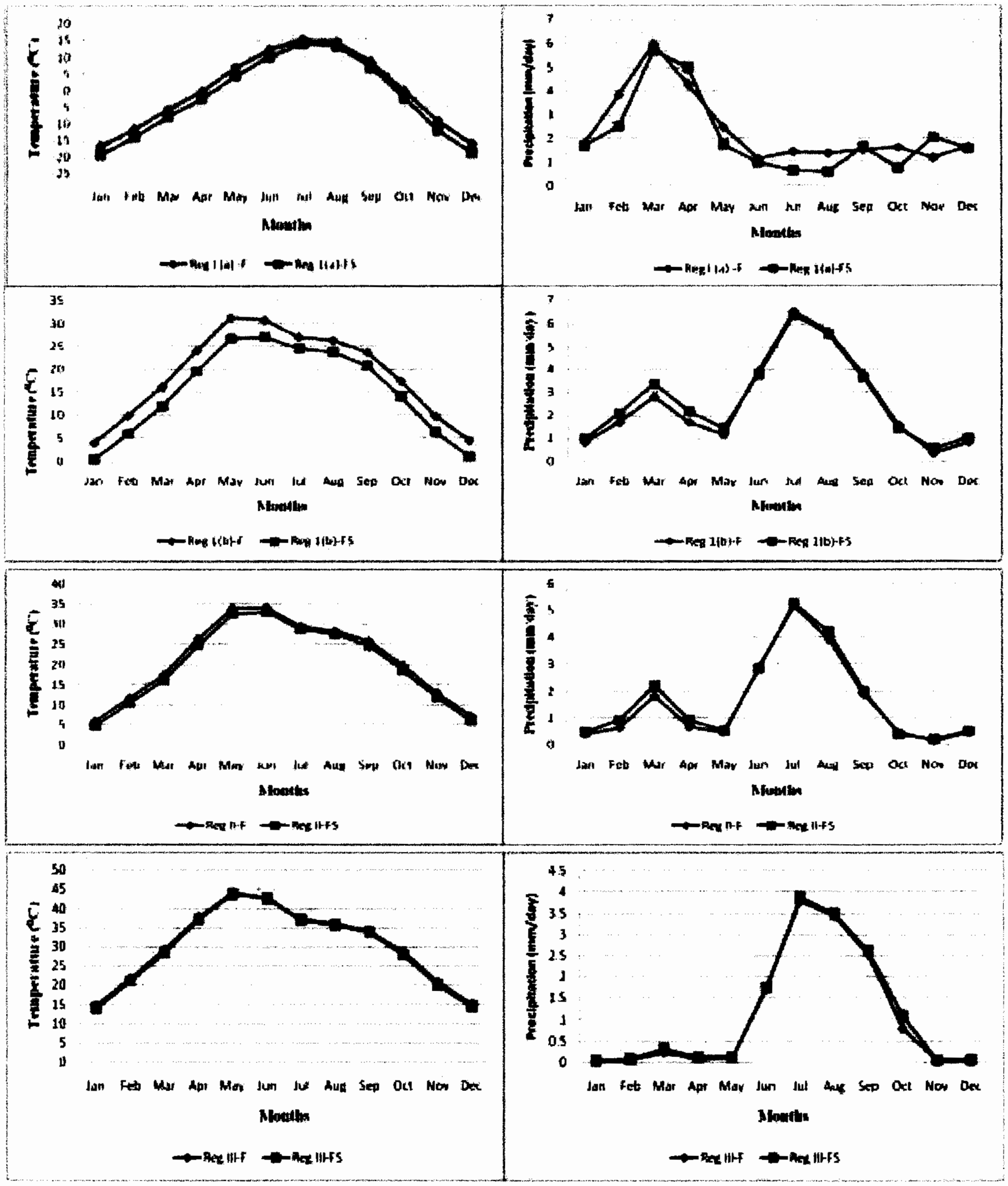
(Source: GAINS Asia model from IIASA)

In case of projected precipitation in table 5, after inclusion of sulphur cycle in model, there was prominent reduction in precipitation in almost all regions expect region I (a) for projected change with sulphur. Table 5 shows that for precipitation, the impact of sulphate aerosols was significant in almost all regions expect few which supported the view point that reduction in precipitation was due to life time effect of sulphate aerosols and was an important property of these aerosols.

Table 5. Projected precipitation changes (%) over climatic regions

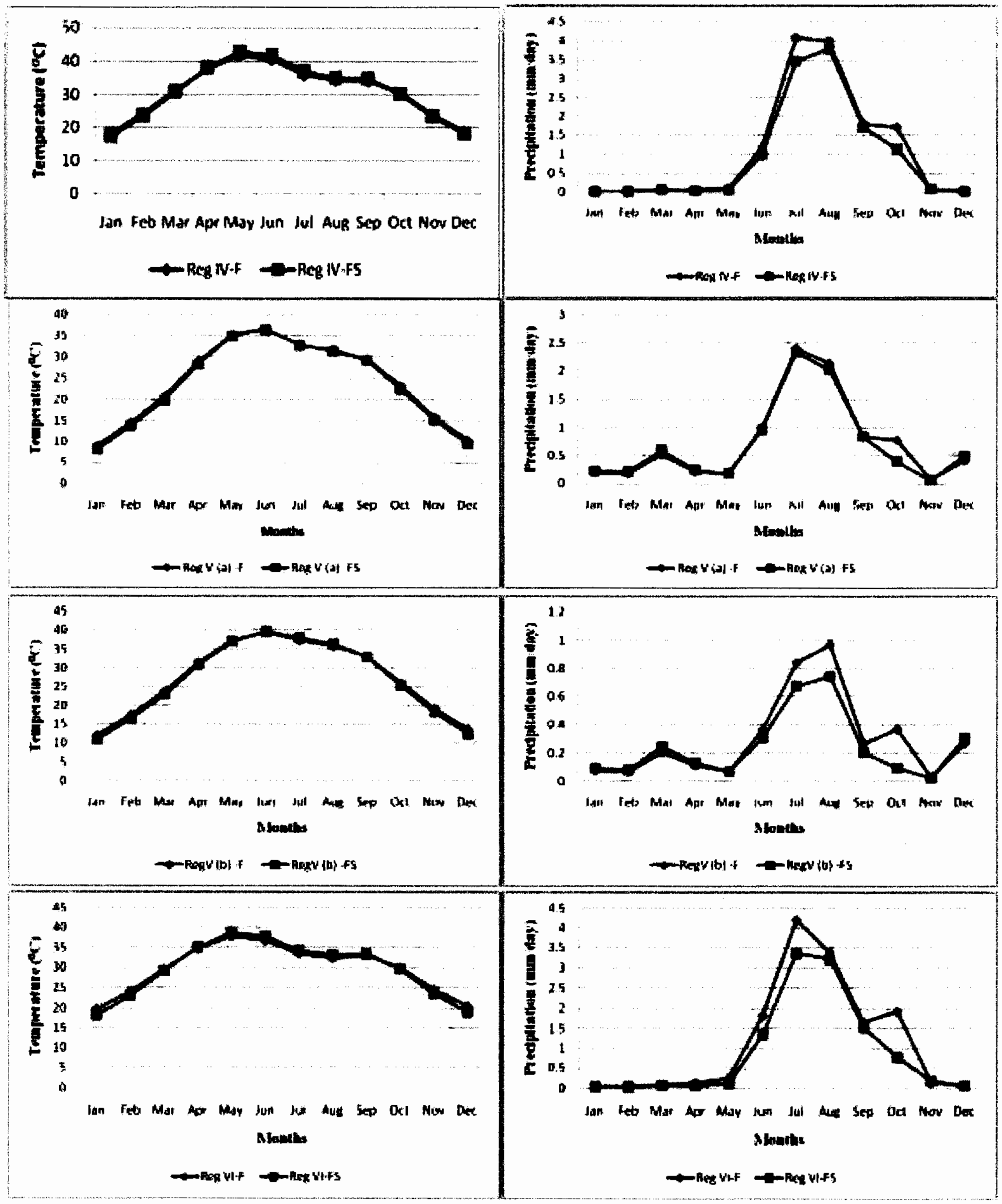
PROJECTED PRECIPITATION ΔP (%)			
Climatic Regions	**Projected Change without Sulfur A=(F-B/B *100)**	**Projected Change with Sulfur B=(FS-BS/BS *100)**	**Difference =B-A**
I (a): Greater Himalayas (Winter dominated)	-0. 63	3. 01	3.64
I (b): Sub-montane region and Monsoon dominated	-4. 65	-7. 34	-2.69
II: Western Highlands	-7. 77	-11. 87	-4.1
III: Central & Southern Punjab	-15. 71	-16. 73	-1.02
IV: Lower Indus Plains	-7. 33	-17. 33	-10.0
V (a) : Balochistan Plateau (Northern) (Suleman & Kirthar Ranges)	-11. 97	-18. 32	-6.35
V (b): Balochistan Plateau (Western)	-11. 78	-17. 28	-5.5
VI: Coastal Belt	5. 59	-12. 37	-17.96

Effect of the inclusion of sulfur scheme on future temperature and precipatation for the time period of 2071-2080 by developing annual cycles were also analyze as shown in Figure 20 (a and b) . Both of the time series were for future but one time series was drawn with out any influence from model sulphur scheme while the othere one has sulphate aerosols influence. In most of the cases both the time series were almost similar except the drop of 2^0C and 4^0C in Region I(a) and Region I(b). In cae of precipitatation, again there was no significant changes observed over different climatic regions of Pakistan expect in Region I(a) and Region I(b) with reduction in winter precipitation while in Region IV, RegionV(b) and in Region VI monsoon was weak.



(Reg= Region, F= Future, FS= Future with sulphur, CRU= Climate Research Unit (Observed temperature and Precipitation)

Figure 20 (a). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the period of 2071-2080 over different climatic region of Pakistan



(Reg= Region, F= Future, FS= Future with sulphur, CRU= Climate Research Unit (Observed temperature and Precipitation)

Figure 20 (b). Annual cycles of mean temperature (^{0}C) (Left Column) and precipitation (mm/day) (Right Column) for the period of 2071-2080 over different climatic region of Pakistan

CHAPTER 5

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- The analysis for South Asia region showed that, first and second impact of sulphate aerosols on annual as well as seasonal basis showed no significant change supporting the view that impact of sulphate aerosols was localized and for few days. These large scale patterns over whole South Asia lead us to conclude that sulphate aerosol didn't contribute significantly to climate change when compared with other Green house gases.

- Further, the detailed analysis conducted over Pakistan showed that the Sulphate aerosol impact was again not that significant when considered annually. However, in case of seasons the impact of sulphate aerosols showed an increase in precipitation during summer and decrease in winter on some regions in Pakistan. Reduction in temperature was mainly significant in Northern parts i-e, Region

(I(a,b) and II) and central and southern Punjab i-e Region (III) where the sulphur dioxide emissions in sulphate aerosols formation were high due to industrial and transportation activity. There was prominent reduction in precipitation in almost all regions expect region I (a) for projected change with sulphur.

- The results showed that the particular difficulty in calculating the indirect effect was not only depended on uncertain distribution and composition of the aerosol and its interaction with clouds and the cloud development.

- Pakistan, being a developing country, contributes very little in emissions supporting the reason that the impact of sulphate aerosols was not that significant over Pakistan except for few regions which were under heavier industrial actions and transport activities.

- Another impact of sulphur dioxide emissions which is not studied but must not be ignored was health impact (SO_2 may also cause respiratory disorders[6]) of Sulphur dioxide (SO_2) as a gas which created sulphurous materials, particularly oil and coal when combusted in a number of industrial processes.

- In this study reduction in temperature and precipitation resulted in masking warming effect of greenhouse gases over few regions of Pakistan.

[6]Source: Statistics Norway, 2007 at http://www.ssb.no/svoveln_en/).

5.2 Recommendations

- Stringent control strategies are required in those regions (region III) of Pakistan which exhibited reduction in temperature and precipitation due to high industrial, transport activities along with quite heavy fuel use at domestic level. These strategies include Electrostatic precipitators; Baghouses, Particulate scrubbers[7] etc will reduce sulphur dioxide emissions which are precursors of sulphate aerosols.

- Control on transboundary pollution and implementation mechanism to control emissions which equally contribute to the formation of sulphate aerosols are needed to be considered by policy planners of the country while discussing the appropriate issues at regional or international forums

- Climate models are not absolutely accurate in predicting the future of climate change. However ,future modeling studies should include all major and minor contributing factors such as high resolution climate models, data handling/storage facilities, inclusion of data of GHG's ,refinement of techniques and scope of minor gases which may alter the climate.

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[7]Sourcehttp://en.wikipedia.org/wiki/Air_pollution#Control_devices

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