IMPACT OF CLIMATE CHANGE ON INDIAN PLANTATION SECTOR WITH SPECIAL REFERENCE TO NATURAL RUBBER

Ph.D. Thesis

Submitted to

Mahatma Gandhi University

Kottayam, Kerala, India

By

SATHEESH P.R.

In partial fulfillment of the requirements for the award of the degree of

Doctor of Philosophy in

BOTANY

Rubber Research Institute of India

Kottayam, Kerala, India

January 2014

"Man is made by his belief.
As he believes, so he is."

Bhagavad Gita

Dedicated to My Family & Teachers

DECLARATION

I do hereby declare that the thesis entitled "**Impact of climate change on Indian plantation sector with special reference to natural rubber**" submitted to Mahatma Gandhi University in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy in Botany, is an authentic record of the work carried out by me under the supervision and guidance of Dr. James Jacob (Director) and Dr. A. Thulaseedharan (Deputy Director, Biotechnology), Rubber Research Institute of India, Kottayam, Kerala, India. No part of this work has been presented for the award of any degree, diploma or other title in any university.

Kottayam
20/01/2014

Mr. Satheesh P. R.

The Rubber Research Institute of India
Rubber Board, Ministry of Commerce and Industry
Government of India, Kottyam-686 009, Kerala, India

Kottayam
20/01/2014

CERTIFICATE

This is to certify that the thesis entitled "**Impact of climate change on Indian plantation sector with special reference to natural rubber**" is an authentic record of original research carried out by Mr. Satheesh P. R., at the Rubber Research Institute of India, Kottayam, under our supervision and guidance for the award of the Degree of Doctor of Philosophy in Botany, under the Faculty of Science, Mahatma Gandhi University, Kottayam. It is also certified that no part of this work has been presented earlier for any degree, diploma or any other similar titles in any university.

A. Thulaseedharan Ph.D.
Deputy Director (Biotechnology)

James Jacob Ph.D., D.I.C., Ph.D.
Director

Tele Phone : +91-481-2353311 to 2353320 Fax: +91-481-2353327
E-mail: james@ rubberboard.org.in; thulaseedharan@rubberboard.org.in

ACKNOWLEDGEMENTS

I have been very fortunate to do my Ph.D. research in a highly challenging, important and relevant area of science in the inspiring and stimulating environments of the Rubber Research Institute of India (RRII) under the Rubber Board, Ministry of Commerce & Industry, Government of India, Kottayam, Kerala.

I thank my guides and supervisors, Dr. James Jacob, Director and Dr. A. Thulaseedharan, Deputy Director (Biotechnology), Rubber Research Institute of India, Kottayam for their wholehearted support and encouragement. Dr. R. Krishnakumar, Joint Director (Crop Pysiology), Dr. K. Annamalainathan, Deputy Director (Crop Physiology), Dr. C.P. Reghu, Deputy Director (Germplasm) and all scientists and staff and research fellows in the Physiology Division were extremely helpful.

Statistical and computing help provided by Mr. Ramesh B. Nair, Mr. P. Anish and Mr. B. Biju are gratefully acknowledged. I also thank all officers and staff working in the RRII library for their excellent service.

I remember with gratitude all seniors and friends at RRII and outside for their constant encouragement. I am particularly indebted to Mr. Amith Abraham, Mr. Arun V.K. and Mr. Pramod S. for their valuable suggestions and encouragements.

I bow down to **my beloved parents and family members** for their moral support, immense patience and loving care that made me more confident.

Finally and foremost I thank the **God Almighty** for having made possible the successful completion of my thesis.

I thank Rubber Board for providing the financial support in the form of a research fellowship.

Satheesh P.R.

Table of Contents

List of Figures

List of Tables

Abbreviations

^{0}C	Degree celsius
Aeco	Ecosystem assimilation
AGGI	Annual Greenhouse Gas Index
ann	Annual
AR4	Fourth Assessment Report (of IPCC)
AR5	Fifth Assessment Report (of IPCC)
BASIC	Brazil, South Africa, India and China
CDM	Clean Development Mechanism
CERs	Certified Emission Reductions
CES	Central Experimental Station
CFC	Chlorofluorocarbons
CH_4	Methane
CIA	Central Intelligence Agency
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CoP	Conference of the Parties
DES	Department of Economics and Statistics
EC	Eddy covariance
ET	Evapotranspiration
et al.	et alia (and others)
FACE	Free Air Carbon dioxide Enrichment
FAO	Food and Agriculture Organization
FAR	First Assessment Report (of IPCC)
Fc	Carbon dioxide flux
$g\ t^{-1}t^{-1}$	Gram per tree per tap
GDD	Growing degree-days
GDP	Gross Domestic Product
GEE	Gross ecosystem exchange
Gg	Giga gram
GHGs	Greenhouse Gases
GJ	Gigajoule
GtC	Giga ton Carbon

GWP	Global Warming Potential
ha	Hectare
Hd	Hot day
HDI	Human Development Index
HDR	Human Development Report
HFCs	Hydrofluorocarbons
IET	International Emissions Trading
IFPRI	International Food Policy Research Institute
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
IRSG	International Rubber Study Group
JI	Joint Implementation
kg	Kilogram
KP	Kyoto Protocol
LE	Latent heat flux
LUCF	Land use change and forestry
M ha	Million hectare
MLR	Multiple linear regression
mm	Millimeter
Mt	Million ton
N_2O	Nitrous oxide
NAMAs	Nationally appropriate mitigation actions
NASA	National Aeronautics and Space Administration
NE	Northeast
NEE	Net Ecosystem Exchange
NEM	Northeast monsoon
NOAA	National Oceanographic and Atmospheric Administration
NR	Natural Rubber
O_2	Oxygen
OECD	Organization for Economic Cooperation and Development
PES	Payment for ecosystem/environmental services
PFCs	Perfluorocarbons
Pg	Peta gram

PgC	Peta gram carbon
ppb	Parts per billion
ppm	Parts per million
QELRCs	Quantified Emissions Limitation and Reduction Commitments
Reco	Ecosystem respiration
RF	Radiative forcing
RFD	Rainy days
RH	Relative humidity
RRIC	Rubber research Institute of Colombo
RRII	Rubber research Institute of India
RRIM	Rubber research Institute of Malaysia
RRS	Regional Research Station
SAR	Second Assessment Report (of IPCC)
SD	Standard deviation
SF_6	Sulfur hexafluoride
SLE S	Sea Level Equivalent
SRES	Special Report on Emission Scenarios
SW	Southwest
SWM	Southwest monsoon
TAR	Third Assessment Report (of IPCC)
Tmax	Maximum temperature
Tmin	Minimum temperature
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VPD	Vapour pressure deficit
Wm^{-2}	Watts per meter square
WMO	World Meteorological Organization
Wn	Warm night

PREFACE

Ordinary rubber growers in India and other rubber growing countries are concerned about climate change and how this will affect growth and productivity of rubber. Several studies have shown that supply of natural rubber will become deficient in the years ahead and climate change occurring in the major rubber producing countries in South and South East Asia may make things even worse. International agencies such as the Singapore-based International Rubber Study Group and the Kuala Lumpur-based Association of Natural Rubber Producing Countries and the International Rubber Research and Development Board are also concerned about this issue. Indian Rubber Board has been associating with these agencies to assess the impact of climate change on natural rubber. The Rubber Research Institute of India (RRII) under Rubber Board has done pioneering work in this area which is well acknowledged by the international community.

I joined RRII in 2006 to work on climate change and rubber and took up a Research Fellowship position there in 2009. Climate change is a complex phenomenon and rubber is not an easy crop to work with. I had little experience in climate change science or rubber research before joining the RRII. When this subject was selected for my Ph. D. research, I had my own reasonable and serious apprehensions if I could achieve any progress. But with the excellent support that I got from RRII, today I am happy that I could accomplish some good success in assessing how climate has changed in the plantation belts of India and to what extent that can affect natural rubber.

It was somewhat surprising that climate warming had different impacts on rubber yield in Kerala and Northeast India. I could quantify to what extent rubber yield will decline if temperature goes up by one degree celsius which has not been accomplished in any country before. Rising temperature will markedly reduce rubber yield in Kerala, but this can have a stimulatory effect on rubber yield in Northeast. Another interesting aspect of my study has been on carbon sequestration by rubber plantations. This was studied in real time and continuously for two years using the latest eddy covariance technique. This is the first such study in any ecosystem in India.

This thesis is arranged in seven chapters. Chapters 1 and 2 are introductory chapters. In chapter 1 I have given some general information about Indian plantation crops and their agro-climatic requirements. Chapter 2 introduces the science and signs of climate change. Chapter 3 analyses the extent of climate change that has happened in the plantation crops growing regions of India. Chapter 4 examines how climate change has affected productivity of natural rubber and how growers respond to it. Chapter 5 discusses the ecosystem services provided by natural rubber plantations in terms of CO_2 sequestration. Chapter 6 describes international climate change negotiations and analyses global emission data of different countries. Chapter 7 gives salient conclusions of this thesis. Detailed references are given at the end of each chapter for further reading.

Satheesh P. R.

ABSTRACT

India has a long history of cultivation of plantation crops such as tea, coffee, cardamom and rubber. Among them, tea is perhaps the oldest plantation crop and rubber the most recent, which also has the largest area. These crops are concentrated mostly in South India, but parts of Northeast India also have sizable area under tea, followed by natural rubber. Together, these crops are cultivated by about two million growers. India has a total area of 0.76 million ha under natural rubber cultivation. India is the sixth largest country in terms of area under natural rubber. It is also the fourth largest producer and third largest consumer of natural rubber. As the Indian economy grows, there will be increasing demand for natural rubber supply. However, climate has been changing in the plantation belts of India, including areas where natural rubber is cultivated which may pose a major obstacle to the efforts to increase natural rubber supply in the country.

Simple linear trend analyses and Mann-Kendall significance test of the long term temperature data collected from different sources like Indian Meteorology Department, Indian Institute of Tropical Meteorology and the Regional Research Stations of the Rubber Research Institute of India (RRII) under the Rubber Board showed that climate has undergone significant changes in the plantation growing regions of India. Minimum and maximum temperatures showed an increasing trend in all plantation growing regions in India, except a cooling trend in some seasons in a few regions. Central Kerala where natural rubber cultivation is widespread has been warming faster (average of 0.45 ^{0}C per decade) than the country as a whole, which can have major implications for natural rubber cultivation. Changes were more conspicuous in temperature than in rainfall. Extreme temperature events showed an increasing trend but extreme rainfall events did not show any change. These changes might have impacted the productivity of natural rubber in the country. Multiple linear regression model analysis on yield and weather parameters showed that climate warming has qualitatively and quantitatively different impacts in different agro-climatic regions where this crop is presently cultivated in India. In the traditional regions warming will reduce rubber yield, but not in Northeast India where warming may increase rubber productivity. No marked variations in the response of rubber clones to rising temperature were noticed in this study.

Eddy covariance and biomass inventory studies for assessing the carbon sequestration potential of rubber plantation showed that a 4-6 year old rubber ecosystem can sequester as much as 44 $tCO_2ha^{-1}yr^{-1}$. Taking a sequestration rate of 30 $tCO_2\ ha^{-1}yr^{-1}$, world's total 12.2 million hectare of rubber plantation can fix as much as 366 million tCO_2 every year which is equal to 2.5% of the current rate of buildup of CO_2 in the atmosphere which is about 1.9 ppm $CO_2\ yr^{-1}$. The results of the analyses on global carbon balance revealed that planting trees will not alone answer the problem of CO_2 buildup in the atmosphere and associated climate change.

The adverse effects of climate change will hit harder on poor countries than rich nations. As a developing country, India faces many challenges due to climate change. India's first primary challenge is eradication of poverty by assuring food security through sustainable development. India's economy is one of the biggest in the world, but the per capita income in India is one of the lowest; not even coming in the top 100 positions among the comity of nations. Neither is per capita emission in India large. While negotiating for any capping CO_2 emission by developing nations in international climate meets, treating China and India together is not fair or correct. Both are developing nations, but China is far ahead of India by several folds in emission, economy, energy consumption, carbon intensity of economy etc.

Keywords: Carbon Dioxide, Carbon Sequestration, Climate Change, Eddy Covariance, Greenhouse Gas, Multiple Linear Regression, Natural Rubber

CHAPTER 1

PLANTATION CROPS OF INDIA: DISTRIBUTION AND AGRO-CLIMATIC REQUIREMENTS

"What we are doing to the forests of the world is but a mirror reflection of what we are doing to ourselves and to one another"

Mahatma Gandhi

1.1. Introduction

Plantation crops are perennial (and mostly tree) species that are cultivated in large extents of contiguous areas as a monocrop. India has a long history of cultivation of plantation crops such as tea, coffee, cardamom and natural rubber (NR). Among them, tea is perhaps the oldest plantation crop and natural rubber the most recent, which also has the largest area among these crops (IRSG, 2013). These crops are concentrated mostly in South India, but parts of Northeast India also have sizable area under tea, followed by natural rubber. Together, these crops are cultivated by about two million growers. Crops such as coconut, areca nut, cocoa, cashew and oil palm are also considered as plantation crops and about 8-10 million smalltime farmers grow these crops in India. Another equal number of people may be directly or indirectly depending on these crops for their livelihood.

Plantation crops are cultivated in remote and rural parts of India where they provide considerable employment opportunities and make significant contributions to the rural economy. These crops also earn foreign exchange for the country. As these are essential commodities, their domestic production helps avoid imports. Crops such as coffee and tea are grown in ecological niches along the hilly tracts of Western Ghats, pockets in the Eastern Ghats and in the sub Himalayan regions of Northeast India. The other crops are grown mostly in the plains or foot hills of the Western Ghats. Coconut is more ubiquitous and this is cultivated throughout the coastal belt of India and in the Deccan plateau.

Different altitudes of the Western Ghats are home to various species and plantation crops. Western Ghats, a hotspot of biological diversity, has been subjected to severe ecological degradation over the past several decades. These crops were first cultivated during the colonial period in the Western Ghats after cutting forests one or two centuries ago when ecological considerations were not as strong as they are today. These regions produce the lion share of spices and plantation crops in the country. The recent reports of the Western Ghats Ecology Expert Panel and the High Level Working Committee appointed by the Ministry of Environment and Forests, Government of India to look into the issue of ecological degradation of Western Ghats included large extents of these crops grown the Western Ghats in ecologically sensitive zones/areas with serious implications for their continued cultivation (Thomas and Jacob, 2013). Western Ghats provide some of the congenial agro-climatic niches in the country where these crops can be best grown.

This chapter gives general information about the area under cultivation and production of the different plantation crops in India with special emphasis on natural rubber. The agro-climatic requirements for growing these crops and their distribution in the world and in India are also briefly given. Different plantation crops grown in India are tea, coffee, rubber, cardamom, cocoa, cashew, oil palm, coconut and areca nut. Among these, rubber, tea and coffee are the major plantations crops cultivating in India and the area under cultivation in different states in India is given in the table 1.1. Different parts of the country have suitable agro-climatic conditions to grow these crops, but Kerala is one state that is suitable for growing almost all of them. Among the plantation crops, natural rubber is the only non-edible commodity and is an engineering/industrial raw material of strategic importance. This is one crop for which India has the highest productivity. India is the largest producer and consumer of tea which is grown at the highest elevations among all the plantation crops, followed by cardamom, coffee, rubber and cocoa. The most congenial range of temperature for growing these crops is; tea (15 to 30 ^{0}C), coffee (18 to 30 ^{0}C), cocoa (18 to 32 ^{0}C), coconut (20 to 34 ^{0}C), cashew (22 to 35 ^{0}C), oil palm (24 to 28 ^{0}C), areca nut (14 to 36 ^{0}C) and rubber (21 to 35 ^{0}C) (George and Kuruvilla, 2000). Being rain-fed crops, all these crops require a well distributed rainfall throughout the year for their optimal growth and performance.

Table 1.1. Area (ha) under major plantation crops in some Indian states

Major Plantation Crops	Tamil Nadu	Kerala	Karnataka	West Bengal	Assam	Meghalaya	Tripura	INDIA Total
RUBBER 2010-11p	19767 (2.8)	534228 (75.0)	38110 (5.4)	625 (0.1)	32659 (4.6)	10584 (1.5)	59285 (8.3)	711560 (2010-11p)
TEA As on 31.12.2011	80460 (13.9)	37140 (6.4)	2140 (0.4)	115100 (19.9)	322210 (55.6)	North Indian states including Tripura & Meghalaya 22300 (3.8)		579350 (as on 31.12.2011)
COFFEE 2012-13p	31544 (7.6)	85359 (20.6)	230333 (55.5)			North Eastern Region Total 6039 (1.5)		415341 (2012-13p)

Figures in parenthesis indicates the percentage share of the total area in each states. p: Projection.

Sources: Rubber :- Indian Rubber Statistics Vol 36, 2012; Tea :- www.teaboard.gov.in About Tea Board - Databank – Tea Statistics – Annual – Area; Coffee :- www.indiacoffee.org Database on Coffee Sep 2013 by Market Intelligence & Statistical Unit, Coffee Board, Bangalore

1.2. Agro-climatic requirements and distribution of natural rubber in India

Hevea brasiliensis, widely known as the para rubber tree, is the primary source of natural rubber, the indispensable industrial/engineering raw material that goes into making over 50000 products that are in everyday use (George and Kuruvilla, 2000). *Hevea* is one of the most recently domesticated crops in the world, which is being cultivated commercially for the extraction of natural rubber. Natural rubber was first introduced in Asia in 1876, when its seeds were shipped from the Amazonas to Sri Lanka via the Kew Gardens in the United Kingdom (George and Kuruvilla, 2000). In 1876, Sir Henry A. Wickham collected 70000 seeds of *Hevea brasiliensis* from the Amazon basin and transferred to England. Only 2700 seeds germinated and they were sent to Ceylon of which 90 % survived. After several years of continuous research, rubber plantations were established in different countries in Southeast Asia. In India it was introduced from the Royal Botanic Gardens, Heneratgoda, Sri Lanka and the Indian rubber plantation industry started its cultivation largely in Kerala. The first commercial rubber plantation or estate in India was started in 1902 at Thattekad on the Periyar river bank (see www.rubberboard.org.in).

Hevea brasiliensis is found in its native places like northern part of South America, from Brazil to Venezuela, and Colombia to Peru and Bolivia. Rubber is now mostly grown in Malaysia, Indonesia, Thailand, Vietnam, Sri Lanka, China, India and Papua New Guinea in Asia, as well as to a much smaller extent in Nigeria, Côte d'Ivoire, Cambodia, Laos Cameroon, Liberia and Gabon in Africa and Guatemala, Mexico, Colombia etc. in Central America.

India has a total area of 0.76 million ha under NR cultivation (IRSG, 2013). India is the sixth largest country in terms of area under NR. It is also the fourth largest producer and third largest consumer of NR. India ranks first in the world in terms of NR productivity. More than 85% of NR area is in the traditional rubber growing regions which include the state of Kerala and the Kanyakumari district of Tamil Nadu. Northeast India, parts of Karnataka, and the Konkan region and limited areas in the Eastern Ghats are non-traditional regions where NR cultivation is newly being expanded. As the Indian economy grows, there will be increasing demand for NR supply.

Natural rubber trees may grow to over 40 m and live for 100 years, but in plantations they rarely exceed 25 m because growth is reduced by tapping for rubber latex. In plantations, trees are usually replanted after 25-35 years when yields fall to an uneconomic level. The latex of *Hevea brasiliensis* is produced by the latex vessels in the phloem. Rubber is water-resistant, does not conduct electricity, is durable and most importantly, is highly elastic. These useful properties are due to the large and complex molecular structure of rubber (1,3 cis-poly isoprene).

Hevea is the main source (almost 98%) of the global requirements of natural rubber. World total area under rubber cultivation was 12.23 million ha with a total production of around11.4 million ton in 2012 (Table 1.2).

Table 1.2. Area, production, productivity, consumption, export and import of natural rubber in main NR cultivating countries of the world.

Country	Area	Production	Productivity	Consumption	Export	Import
	('ooo ha)	('ooo tons)	(tons ha-1)	('000 tons)	('000 tons)	('000 tons)
Brazil	185[a]	172	1094[a]	343	--	157
Guatemala	90[b]	65	1660[b]	6	88	--
Mexico	14[b]	--	--	94	--	83
Cameroon	52[a]	55	1602[a]	--	55	--
Cote d'Ivore	190[a]	255	1664[a]	--	279	--
Ghana	29[b]	17	1220[b]	--	--	--
Gabon	12[a]	20	1868[a]	--	--	--
Guinea	--	15	--	--	--	--
Liberia	109[e]	64	--	--	64	--
Nigeria	182[a]	56	899[a]	13	43	--
D.R. of Congo	35[e]	9	--	--	--	--
Bangladesh	41[c]	19	865[c]	9	--	0
Cambodia	213[a]	61	1150[a]	2	62	--
China	1110	795	1161	3853	--	3176
India	760	915	1819	988	15	246
Indinesia	3466	3015	1080	488	2543	20
Malaysia	1050	923	1510	441	1303	871
Myanmar	505[a]	136	686	--	69	--
Papua New Guinea	25[d]	8	--	--	--	--
Philippines	145[a]	111	1373[a]	59	52	--
Srilanka	128	150	1557	110	37	--
Thailand	2785	3512	1798	490	2911	2
Vietnam	853	955	1720	15	1023	182
Others	248	56		2868	3661	
World Total	12227	11383	1374	13792	12206	4737f

[a]2011 value; [b]2010 value; [c]2009 value; [d]2007 value; [e]1999 value; [f]Total import of NR producing countries only

Source: IRSG, 2013

India ranks first in rubber productivity since 2006 with a per hectare yield of 1819 kg yr^{-1} (Indian Rubber Statistics, 2012). Total area under natural rubber cultivation in India is about 0.76 million ha with a total annual production of 0.92 million tons in 2012 (IRSG, 2013). In India natural rubber is cultivated mainly in the traditional regions such as Kerala (75.08%), Tamil Nadu (2.78%) and non-traditional regions (22.14%) like Karnataka,Tripura, Assam, Meghalaya, Maharashtra etc.

Rubber tree is cultivated in many types of soils provided that the soils are deep and well drained. It can be cultivated in the tropical regions of Asia, Africa and America. An evenly distributed annual rainfall of 2000 mm or more is optimal for rubber cultivation (Annamma et al., 2006). The optimum temperature for rubber cultivation is in the range of 21 ^{0}C to 35 ^{0}C with a warm humid climate (Webster and Paardekooper, 1989; Rao and Vijayakumar, 1992). Non-traditional regions like Northeastern states of India with a cold climate is a limiting factor for rubber cultivation presently. But as a result of climate warming those regions may be come suited for rubber cultivation in the near future (Satheesh and Jacob, 2011).

1.3. Agro-climatic requirements and distribution of other plantation crops in India

1.3.1. Tea

Tea (*Camellia sinensis* (L.) O.Kuntze) is one of the important plantation crops, which is cultivated in more than 3.7 million hectare around the world (Basu et al., 2010). The area under cultivation in India is about 0.57 million ha with a national production of 986.43 million kg in 2007 (Bulletin of Tea Board of India, 2010, Vol. 1 April-September 2010). India is the largest producer and consumer of tea in the world. In India tea is cultivated in traditional regions like Assam in Northeast India and along the Western Ghats of South India. Recently, tea cultivation started in non-traditional regions like Meghalaya, Nagaland, Mizoram, Sikkim, Orissa and Tripura. NE India accounts more than 78% of total area with 76% of total national production.

Commercial cultivation of tea extends within the latitudinal range of 45^0 N to 34^0 S. This crop is cultivated in the sloppy mountains and high plateaus of tropical belt having an altitudinal range of 700 to 2400 m above sea level and lower hills of temperate zones with an altitude of less than 700 m. The optimum range of temperature is from 18 to 30 ^{0}C with an annual rainfall of 700 to 5000 mm (Deka et al., 2006)

1.3.2. Coffee

Globally, coffee covers more than 12 million hectares of land in almost 80 tropical and subtropical countries with a total production of roughly 7 million tons of unprocessed coffee (see www.faostat.fao.org). Arabica (*Coffea arabica* L) and Robusta (*Coffea canephora* Pierre) are the two varieties cultivated commercially in the world. In India, coffee is cultivated in about 0.41 million ha and this is mainly confined to the traditional regions in the southern states of Karnataka (59%), Kerala (22%), Tamil Nadu (8%) and in the non-traditional areas (11%) like Andra Pradesh and Orissa. Total production of coffee in India during 2012 was about 0.31 million ton; which accounts for about 68% from Robusta and 32% from Arabica (Database on Coffee, Nov. 2012 available at www.indiacoffee.org).

Coffee in India is cultivated under shade canopy. Almost 50 different types of shade trees are identified in coffee plantations in India. Coffee can be cultivated only in the climatic conditions prevailing in the subtropical, tropical or equatorial regions with latitudinal range of 22 ^{0}N and 26 ^{0}S with an altitudinal range of about 1000-1500 m above sea level (Descroix and Snoeck, 2004). The optimum temperature range is about 15 to 25 ^{0}C for Arabica variety and 20 to 30 ^{0}C for Robusta variety. An annual rainfall of 1000-2500 mm is optimum for the cultivation of coffee (Sreenath and Prakash, 2006). This crop requires timely showers for initiation of flowering.

1.3.3. Cocoa

Cocoa (*Theobromoa cacao* L), a native of Amazon basin, has more than 3000 years of history of cultivation by man. It is the primary raw material for confectionaries and chocolates. Total area under cultivation in the world during 2011 was 10 million ha with a total production of 4.4 million tons (see www.faostat.fao.org). In India, cocoa is mainly cultivated in the states of Kerala, Karnataka, Tamil Nadu and Andhra Pradesh. Total area under cultivation in India is about 56500 ha with annual production of 144000 tons in 2011.

Cocoa cultivation needs a high and well distributed rainfall, with a dry season of not more than three months. Annual rainfall requirement for cocoa cultivation is in the range of 1250-3000 mm (available at www.dccd.gov.in). The optimum temperature varying between 18-21 ^{0}C mean minimum and 30 to 32 ^{0}C mean maximum with an average daily temperature of 25 ^{0}C is considered to be favourable for growing this crop. The most suitable climatic conditions for cocoa cultivation in India are found in Northern Kerala and coastal Karnataka of Southern India (Balasimha, 2006a).

1.3.4. Coconut

Coconut (*Cocos nucifera* L.) is one of the important plantation crops cultivated in different agro-climatic conditions. Total area under cultivation in the world is 11.4 million ha with a total world production of 59.2 million tons in 2011. Indonesia is the largest producer in the world with an annual production of 17.5 million ton during 2011. India ranks third in world production (11.2 million tons) from an area of 1.96 million ha in 2011(available at www.faostat.fao.org). In India, coconut is cultivated mainly in the southern states such as Kerala (50% area), Tamil Nadu (17%), Karnataka (18%) and Andhra Pradesh (5.7%). Coconut is also cultivated in the non-traditional regions (9.3%) like Assam, Goa, Maharashtra, Orissa, Tripura, West Bengal etc. Anadaman Nicobar Islands, Lakshadweep and Pondicherry also cultivate coconut.

Coconut is cultivated mainly in the coastal areas of tropics within the latitudinal range of 20^0 N and 20^0 S. In India coconut palm is found in different altitudes, but for maximum productivity the altitude should be below 600 m above sea level (Menon and Pandalai, 1960). An annual precipitation of 1000-2250 mm with a temperature range of 20 ^{0}C to 34 ^{0}C is considered as the optimum condition for the cultivation of coconut palms. A warm humid climate with abundant sunlight is required for its good growth and productivity (Rajagopal et al., 2006).

1.3.5. Cashew

Cashew (*Anacadium occidentale* L.) is cultivated as commercial plantation, which is a native of Eastern Brazil. The area under cashew in the world was 4.7 million ha with a total production of 4.2 million tons in 2011. India has the largest the area (0.95 million ha) under cultivation of this crop with an annual production of 0.67 million tons during 2011 (see www.faostat.fao.org). In India cashew is mainly cultivated in Maharashtra, Andhra Pradesh, Kerala, Goa, Karnataka, Orissa, Tamil Nadu and West Bengal and also to a limited extent in the Northeastern states of Manipur, Meghalaya and Tripura.

Cashew is mainly grown in tropical climate with sufficient annual rainfall and a pronounced dry season. Its cultivation can be extended to a latitudinal range of 31^0 N and 31^0 S and with an altitudinal range of 700-1200 m above sea level. Optimum temperature for this crop is in the range of 22 to 35 ^{0}C with an annual rainfall of 800-1500 mm (Rao et al., 2006).

1.3.6. Oil palm

Oil palm (*Elaeis guineensis* Jacq.) is a native of Africa, but its cultivation is mainly concentrated in Southeast Asian region. Malaysia and Indonesia are the largest palm oil producers in the world (Wahid et al., 2004). Total area under cultivation in the world is about 16.2 million ha with a total production of 233.8 million tons of fruits and 48.6 million tons of palm oil in 2011. In India this crop is cultivated mainly in Andhra Pradesh, Karnataka, Tamil Nadu, Kerala, Orissa, Gujrat, Goa, Tripura, Mizoram, Maharashtra, Andaman & Nicobar and Chhattisgarh. Oil palm is cultivated in India in 0.16 million ha with a total crude palm oil production of about 70000 tons in 2010 (see www.dopr.gov.in).

Oil palm can grow in a wide range of soil condition. Soils should be well drained, fertile and deep. It can be commercially cultivated in the areas with an annual mean temperature of 24 to 28 °C. The region with a maximum temperature of 38 °C and minimum of 8 °C is most suitable for its cultivation. Annual rainfall varies in oil palm growing regions from 1500-8400 mm (Nampoothiri et al., 2006), but rainfall is negatively correlated with fruit set, fruits per bunch and yield of oil per bunch.

1.3.7. Arecanut

Arecanut (*Areca catechu* L.) is another commercial crop in India. Areca nut plantation covers 0.87 million ha of land area in the world with a global production of 1.1 million tons during 2011. India ranks first in both area under cultivation (45.8%) and production (44.2%) in the world. Total area of cultivation in India was about 0.4 million ha and the national production during 2011 was about 0.48 million tons (see www.faostat.fao.org). This crop is the economic backbone of more than 10 million small growers in India. In India areca nut is largely cultivated in Kerala, Karnataka and Assam.

Areca nut is cultivated mainly in the sub-humid tropics within a latitudinal range of 28° N and 28° S. The altitude depends upon the latitude, but it can be grown up to an elevation of 1000 m above sea level. The optimum temperature range is in between 14 °C and 36 °C with an annual precipitation of 3000 to 4500 mm (Balasimha, 2006b).

1.4. Conclusion

In this chapter, I have briefly discussed the distribution of various plantation crops in the country and their agro-climatic requirements. As the entire plantation crops are rainfed crops, changes in climate, especially climate warming and alterations in the quantum and pattern of rainfall can affect these crops adversely. Small variations in temperature can have major effects on growth and productivity of the crops as well as on the quality of the produce in some cases. In the light of the global and regional changes happening to climate, it is important to study the influence of these changes on plantation crops.

Although several plantation crops are being grown in India, in the present study, natural rubber is taken as a special case for in-depth study on the impact of climate change. Natural rubber is a strategic engineering raw material which is essentially needed for the industrial and economic growth of the country. There is a direct correlation between per capita rubber consumption and GDP growth. Ranging from condoms to aircraft tyres, and erasers to gloves, there are more than 50,000 products made of either natural rubber alone or in combination with synthetic rubbers that are used in everyday life of modern man. Thus natural rubber is indispensable in our daily lives (George and Kuruvilla, 2000).

1.5. Objectives Of The Thesis

This thesis examines how climate has changed in the plantation crops growing regions of India, and how these changes have impacted them with special reference to natural rubber. The objectives of the present work are as follows:

1. To assess the historic climate change that has happened in the plantation crops growing regions of India
2. To assess the impact of climate change on natural rubber plantations in India
3. To evaluate the CO_2 sequestration and evapotranspiration by natural rubber plantations
4. To review international climate change negotiations and analyze GHG emissions by major nations

This thesis is arranged in seven chapters. Chapters 1 and 2 are introductory chapters. In chapter 1 I have given some general information about Indian plantation corps and their agro-climatic requirements. Chapter 2 introduces the science and signs of climate change. Chapter 3 analyses the extent of climate change that has happened in the plantation crops growing regions of India. Chapter 4 examines how climate change has affected productivity of NR and how growers respond to it. Chapter 5 discusses the ecosystem services provided by NR plantations in terms of CO_2 sequestration. Chapter 6 describes international climate change negotiations and analyses global emission data of different countries. Chapter 7 gives salient conclusions of this thesis.

1.6. References

Annamma, V.Y., Abraham, S.T. and Madhavan, M. (2006). Rubber. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 1. pp. 344-482.

Balasimha, D. (2006a). Cocoa. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 1. pp. 265-344.

Balasimha, D. (2006b). Arecanut. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 2. pp. 421-462.

Basu Majumder A., Bera B. and Rajan, A. (2010). Tea Statistics: Global Scenario. Inc. Journal of Tea Science. 8 (1): 121-124.

Deka, A., Deka, P.C. and Mandal, T.K. (2006). Tea. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 1. pp. 1-148.

Descroix, F. and Snoeck, J. (2004). In: Wintgens, J.N. (Ed.) Coffee: Growing, Processing, Sustainable Production. Wiley-VCH, Weinheim. pp. 164-177.

George, P.J. and Kuruvilla, C.J (2000). Natural Rubber. Published by Rubber Research Institute of India, Rubber Board India, Kottayam, Kerala, India. ISBN 81-87499-00-9.

Indian Rubber Statistics, (2012). Compiled by: The Statistics & Planning Department. The Rubber Board, Kerala, Ministry of Commerce & Industry, Govt. of India. 34: 7-8.

IRSG, (2013). Rubber Statistical Bulletin. April-June 2013. International Rubber Study Group, 111 North Bridge Road #23-06 Peninsula Plaza, Singapore 179098.

Menon, K.P.V. and Pandalai, K.M. (1960). The Coconut Palm- a Monograph. Indian Central Coconut Committee,Ernakulam.

Nampoothiri, K.U.K., Parthasarathy, V.A., Krishnakumar, V. and Ponnamma, K. (2006). Oil Palm. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 2. pp. 283-420.

Rajagopal, V., Parthasarathy, V.A., Naresh, K.S., Reddy, D.V.S. and Iyer, R. (2006). Coconut. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 2. pp. 1-178.

Rao, E.V.V.B., Swamy, K.R.M. and Bhat, M.G. (2006). Cashew. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 2. pp. 179-282.

Rao, P.S. and Vijayakumar, K.R. (1992). In: Sethuraj, M.R. and Mathew, N.M. (Eds.) Natural Rubber. Elsevier, pp. 200-209.

Satheesh, P.R. and Jacob, J. (2011). Impact of climate warming on natural rubber productivity in different agro-climatic regions of India. Natural Rubber Research. 24 (1): 1-9.

Sreenath, H.L. and Prakash, N.S. (2006). Coffee. In: Parthasarathy, V.A., Chattopadhyay, P.K. and Bose, T.K. (Eds.). Plantation Crops. Vol. 1. pp. 149-264.

Thomas, S. and Jacob, J. (2013). The Gadgil-Kasthurirangan reports on Western Ghats and concerns of the plantation sector. Rubber Science. 26(2): 167-174.

Wahid, M.B., Abdullah, S.N.A. and Henson, I.E. (2004). 4th International Crop Science Congress. Brisbane, Australia, 2004.

Webster, C.C. and Paardekoper, E.C. (1989). In: Webster, C.C. and Baulkwill, W.J. (Eds.) Rubber. Longman Scientific and Technical, Essex, UK. pp. 57-84.

CHAPTER 2

AN INTRODUCTION TO CLIMATE CHANGE

"At first I thought I was fighting to save rubber trees, then I thought I was fighting to save the Amazon rainforest. Now I realize I am fighting for humanity"

Chico Mendes

2.1. Introduction

In the previous chapter, I have given a brief description on the agro-climatic requirements of various plantation crops, their distribution in India and the possibility of climate warming/change adversely affecting their growth and productivity. Before analysing how climate has changed in the plantation belts of India and how this has affected these crops, especially natural rubber, it is important that the science of climate change is examined which is briefly addressed in this chapter. This chapter is mainly prepared based on the findings of IPCC given in its fourth assessment report (IPCC, 2007).

The remarkable economic growth achieved by the developed world since the industrial revolution fuelled by large scale consumption of fossil energy is mostly responsible for global warming and climate change (IPCC, 2007). Accumulation of greenhouse gases (GHGs) such as carbon dioxide, methane, nitrous oxide, hydro-fluorocarbons and other halocarbons, per-fluorocarbons and sulfur hexafluoride from fossil fuel combustion, cement manufacture, deforestation and other anthropogenic activities responsible for global warming and the resulting climate change (IPCC, 2007). Climate change could be seen as rising temperatures, unpredictable monsoons, occurrence of extreme weather events such as prolonged hot periods, floods, droughts etc. Climate change has begun to seriously impact agriculture in every part of the planet (Rosenzweig, and Hillel, 1995; Rosenzweig, and Liverman, 1992; Richard et al., 1998) especially in tropical countries where rain-fed agriculture is widely prevalent. Climate has changed in the plantation crops cultivating regions of India (Raj et al., 2011; Satheesh and Jacob, 2011) which can have serious impact on growth and productivity of these crops which is the central theme of this thesis.

Climate is a complex and interactive system consisting of the atmosphere, land, snow and ice, oceans and all other terrestrial and water bodies and the living things. Climate is often defined as the average weather of a particular area (IPCC, 2007). Any changes, due to natural or anthropogenic reasons, in the climate system have the potential to affect the quality of life directly or indirectly. Sometimes it may even affect the survival of certain species.

Climate change became a major international issue towards the fag end of the 20th century. This is perhaps the most universally discussed developmental issue of the 21st century. Climate change is a product of human development, but this is now becoming a serious threat to development itself. Its impact will directly affect all sectors of life in every country and nobody can escape from the consequences of climate change (HDR, 2007/2008).

2.2. Science of Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC), climate change is the change in climate over time, whether due to natural variability or as a result of human activity. The definition of climate change by the United Nations Framework Convention on

Climate Change (UNFCCC) is change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (IPCC, 2007). Climate has variability on time and space scales and this will always be changing. But what is alarming today is the significant anthropogenic causes behind the observed warming and the resulting changes in climate which is in addition to any naturally existing climate drivers.

2.2.1. Natural drivers of climate change

The causes of climate change can be divided into two categories - those that are due to natural and those that are created by man. There are a number of natural factors responsible for climate change. Some of the important ones are the earth's orbital cycles, continental drift, volcanic eruptions and ocean currents. Even if there is no change in the energy output from the sun, changes in the orbital parameters of the earth in several thousands of years can significantly affect the amount of solar energy incident on the earth (Hays et al., 1976). Continental drifts occurring over long periods of time can impact the climate because it changes the physical features of the landmass, their positions and the positions of water bodies.

Volcanic eruptions can inject significant quantities of sulphates and other aerosols into the atmosphere which will reduce the incoming solar radiation reaching on the earth's surface causing a cooling effect and significant short-term climate changes (Stechikov et al., 1998). It appears that a significant part of the fluctuations in global mean temperature over the past century has been due to the effects of volcanic eruptions. The largest volcanic eruption in the 20th century was that of Mount Pinatubo in the Philippines in 1991. This injected about 20 million tons of sulphur into the stratosphere (Wolfe, 2000) which spread around the tropics producing a blanket of haze for more than two years. It is believed that the relatively cool surface and lower troposphere temperatures observed in 1992 and 1993 were due to the Mount Pinatubo eruption.

Close to 71% of the earth's surface is covered by oceans that have an average depth of 3800 m. With a heat capacity of about 1000 times larger than that of atmosphere oceans play a key role in redistributing the planet's heat energy (Bindoff et al., 2007; Levitus et al., 2005; Levitus et al., 2009). Water circulates globally through the oceans as though carried by a huge conveyor belt. Warm water from the equatorial region moves to northward in the North Atlantic. It cools and sinks to the deep ocean and resurfaces only to be rewarmed in the Southern, Indian and North Pacific Oceans and the cycle continues and this circuit can take almost 1000 years (Warren, 1981).

Marked changes occur in the climate in the short term due to the El Niño and La Niña phenomena. El Niño occurs on time-scales of 3 to 8 years and involves a well-defined life cycle of warming and cooling in the central tropical Pacific Ocean with associated shifts in surface pressure patterns (the Southern Oscillation) (Philander, 1990). El Niño years witness extreme precipitation, drought or above normal temperature. For example, the El Niño event during 1997-98 (most intense El Niño on record) resulted in drought that led to forest fires in Asia. Thousands of square miles of rainforests, plantations and scrublands were lost to fire in Indonesia alone. El Niño generally means drought in India and it may vary with season. La Niña impacts are roughly opposite to those of El Niño (Philander and Rasmusson, 1985).

2.2.2. Anthropogenic drivers

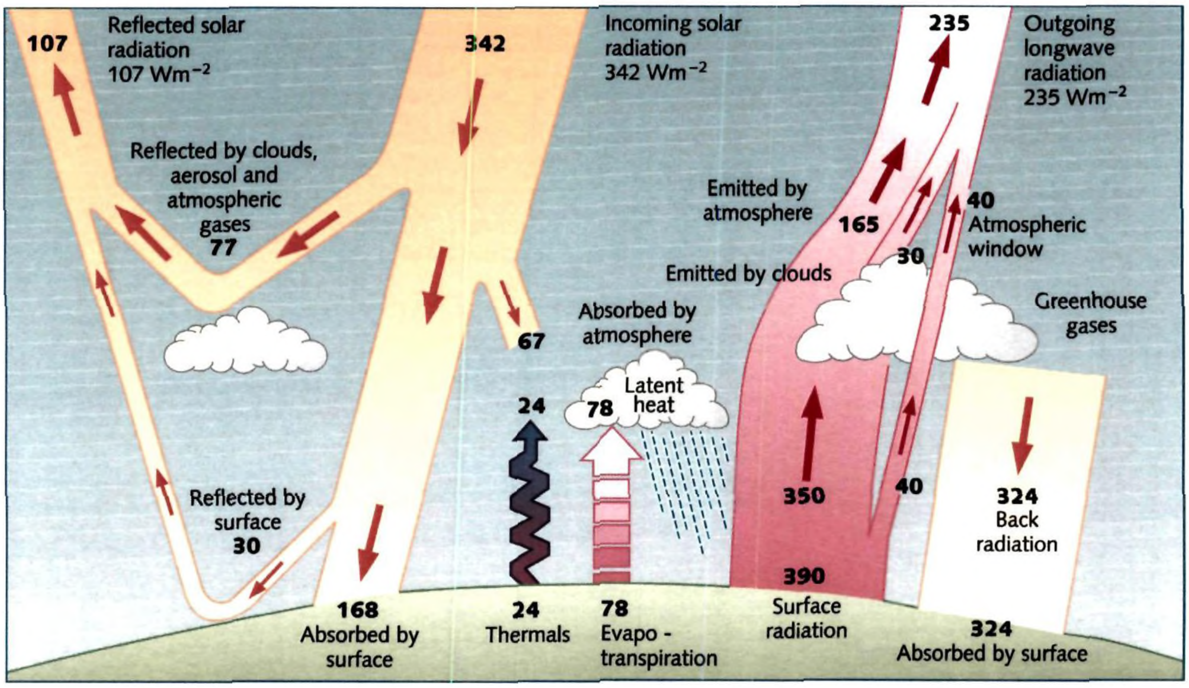
Apart from any natural factors that are in operation, there is convincing evidence that anthropogenic factors have contributed most of the warming and climate change that the world has been experiencing in the recent decades (IPCC reports available at www.ipcc.ch; Ehrlich and Holdren, 1971; Rosa and Dietz, 2012). Human activities contributed to climate change through the accumulation of greenhouse gases (GHGs) in the atmosphere which can happen in two ways. Industrial activities, use of fossil fuel, cement manufacture etc. result in large emissions of GHGs into the atmosphere. Changing pattern of land use such as deforestation etc. reduces the ability of the planet to sequester carbon dioxide from the atmosphere. When the rate of emission is more than the rate of sequestration of CO_2, GHG accumulated in the atmosphere.

Since the beginning of the industrial revolution towards the end of the 19th century, huge amounts of GHGs have been pumped into the atmosphere. Increased use of fossil fuels in every sector of the industrialization is the major source of anthropogenic greenhouse gases. Increasing population put pressure on forests for development. The rampant level of consumerism (which can be defined as use of excess resources by individuals) has led to large carbon foot print for people living in the developed countries (Jacob, 2005).

2.2.3. Greenhouse gases (GHGs) and greenhouse effect

The gases that contribute to the greenhouse effect by absorbing infrared radiation and cause warming of the earth's atmosphere are known as greenhouse gases. Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), Hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6) are the main greenhouse gases. Water vapour is also considered as a greenhouse gas, but it stays in the atmosphere for only a short time. However, in humid tropics, a high concentration of CO_2 in the atmosphere can have a more powerful warming effect due to the prevailing high atmospheric humidity. Some species of the GHGs (CO_2, CH_4, N_2O and water vapour) have been naturally occurring; while the others (PFCs, HFCs and SF_6) are produced purely as a result of industrial activities.

Being heteroatomic molecules, GHGs present in the atmosphere will absorb or trap infrared radiation that is reflected back from the planet into deep space. Life on earth depends on the energy which is received from the sun, the ultimate source of energy. About 30% of the sunlight that beams toward earth is reflected by the earth surface, clouds and aerosols and scattered back in to the space (Figure 2.1). The rest of the light reaches the earth surface and again reflected as a type of long wave radiation (in the infrared range).



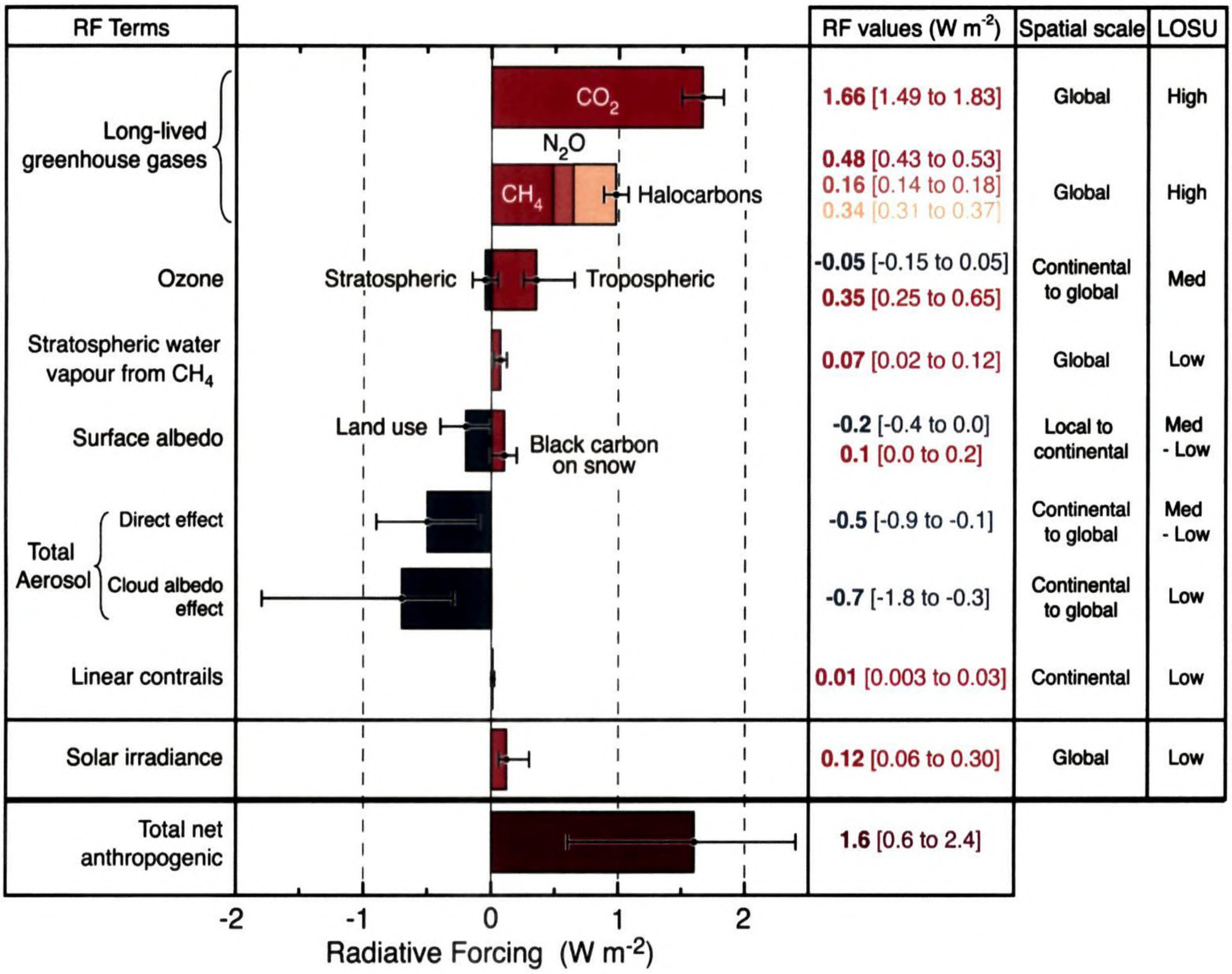
Source: Houghton, 2009

Figure 2.1. Global energy budget showing different components of incoming and outgoing radiation (number indicates radiation in Wm^{-2}).

Greenhouse gases present in the atmosphere absorb the infrared radiation leaving the planet and reflect it again back to the earth's surface and this causes the atmosphere to warm. This phenomenon is known as "greenhouse effect" and it plays a significant role in shaping the earth's climate. It produces the relatively warm and hospitable environment near the earth's surface where humans and other life-forms have been able to develop and prosper. With no GHGs present in the atmosphere, the mean temperature of earth would be around -18 ^{0}C (Le Treut et al., 2007; IPCC, 2007), much below the current mean temperature of about 14 to 14.5 ^{0}C and unsuitable for human inhabitation. Greenhouse effect is one of a large number of physical, chemical and biological processes that determine the earth's climate. While the greenhouse gases are an essential prerequisite for life on earth, the uncontrolled emission of GHGs by anthropogenic activities will enhance the warming of the earth's climate system and this is referred as human enhanced greenhouse effect.

2.2.4. Radiative Forcing (RF)

Radiative forcing by a climate variable is a change in earth's energy balance between incoming solar radiation energy and outgoing thermal infrared (IR) emission. The changes can be brought about by the changes in the concentrations of human induced radiatively active species like GHGs and aerosols (anthropogenic RF) or the changes in the solar irradiance incident upon the planet (natural RF) (Figure 2.2). Volcanic aerosols contribute an additional natural forcing. Normally, forcings due to volcanic aerosols are not considered for estimating the global RF, because of its occasional nature (IPCC, 2007). Radiative forcing is quantified at the tropopause in units of watts per square meter (Wm^{-2}) of earth's surface. A positive forcing (more incoming energy) warms the system, while negative forcing (more outgoing energy) cools it.



Source: IPCC AR4, Climate change 2007:The Physical Science Basis, 2007

Figure. 2.2. Human induced and natural components of radiative forcing of climate change between 1750 and 2005. LOSU - Level Of Scientific Uncertainity.

As the GHGs are heteroatomic molecules, they can trap the outgoing infrared radiation from the earth surface. Thus, concentrations of GHGs in the atmosphere, specifically in the troposphere play an important role in global warming. The concentration of GHGs is inversely proportional to the net outgoing radiation and directly proportional to the change in atmospheric temperature. For the calculation of radiative forcing due to increases in GHGs are usually taken as the concentrations in 1750, at the beginning of the Industrial Revolution (IPCC, 2001). For CO_2, the baseline value, C_0, is 278 ppm (Myhre et al., 1998). The radiative forcing for another concentration CO_2 for a given time, C then calculated as;

Radiative forcing for C ppm $(\Delta F) = 5.35 \times \ln (C/C_0)\ W m^{-2}$

Likewise IPCC recommended expressions to determine the total radiative forcing of other the greenhouse gases also (Table 2.1) (IPCC, 2001). These empirical expressions are derived from atmospheric radiative transfer models and generally have an uncertainty of about 10%. The uncertainties in the global average abundances of the long-lived greenhouse gases (LLGHGs) are much smaller (<1%).

Table 2.1. Expressions for calculating radiative forcing (Wm^{-2}).

GHG	Expression	Constant
CO_2	$\Delta F = \alpha \ln(C/C_0)$	$\alpha = 5.35$
CH_4	$\Delta F = \beta(M - M_0) - [f(M,N_0) - f(M_0,N_0)]$	$\beta = 0.036$
N_2O	$\Delta F = \varepsilon (N - N_0) - [f(M_0,N) - f(M_0,N_0)]$	$\varepsilon = 0.12$
CFC-11	$\Delta F = \lambda(X - X_0)$	$\lambda = 0.25$
CFC-12	$\Delta F = \omega(X - X_0)$	$\omega = 0.32$

The subscript "0" denotes the unperturbed (1750) abundance
f(M,N) = 0.47ln[1 + 2.01x10-5 (MN)0.75 + 5.31x10-15M(MN)1.52]
C is CO_2 in ppm, M is CH_4 in ppb
N is N_2O in ppb, X is CFC in ppb
C_0 = 278 ppm, M_0 = 700 ppb, N_0 = 270 ppb, X_0 = 0
Source: IPCC, 2001

The Earth System Research Laboratory of National Oceanic & Atmospheric Administration (NOAA/ESRL) prepared an Annual Greenhouse Gas Index (AGGI) for measuring the warming influence of LLGHGs and how that influence is changing each year. This index is almost same as the radiative forcing, which is calculated from the baseline concentration of GHGs in the year 1750. Annual Greenhouse Gas Index (AGGI) has been defined as the ratio of the total direct radiative forcing due to long-lived greenhouse gases for any year by taking the base year as 1990. 1990 was chosen for calculating AGGI because it is the baseline year for the Kyoto Protocol (http://unfccc.int/kyoto_protocol/items/2830.php). The radiative forcing for the 2012 total GHG concentration, 476 ppm CO_2-eq, was 2.87 Wm^{-2} and the AGG index was 1.32.

Table 2.2. Global Radiative Forcing, CO_2-eq. concentration of GHGs in the atmosphere and the AGGI from 1979 to 2012.

Year	CO_2	CH_4	N_2O	CFC12	CFC11	15-minor	Total	CO_2-eq (ppm) Total	AGGI 1990 = 1	AGGI % change
1979	1.03	0.42	0.10	0.09	0.04	0.03	1.71	383	0.79	
1980	1.06	0.43	0.10	0.10	0.04	0.03	1.76	386	0.81	2.80
1981	1.08	0.43	0.11	0.10	0.04	0.04	1.80	389	0.83	2.20
1982	1.09	0.44	0.11	0.11	0.05	0.04	1.83	391	0.84	1.80
1983	1.12	0.44	0.11	0.11	0.05	0.04	1.87	395	0.86	2.20
1984	1.14	0.45	0.12	0.12	0.05	0.04	1.91	397	0.88	2.20
1985	1.16	0.45	0.12	0.12	0.05	0.05	1.95	401	0.90	2.10
1986	1.18	0.46	0.12	0.13	0.06	0.05	2.00	404	0.92	2.20
1987	1.21	0.46	0.12	0.14	0.06	0.05	2.04	407	0.94	2.20
1988	1.25	0.46	0.12	0.14	0.06	0.06	2.10	412.	0.96	3.00
1989	1.27	0.47	0.13	0.15	0.06	0.06	2.14	415	0.98	2.10
1990	1.29	0.47	0.13	0.15	0.07	0.07	2.18	418	1.00	1.60
1991	1.31	0.48	0.13	0.16	0.07	0.07	2.21	420	1.02	1.60
1992	1.32	0.48	0.13	0.16	0.07	0.07	2.24	422	1.03	1.10
1993	1.33	0.48	0.13	0.16	0.07	0.07	2.25	424	1.04	0.70
1994	1.36	0.48	0.13	0.17	0.07	0.08	2.28	426	1.05	1.30
1995	1.38	0.49	0.14	0.17	0.07	0.08	2.32	429	1.06	1.50
1996	1.41	0.49	0.14	0.17	0.07	0.08	2.35	431	1.08	1.40
1997	1.43	0.49	0.14	0.17	0.07	0.08	2.37	433	1.09	0.90
1998	1.47	0.49	0.15	0.17	0.07	0.08	2.42	437	1.11	2.00
1999	1.50	0.49	0.15	0.17	0.07	0.08	2.46	440	1.13	1.60
2000	1.51	0.49	0.15	0.17	0.07	0.08	2.48	442	1.14	0.90
2001	1.54	0.49	0.15	0.17	0.07	0.09	2.51	444	1.15	1.00
2002	1.56	0.49	0.16	0.17	0.07	0.09	2.54	447	1.17	1.30
2003	1.60	0.50	0.16	0.17	0.06	0.09	2.58	450	1.19	1.60
2004	1.63	0.50	0.16	0.17	0.06	0.09	2.61	453	1.20	1.10
2005	1.66	0.50	0.16	0.17	0.06	0.09	2.64	455	1.21	1.20
2006	1.69	0.50	0.17	0.17	0.06	0.10	2.68	458	1.23	1.30
2007	1.71	0.50	0.17	0.17	0.06	0.10	2.71	461	1.24	1.10
2008	1.74	0.50	0.17	0.17	0.06	0.10	2.74	464	1.26	1.30
2009	1.76	0.50	0.17	0.17	0.06	0.10	2.77	466	1.27	1.00
2010	1.79	0.50	0.17	0.17	0.06	0.11	2.81	470	1.29	1.30
2011	1.82	0.51	0.18	0.17	0.06	0.11	2.84	473	1.30	1.20
2012	1.85	0.51	0.18	0.17	0.06	0.11	2.87	476	1.32	1.20

Source: NOAA, 2013. Available at http://www.esrl.noaa.gov/gmd/aggi

Changes in radiative forcing before 1978 are derived from atmospheric measurements of CO_2, started by David Keeling in the 1950s (Keeling, 1960) and from measurements of CO_2 and other greenhouse gases in air trapped in snow and ice in Antarctica and Greenland (Etheridge et al., 1996). These results define atmospheric composition changes going back to 1750 and radiative forcing changes since preindustrial times. The radiative forcing AGG index for all greenhouse gases for the period of 1979 to 2012 is given in the Table 2.2. CO_2 has brought in the maximum radiative force among all greenhouse gases.

2.2.5. Global Warming Potential

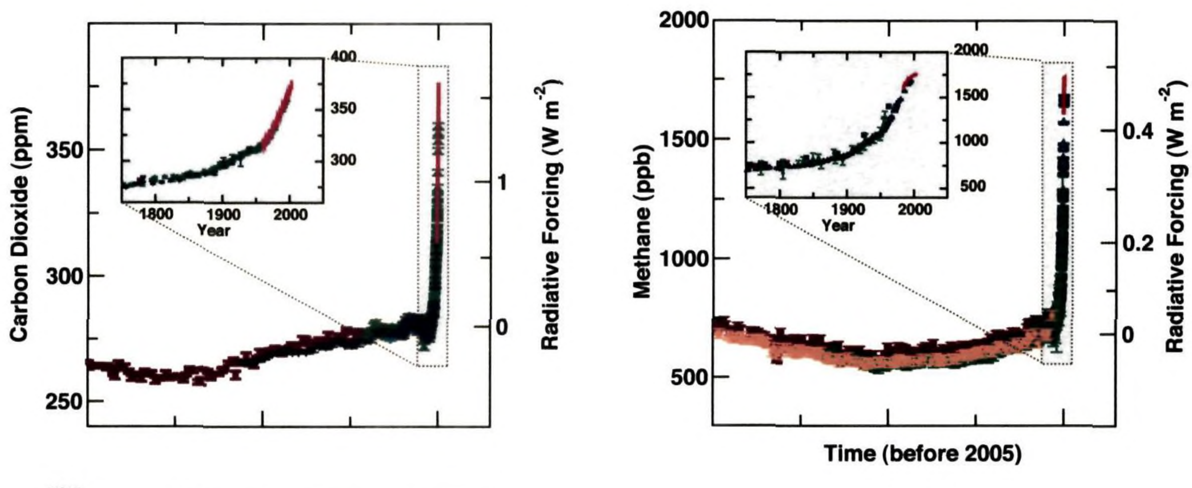
The Global Warming Potential (GWP) provides a simple measure of the radiative effects of emissions of various greenhouse gases, integrated over a specified time horizon, relative to an equal mass of CO_2 emissions (See Chapter 6, Table 6.2. for GWP of individual GHGs). IPCC's definition of GWP is the ratio of the time-integrated radiative forcing from the instantaneous release of 1 Kg of a trace substance relative to that of 1 Kg of a reference gas (IPCC, l990). The GWP with respect to CO_2 is calculated using the formula (IPCC, 2007);

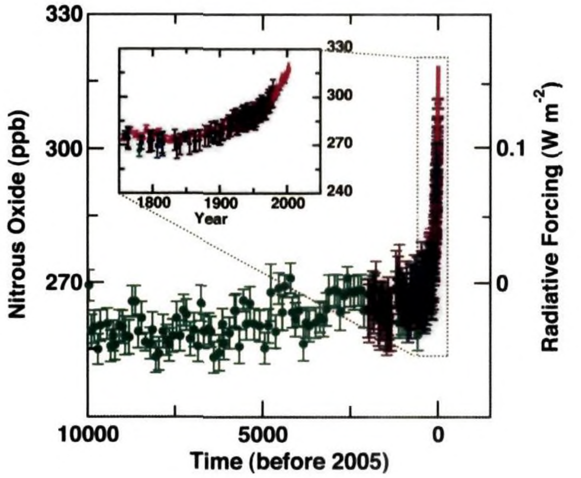
$$GWP_i = \frac{\int_{TR}^{TH} a_i c_i(t)dt}{\int_{TR}^{TH} a_{CO_2} c_{CO_2}(t)dt}$$

where a_i is the instantaneous radiative forcing due to the release of a unit mass of trace gas, i, into the atmosphere, at time TR, C_i is the amount of that unit mass remaining in the atmosphere at time, t, after its release and TH is TR plus the time horizon over which the calculation is performed. GWP of carbon dioxide is standardized as 1 and for other GHGs it is expressed as a factor of the GWP of CO_2. For example, the 20 year GWP of methane is 72, which means that if the same mass of methane and carbon dioxide were introduced into the atmosphere, that methane will trap 72 times more heat than the carbon dioxide over the next 20 years. Note that a substance's GWP depends on the timespan over which the potential is calculated. A gas which is quickly removed from the atmosphere may initially have a large effect but for longer time periods as it has been removed becomes less important. Thus methane has a potential of 25 over 100 years but 72 over 20 years; conversely sulfur hexafluoride has a GWP of 22,800 over 100 years but 16,300 over 20 years (Ramaswamy et. al., 2001). The GWP value depends on how the gas concentration decays over time in the atmosphere.

2.3. Increase in Atmospheric GHG Concentration

David Keeling's continuous and accurate measurements of atmospheric CO_2 concentration since 1958 on Mauna Loa in Hawaii provide the best data on global carbon cycle. Observations on the atmospheric abundances of $^{13}CO_2$ isotope (Francey and Farquhar, 1982) and molecular oxygen (O_2) (Keeling and Shertz, 1992; Keeling et al., 1993) indicated that as fossil fuel consumption increased, atmospheric concentration of CO_2 also went up. The ice core data also provided that the CO_2 concentration in the ice age periods was significantly lower than the industrial period. For several thousands of years before industrial revolution began, CO_2 concentration in the atmosphere stayed within the range 280±20 ppm (Indermühle et al., 1999). During the industrial era, CO_2 concentration increased exponentially to 367 ppm in 1999 (Neftel et al., 1985; Etheridge et al., 1996) and to 379 ppm in 2005 (IPCC, 2007) and 395 ppm in 2013 (see www.esrl.noaa.gov/gmd/ccgg/trends/). Measurements of the atmospheric concentration of the two other major greenhouse gases, methane (CH_4) and nitrous oxide (N_2O) since 1970 have also showed an increasing trend (Graedel and McRae, 1980). When ice core measurements extended the CH_4 concentration back 1 kyr, they showed a stable, relatively constant abundance of 700 ppb until the 19th century when a steady increase brought CH_4 abundances to 1,745 ppb in 1998 and 1,774 ppb in 2005 (IPCC, 2007). For N_2O the increase over the period from 1998 to 2005 was only 5 ppb (314 ppb in 1998 and 319 ppb in 2005), but the changes from the glacial-interglacial cycles (180-260 ppb) was much higher (Figure 2.3).





Source: IPCC AR4, Climate change 2007: The Physical Science Basis, 2007

Figure 2.3. Atmospheric concentration and radiative forcings of carbon dioxide, methane and nitrous oxide over the past 10000 years (large panel) and since 1750 (inset panels). Red line which represents the recent years indicate the data from atmospheric measurements.

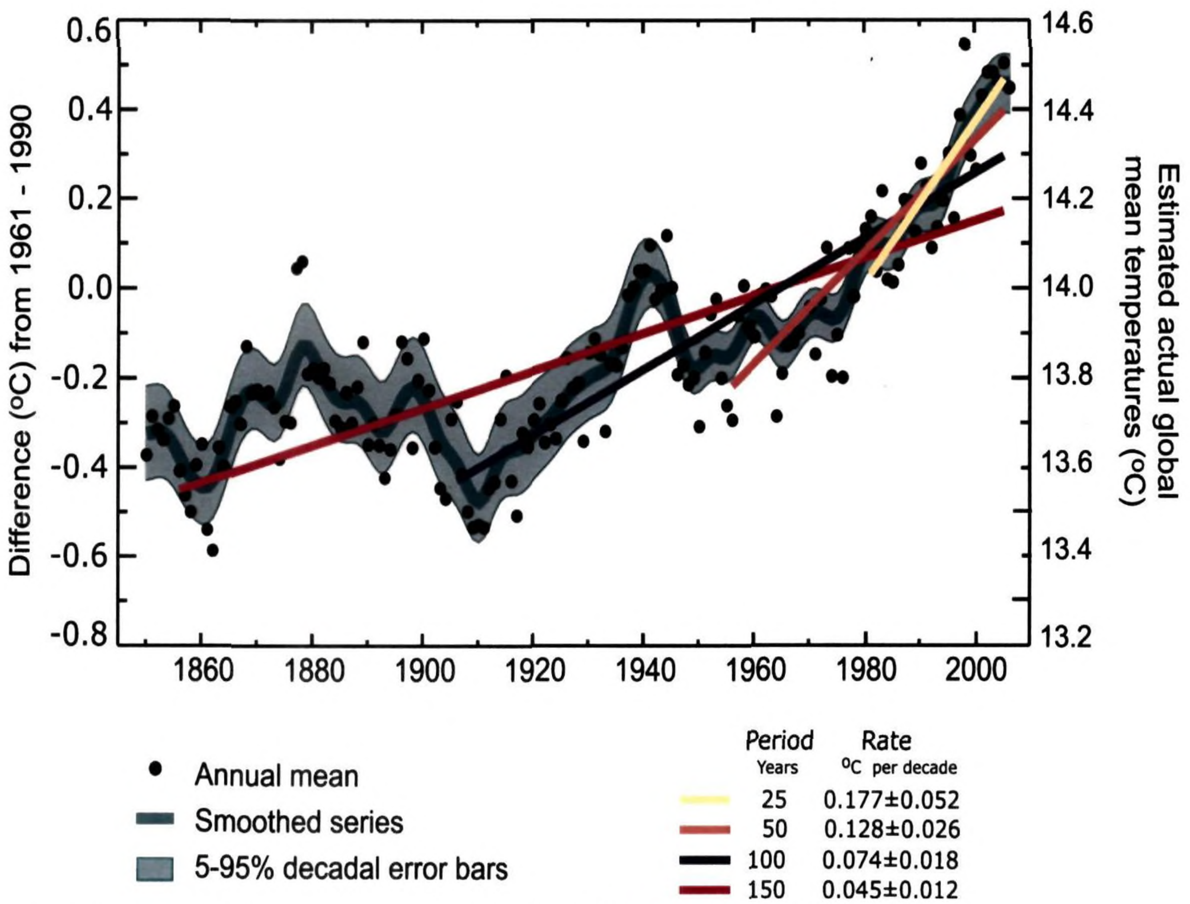
2.4. Temperature Rise

Global land surface temperature (LST) and sea surface temperature (SST) have been increasing at an increasing rate in recent decades and according to IPPC, this is unequivocal and anthropogenically induced (IPCC, 2007). The present global average surface temperature is much higher than that of the pre-industrial period. The current warming trend is very likely due to accumulation of human-induced greenhouse gases in the atmosphere and proceeding at a rate that is unprecedented in the past 1,300 years (IPCC, 2007).

Rate of global warming during 1910s-1940s was 0.35 ^{0}C per decade and from 1970s to the first decade of this millennium was 0.55 ^{0}C per decade (IPCC, 2007). Eleven of the 12 warmest years on record have occurred in the most recent 12 years. According to an assessment by NOAA, the year 2012 was one of the 10 warmest years since global average temperatures have been recorded and the planet has transformed by rising temperatures (Blunden and Arndt, 2013). Global average surface temperatures have increased by about 0.74 ^{0}C over the past 100 years since 1906 (Figure 2.4).

Generally the temperature has been increasing in an increasing rate in the last one and half century (IPCC, 2007). The rate of increase for last 150 years was 0.045 ^{0}C per decade while the rate for the last 25 years was 0.177 ^{0}C per decade. Even as there was consistency between the land and ocean temperature changes, the latter increased more slowly than land temperatures because of the larger effective heat capacity of the oceans and the ocean loses more heat by evaporation (Sutton et al., 2007). Since the beginning of industrialization, the inter-hemispheric temperature difference has increased due to melting of sea ice and snow in the North (Fuelner et al., 2013). Average arctic temperatures have been increasing at almost twice the rate of the rest of the world in the past 100 years, however arctic temperatures are also highly variable (IPCC, 2007). Although more greenhouse gases are emitted in the Northern than Southern Hemisphere, this does not contribute to the difference in warming because the major greenhouse gases persist long enough to mix between hemispheres (IPCC, 2001). Indian subcontinent also experienced significant warming trend during the last century and this is discussed in details in the Chapter 3 of this thesis.

IPCC projected an increase in global mean surface air temperature (SAT) which will continue over the 21st century if the anthropogenic greenhouse gases keep on emitting with the current rate. Geographical patterns of projected surface air temperature warming show greatest temperature increases over land (roughly twice the global average temperature increase) and at high northern latitudes, and less warming over the southern oceans and North Atlantic, consistent with observations during the latter part of the 20th century. The equilibrium global mean surface temperature warming for a doubling of atmospheric carbon dioxide is likely to lie in the range 2 °C to 4.5 °C, with a most likely value of about 3 °C. Best estimates and likely ranges for global average surface air warming for six IPCC SRES (Special Report on Emission Scenarios) are given in the Table 2.3. The best estimate for the low scenario (B1) is 1.8 °C (likely range is 1.1 °C to 2.9 °C), and the best estimate for the high scenario (A1FI) is 4.0 °C (likely range is 2.4 °C to 6.4 °C) (Table 2.3). It is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the middle and high latitudes, with a comparable increase in growing season length (IPCC, 2007).



Source: IPCC AR4, Climate change 2007:The Physical Science Basis, 2007

Figure 2.4. Annual global mean temperatures (black dots) with linear fits to the data. The left hand axis shows temperature anomalies relative to the 1961 to 1990 average and the right hand axis shows estimated actual temperatures, both in °C. Linear trends are shown for the last 25 (yellow), 50 (orange), 100 (magenta) and 150 years (red). The smooth blue curve shows decadal variations with the decadal 90% error range shown as a pale blue band about that line. The planet has been warming at increasing rate.

Table 2.3. Projected global average surface warming and sea level rise at the end of the 21st century.

Case	Temperature Change (°C at 2090-2099 relative to 1980-1999)		Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
	Best estimate	Likely range	
Constant Year 2000 concentrations	0.6	0.3 - 0.9	NA
B1 scenario	1.8	1.1 - 2.9	0.18 - 0.38
A1T scenario	2.4	1.4 - 3.8	0.20 - 0.45
B2 scenario	2.4	1.4 - 3.8	0.20 - 0.43
A1B scenario	2.8	1.7 - 4.4	0.21 - 0.48
A2 scenario	3.4	2.0 - 5.4	0.23 - 0.51
A1FI scenario	4.0	2.4 - 6.4	0.26 - 0.59

Source: IPCC, 2001

2.5. Precipitation Change

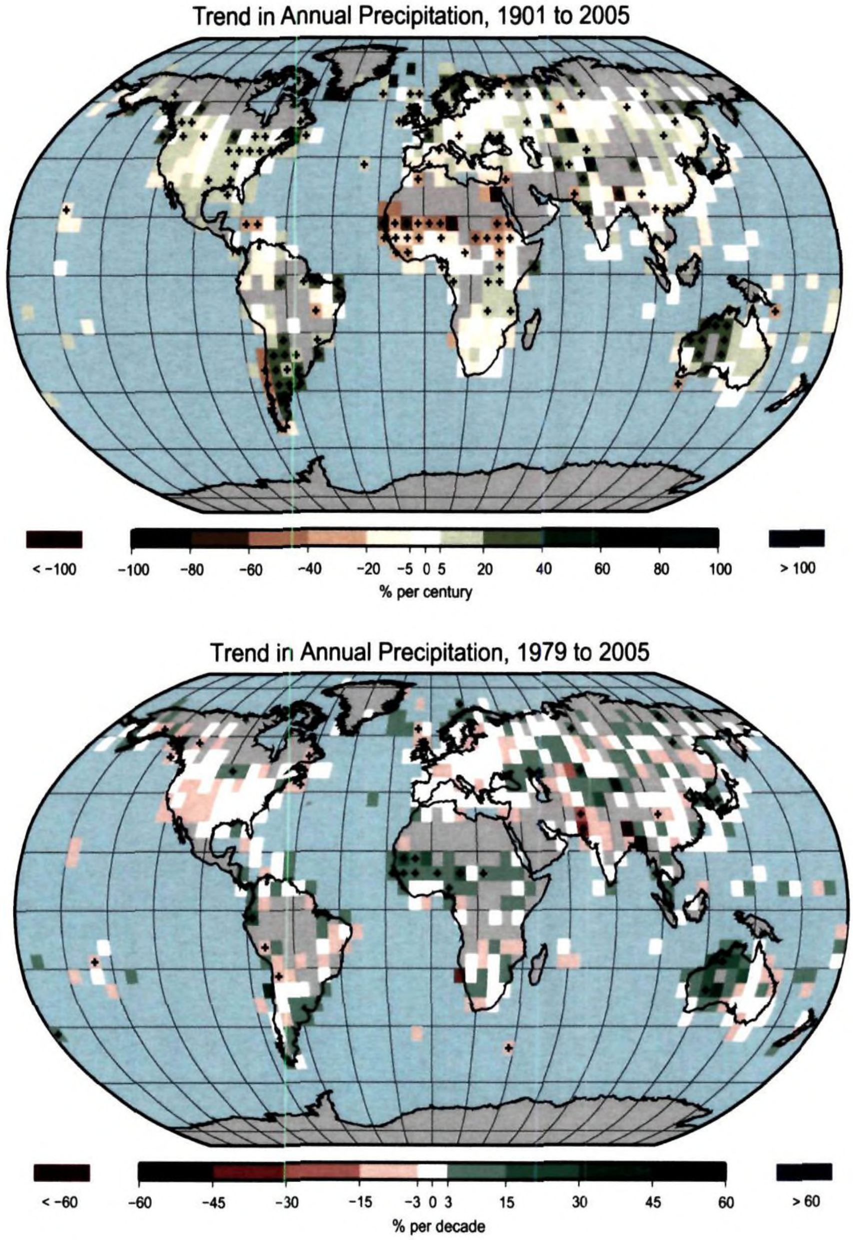
Global land precipitation has increased by about 2% since the beginning of the 20th century (Jones and Hulme, 1996; Hulme et al., 1998). The increase is statistically significant with spatial and temporal variation (Karl and Knight, 1998). Over the 20th century, the Northern Hemispheric mid- and high latitudes, averaged precipitation increased by between 7% and 12%, respectively. Precipitation over the United States has increased by between 5% and 10% since 1900, but this increase has been interrupted by multiyear anomalies such as the drought years of the 1930s and early 1950s (Karl and Knight, 1998; Groisman et al., 1999). Precipitation in Canada has increased by an average of more than 10% over the 20th century (Mekis and Hogg, 1999).

Over the last 50 years, there has been a slight decrease in annual precipitation over China (Zhai and Ren, 1999), which is supported by a significant (5% confidence level) decrease in the number of rainy days (3.9% per decade). There have been marked increases in precipitation in the latter part of the 20th century over northern Europe, with a general decrease southward to the Mediterranean (New, 1998). Over the former USSR, precipitation has increased since 1891 by about 5% in the western region for both warm and cold seasons (Bogdanova and Mestcherskaya, 1998; Groisman and Rankova, 2001). In eastern Russia, a negative precipitation trend was noticed since 1945 with a century long positive precipitation trend (Gruza et al., 1999).

An analysis of rainfall data since 1910 by Haylock and Nicholls (2000) reveals a large decrease in total precipitation and related rain days in south-western Australia. Annual total rainfall has increased over much of Australia with significant increases of 15% to 20% in large areas. The increase in total rainfall has been accompanied by a significant 10% rise in the average number of rain days over Australia (Hennessy et al., 1999).

There is little evidence for a long-term trend in Indian monsoonal rainfall, although there are multi-decadal variations (Kumar et al., 1999; Kumar et al., 1992). More details in the precipitation changes over Indian subcontinent are discussed in the Chapter 3 of this thesis. From 1906 to about 1960, global monsoonal rainfall increased, then decreased through 1974 and has increased since. The trend in annual precipitation has been negative (1 to 2% per decade) over the southwest USA, northwest Mexico and the Baja Peninsula. Across South America, increasingly wet conditions were observed over the Amazon Basin and south-eastern South America, including Patagonia, while negative trends in annual precipitation were observed over Chile and parts of the western coast of the continent. The largest negative trends in annual precipitation were observed over western Africa and the Sahel (IPCC, 2007). The increased atmospheric moisture content associated with warming might be expected to lead to increased global mean precipitation. Global annual land mean precipitation showed a small, but uncertain, upward trend over the 20th century of approximately 1.1 mm per decade. However, the record is characterised by large inter-decadal variability, and global annual land mean precipitation shows a non-significant decrease since 1950. IPCC's demonstration of the spatial patterns of trends in global annual precipitation during the periods 1901 to 2005 and 1979 to 2005 are shown in Figure 2.5.

Heavy precipitation also increased in the last century even with less change in annual total rainfall (Groisman et al., 1999). Analysis of long term climate data show that the most intense precipitation occurs in warm regions (Easterling et al., 2000) and studies have shown that even without any change in total precipitation, higher temperatures lead to heavy and very heavy precipitation events (Karl and Trenberth, 2003). Trenberth et al. (2005) point out that since the amount of moisture in the atmosphere is likely to rise much faster as a consequence of rising temperatures than the total precipitation, this should lead to an increase in the intensity of storms, offset by decreases in duration or frequency of events. IPCC projected the increase in intensity of precipitation events, particularly in tropical and high latitude areas that experience increases in mean precipitation. Even in areas where mean precipitation decreases (most subtropical and mid-latitude regions), precipitation intensity is projected to increase but there would be longer periods between rainfall events. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100) if the recent trends in observed patterns is continuing (IPCC, 2007). National Aeronautics and Space Administration's (NASA) models projected that for every 1 degree fahrenheit of carbon dioxide induced warming, heavy rainfall will increase globally by 3.9 percent and light rain will increase globally by 1 percent. However, total global rainfall is not projected to change much because moderate rainfall will decrease globally by 1.4 percent (Cole and Hansen, 2013).



Source: IPCC AR4, Climate change 2007:The Physical Science Basis, 2007

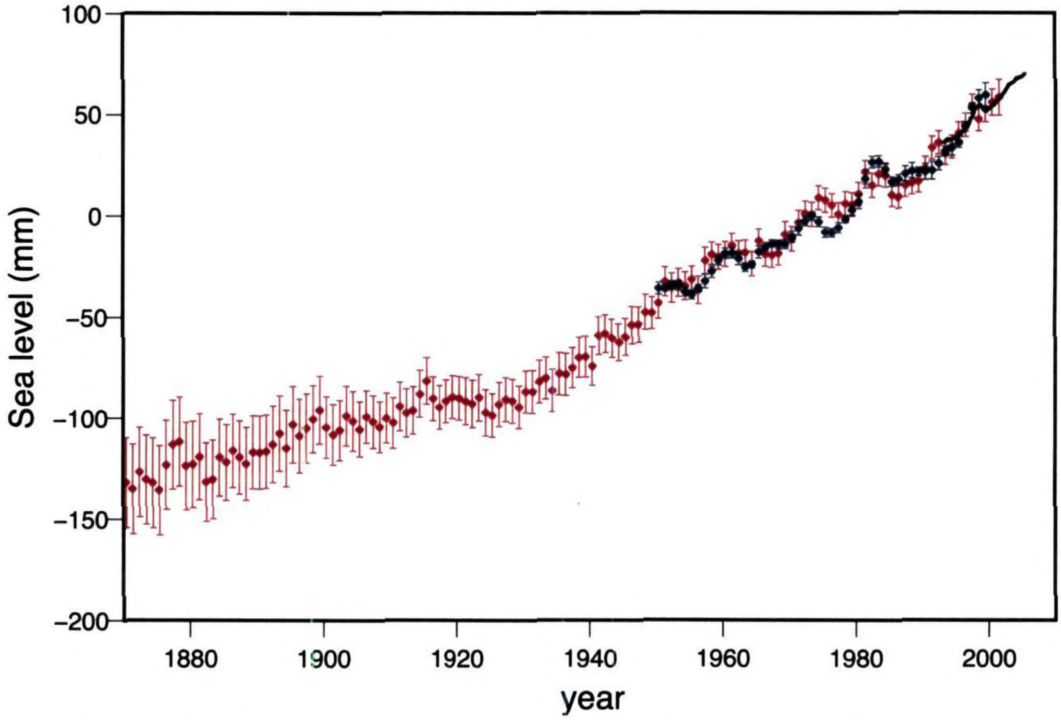
Figure 2.5. Trends in annual land precipitation for 1901 to 2005 (top, % per century) and 1979 to 2005 (bottom, % per decade). The percentage is based on the means for the 1961 to 1990 period. Areas in grey have insufficient data to produce reliable trends. The minimum number of years required to calculate a trend value is 66 for 1901 to 2005 and 18 for 1979 to 2005. An annual value is complete for a given year if all 12 monthly percentage anomaly values are present. Trends significant at the 5% level are indicated by black '+' marks.

2.6. Sea Level Rise

Global ocean temperature has risen by 0.10 ^{0}C from the surface to a depth of 700 m (Willis et al., 2004; Levitus et al., 2005; Ishii et al., 2006). Global ocean heat content (0–3,000 m) has increased during the same period, equivalent to absorbing energy at a rate of 0.21±0.04 Wm^{-2} globally averaged over the Earth's surface. Ocean biogeochemistry is changing. The total inorganic carbon content of the oceans has increased by 118±19 GtC between the end of the pre-industrial period (about 1750) and 1994 and continues to increase. It is more likely than not that the fraction of emitted carbon dioxide that was taken up by the oceans has decreased, from 42±7% during 1750 to 1994 to 37±7% during 1980 to 2005. This would be consistent with the expected rate at which the oceans can absorb carbon, but the uncertainty in this estimate does not allow firm conclusions. The increase in total inorganic carbon caused a decrease in the depth at which calcium carbonate dissolves, and also caused a decrease in surface ocean pH by an average of 0.1 units since 1750. Direct observations of pH at available time series stations for the last 20 years also show trends of decreasing pH at a rate of 0.02 pH units per decade. There is evidence for decreased oxygen concentrations, likely driven by reduced rates of water renewal, in the thermocline (~100–1,000 m) in most ocean basins from the early 1970s to the late 1990s. Global sea level rose by about 120 m during the several millennia that followed the end of the last ice age (approximately 21,000 years ago), and stabilised between 3,000 and 2,000 years ago. Sea level indicators suggest that global sea level did not change significantly from then until the late 19th century.

The instrumental record of modern sea level change shows evidence for onset of sea level rise during the 19th century (IPCC, 2007) (Figure 2.6). The rate of sea level rise has been estimated as 1.8 mm yr^{-1} for the past 70 years (Douglas, 2001; Peltier, 2001). It was estimated a rate of 1.7±0.4 mm yr^{-1}sea level change averaged along the global coastline during the period 1948 to 2002. This study was based on data from 177 stations divided into 13 regions (Holgate and Woodworth, 2004). Church et al. (2004) determined a global rise of 1.8±0.3 mm yr^{-1} during 1950 to 2000, and Church and White (2006) determined a change of 1.7±0.3 mm yr^{-1} for the 20th century. Sea level change is highly non-uniform spatially, and in some regions, rates are up to several times the global mean rise, while in other regions sea level is falling. There is evidence for an increase in the occurrence of extreme high water worldwide related to storm surges, and variations in extremes during this period are related to the rise in mean sea level and variations in regional climate.

The average rate of global sea level (except B1 scenario of IPCC) rise during the 21st century very likely exceeds the 1961 to 2003 average rate (1.8±0.5 mm yr^{-1}). For an average model, the scenario spread in sea level rise is only 0.02 m by the middle of the century, and by the end of the century it is 0.15 m. Projected sea level rise in different IPCC SRES for 2090-2099 relative to 1980-1999 are given in the table 2.3.



Source: IPCC AR4, Climate change 2007:The Physical Science Basis, 2007

Figure 2.6. Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870, the blue curve shows coastal tide gauge measurements since 1950 and the black curve is based on satellite altimetry. The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals.

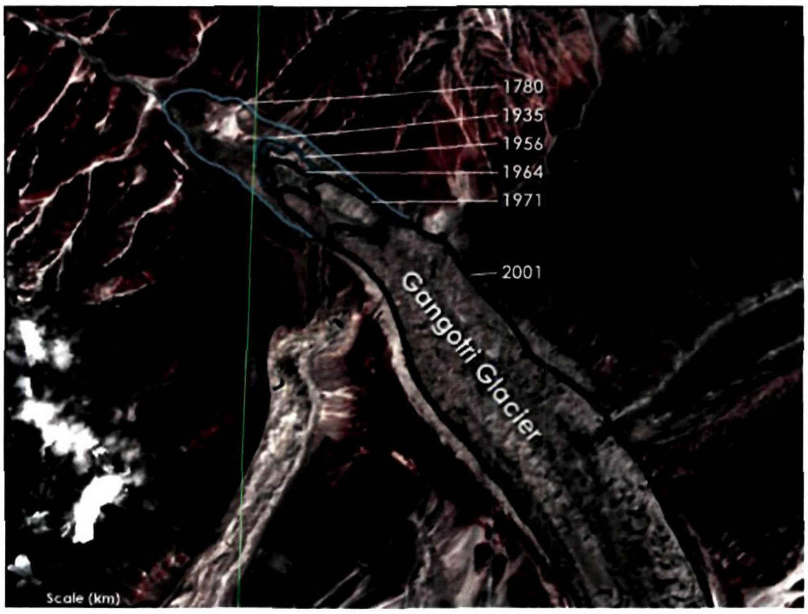
2.7. Glacier Retreat

Retreat of glaciers and ice sheets are considered as the powerful evidence of global climate change because it is directly linked with the rising atmospheric temperature. Global glaciers and ice caps excluding the large ice sheets of Greenland and Antarctica cover an area between $512x10^3$ and 546 $x10^3$ km^2 (Raper and Braithwaite, 2005; Ohmura, 2004; Dyurgerov and Meier, 2005; IPCC, 2001). Total volume of these glaciers and ice caps varies considerably from $51x10^3$ to $133x10^3$ km^3, representing sea level equivalent (SLE) of between 0.15 and 0.37 m. Including the glaciers and ice caps surrounding the Greenland Ice Sheet and West Antarctica, but excluding those on the Antarctic Peninsula and those surrounding East Antarctica, yields 0.72±0.2 m. It was reported that retreat of glacier tongues started after 1800, with substantial mean retreat rates in all regions after 1850 lasting throughout the 20th century. A slowdown was noticed during 1970 (Oerlemans, 2005). Retreat rate was again started rapidly in the 1990s; the Atlantic and the SH curves reflect precipitation-driven growth and advances of glaciers in western Scandinavia and New Zealand during the late 1990s (Chinn et al., 2005).

Studies on three glaciers (Helheim Glacier, Kangerdlugssuaq Glacier, and Jakobshavn Glacier) of Greenland ice sheet showed that they together represented more than 16% of the Greenland ice Sheet. In the case of Helheim Glacier, researchers used satellite images to determine the movement and retreat of the glacier. Satellite images and aerial photographs of Helheim Glacier from the 1950s and 1970s show that the glacier tongue had remained in the same level for decades. During 2001 the glacier began retreating rapidly, and by 2005 the glacier had retreated a total of 7.2 km with a rate of 20 to 35 m per day during that period (Howat et al., 2005; Howat et al., 2011).Using satellite radar interferometry observations of Greenland, it was detected that the acceleration of ice discharge in the west and particularly in the east doubled the ice sheet mass deficit in the last decade from 90 to 220 km^3 per year. This will certainly accelerate the increased contribution of Greenland to global sea-level rise will (Rignot and Kanagaratnam, 2006). Studies on the flow of several large glaciers showed an accelerated retreat of Greenland Ice Sheet. This change, combined with increased melting, suggests that existing estimates of future sea-level rise are too low (Dowdeswell, 2006). Greenland was not an exception; many of the glaciers on the earth surface were facing the threat of shrinking of its size. According to NASA, Gangotri glacier, currently 30.2 km long and between 0.5 to 2.5 km wide, is one of the largest in the Himalayas has been constantly receding since measurements began in 1780. Studies by Bhambri et al. (2012) shows that between 1965 and 2006 Gangotri Glacier lost 0.41±0.03 sq. km from its front which is at the rate of approximately 0.01 sq. km year^{-1}. However, over the last 25 years of the 20th century the rate was increased and it has retreated more than 850 meters (34 meters per year) and 76 meters between 1996 and 1999 (25 meters per year) (Figure. 2.7).

During the 20th century glaciers and snow cover have experienced extensive loss in mass balance which have contributed to sea level rise. Mass loss of global glaciers and ice caps (excluding those around Greenland and Antarctic ice sheets) was estimated to be a sea level equivalent of 0.50±0.18 mm yr^{-1} (Table 2.4). Glacier fluctuations show a strong statistical correlation with air temperature at least at a large spatial scale throughout the 20th century (Greene, 2005). Analyses of glacier mass balances, volume changes, length variations and homogenised temperature records for the western portion of the European Alps (Vincent et al., 2005) clearly indicate the role of precipitation changes in glacier variations in the 18th and 19th centuries. Nesje and Dahl (2003) reported the glacier advances in southern Norway in the early 18th century due to increased winter precipitation rather than colder temperatures. The biggest glacier mass losses reported was from Alaska with 0.11 mm yr^{-1}

sea level equivalent from 1960/1961 to 1989/1990 and 0.24 mm yr^{-1} SLE from 1990/1991 to 2002/2003. Glacier mass balance of different regions for the period of 1960-2003 are shown in the Figure 2.8



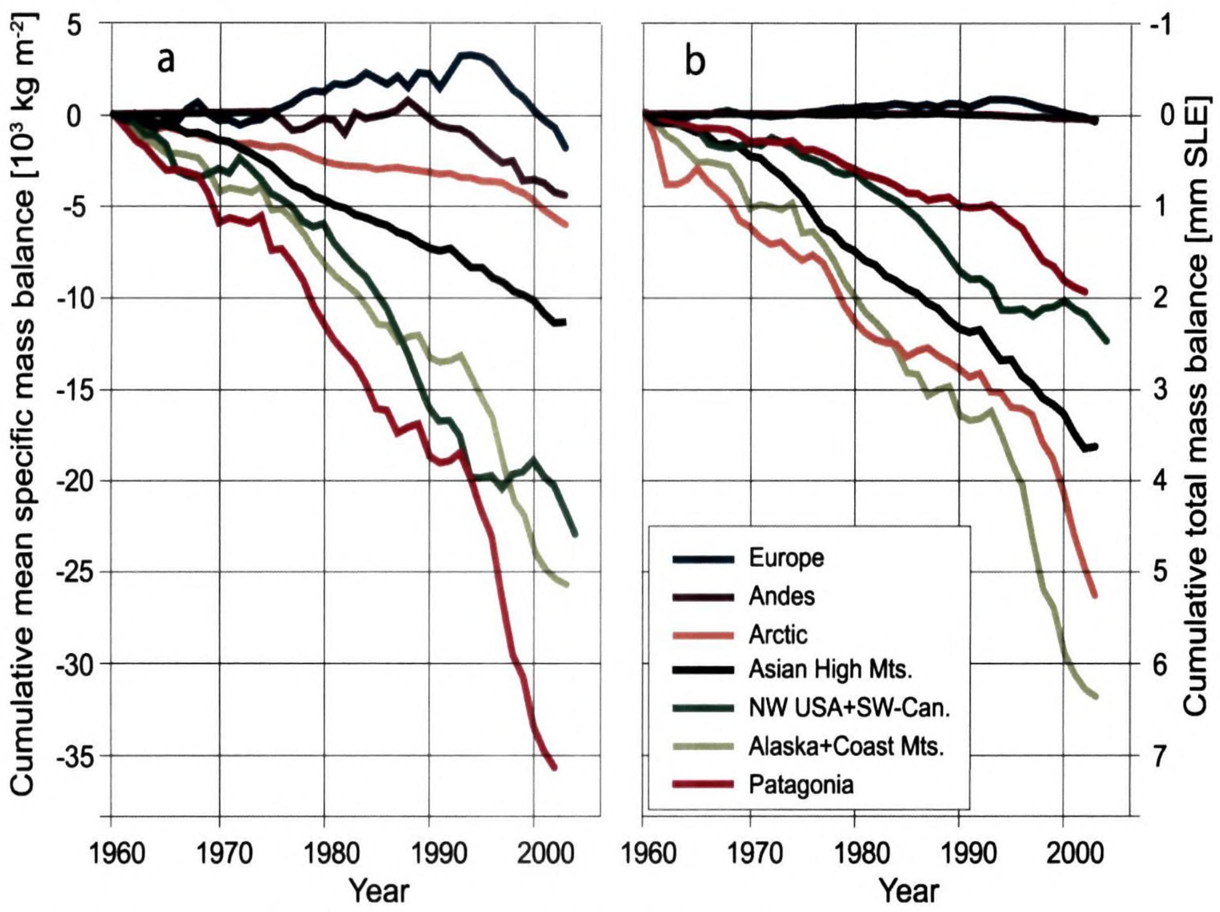
Source: NASA image by Jesse Allen, Earth Observatory; based on data provided by the ASTER Science Team.

Figure 2.7. Retreat of Gangotri glacier since 1780. The false-color image shows the Gangotri Glacier, situated in the Uttarkashi District of Garhwal Himalaya. The blue contour lines drawn here to show the recession of the glacier's terminus over time are approximate.

Table 2.4. Global average mass balance of glaciers and ice caps for different periods, showing mean specific mass balance, total mass balance, and sea level equivalent. Uncertainties are for the 90% confidence level.

Period	Mean Specific Mass Balance[a] (kg m^{-2} yr^{-1})	Total Mass Balance[a] (Gt yr^{-1})	Sea Level Equivalent[a] (mm yr^{-1})	Mean Specific Mass Balance[b] (kg m^{-2} yr^{-1})	Total Mass Balance[b] (Gt yr^{-1})	Sea Level Equivalent[b] (mm yr^{-1})
1960/1961 to 2003/2004	-283 ± 102	-155 ± 55	0.43 ± 0.15	-231 ± 82	-182 ± 64	0.50 ± 0.18
1960/1961 to 1989/1990	-219 ± 92	-120 ± 50	0.33 ± 0.14	-173 ± 73	-136 ± 57	0.37 ± 0.16
1990/1991 to 2003/2004	-420 ± 121	-230 ± 66	0.63 ± 0.18	-356 ± 101	-280 ± 79	0.77 ± 0.22

[a]Excluding glaciers and ice caps around ice sheets; [b]Including glaciers and ice caps around ice sheets

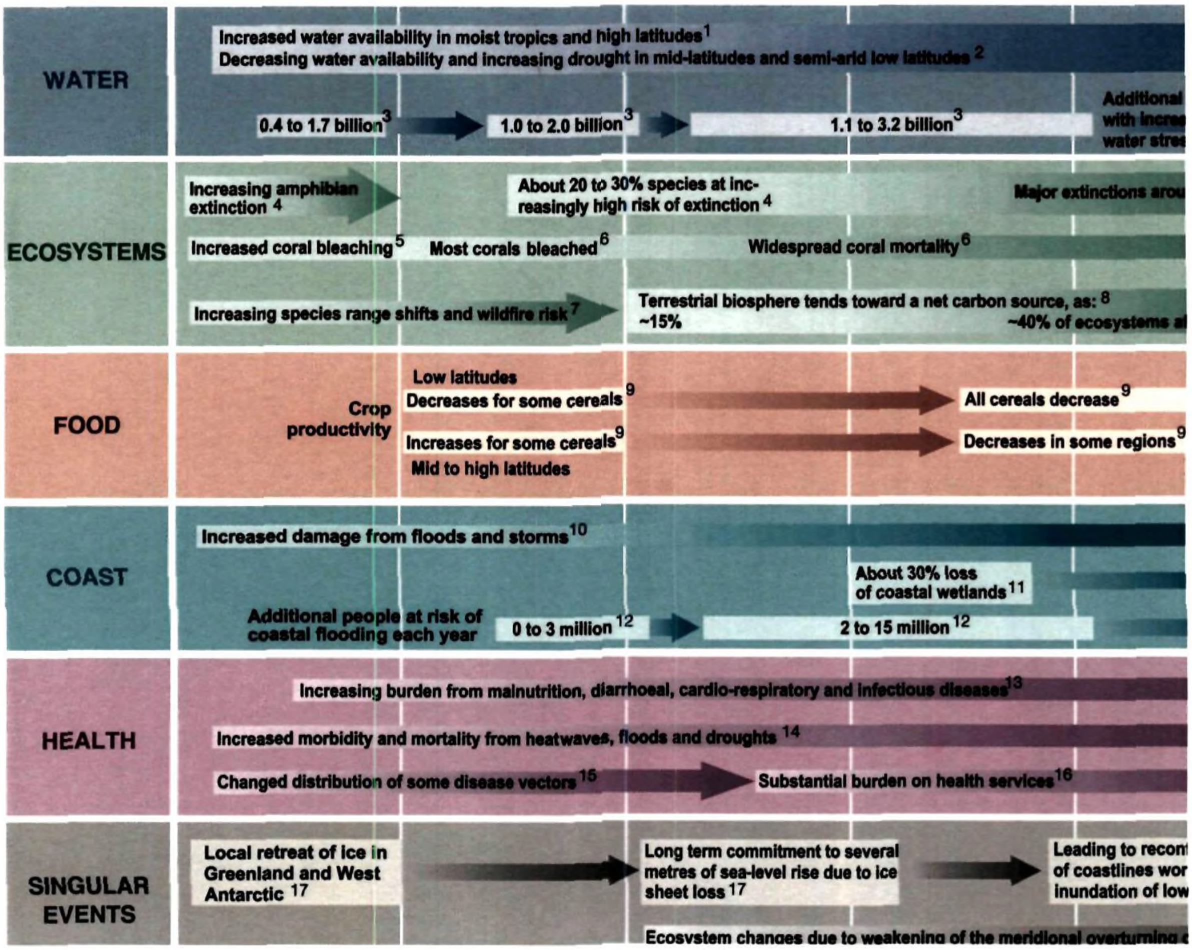


Source: IPCC AR4, Climate change 2007:The Physical Science Basis, 2007

Figure 2.8. Cumulative mean specific mass balances (a) and cumulative total mass balances (b) of glaciers and ice caps, calculated for large regions. Mean specific mass balance shows the strength of climate change in the respective region. Total mass balance is the contribution from each region to sea level rise.

2.8. Impacts of Climate Change

Climate change as a result of global warming has several impacts on the life on earth. These changes will become stronger in the future and it will rapidly alter the land and waters in which we all depend upon for survival. The impacts of the climate change are direct and indirect. Extreme variations in temperature and rainfall, droughts, floods, sea level rise etc. are the direct impacts of climate change and are discussed in the previous sections of this chapter. Indirect impacts of climate change which are adversely affect the life on earth are the impacts on agriculture, food security, water scarcity, pests and disease out breaks, impacts on biodiversity and health of human beings. World's poor nations are more vulnerable to the adverse impacts of climate change because of the less capability for adaptive measures. Major impacts of climate change on some of the important areas are summarised below (Figure 2.9).



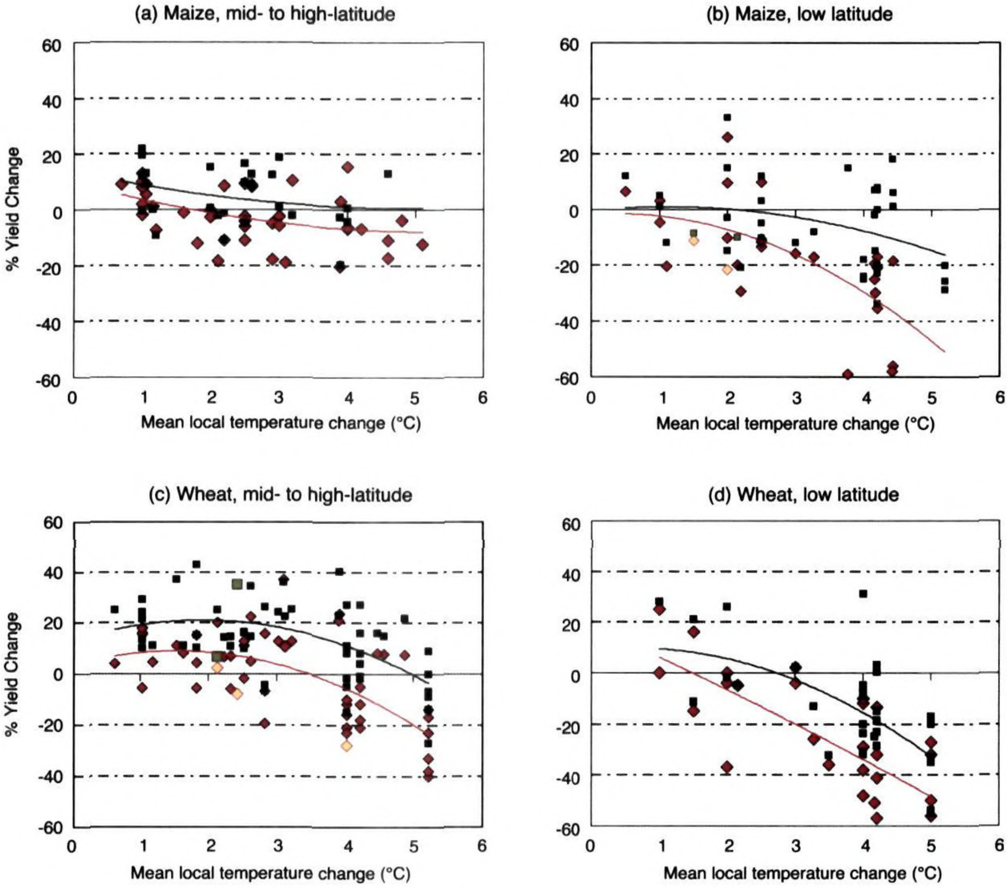
Source: IPCC AR4, Climate change 2007: Impacts, Adaptation and Vulnerability, 2007

Figure 2.9. Examples of global impacts projected for changes in climate (and sea level and atmospheric CO_2 where relevant) associated with different amounts of increase in global average surface temperature in the 21st century.

2.8.1. Agriculture, food security and forests

Agriculture is one of the important sectors which is most affected by climate change. But the potential impacts of climate change on agriculture are highly uncertain. There are large numbers of studies conducted over the past several years for estimating the magnitude or direction of impact of climate change for global and regional scale. However, strong conclusions did not emerge from these studies which tell us the exact impact of climate change on the productivity of agriculture sector. Some marginal areas (mid and high-latitudes) may benefit substantially while others may become unproductive. Crop simulation models show that regional variations of 20 to 30% or more productivity gain in some areas and same magnitude losses in other areas. Mid and high latitudes, where agriculture is limited by short growing seasons are more likely to gain while subtropical and tropical regions (low-latitudes) may be more likely to affect adversely due to higher temperature variations. Crop-pest interactions may shift as the timing of development stages in both hosts and pests is altered due to higher temperature variations.

In its fourth assessment report, IPCC (2007) reported that in mid to high-latitude regions, moderate warming benefits cereal crop and pasture yields, but even slight warming decreases yields in seasonally dry and tropical regions. Crop simulation modeling results for a range of sites showed that, in temperate regions, moderate to medium increases in local mean temperature (1 to 3 ^{0}C), along with associated CO_2 increase and rainfall changes can have small beneficial impacts on crop yields. At lower latitudes, especially the seasonally dry tropics, even moderate temperature increases (1 to 2 ^{0}C) are likely to have negative yield impacts for major cereals, which would increase the risk of hunger. Further warming has increasingly negative impacts in all regions (Figure 2.10).



Source: IPCC AR4, Climate change 2007: Impacts, Adaptation and Vulnerability, 2007

Figure 2.10. Sensitivity of cereal yield to climate change for maize and wheat. Responses include cases without adaptation (orange dots) and with adaptation (green dots). The studies on which this figure is based span a range of precipitation changes and CO_2 concentrations, and vary in how they represent future changes in climate variability. For instance, lighter-coloured dots in (b) and (c) represent responses of rain-fed crops under climate scenarios with decreased precipitation.

Several studies were carried out to estimate the impacts of climate change on global agriculture. But regional impact assessment would more accurately reveal the actual effect, because the meaning of climate change is different for different regions with different agro-climatic conditions. Kane et al. (1992) and Tobey et al. (1992) examined the sensitivity of agriculture to potential yield losses in major temperate grain-growing regions based on several climate change impact assessment methodologies. They loosely linked the potential for yield losses in temperate regions to climate projections that showed increasing aridity in the continental mid-latitude areas. They made alternative assumptions about how agriculture might be affected in higher latitudes and in the tropics. They also developed scenarios that reflected the estimated yield impacts for different parts of the world that were summarized in the first assessment report (FAR) of IPCC (Parry et al., 1990). Hunger and malnutrition should be the first concern while talking about the vulnerability of agriculture to climate change. In that way poorer countries of the world are most vulnerable where the world's lion share of the population exists. Consideration of some of the agricultural indicators like population, income, climate etc. is important while assessing the impact of climate change on global food production (Table. 2.5). More details on the impact of climate change on agriculture on a global and Indian scenario are discussed in the chapter 3 of this thesis. Climate change could potentially interrupt progress toward a world without hunger. The impacts of climate change on crop productivity could have consequences for food availability. The stability of whole food systems may be at risk under climate change because of short-term variability in supply. However, the potential impact is less clear at regional scales, but it is likely that climate variability and change will intensify food insecurity in areas currently vulnerable to hunger and under-nutrition.

Today, 40% of the earth's land surface is occupied by managed ecosystems like agricultural cropland and pasture (Foley et al., 2005). About 3.9 miilion hectare (30%) of land area is covered by natural forests which providing 35% of global round wood (FAO, 2000). The United Nations Food and Agriculture Organization (FAO) estimates that the livelihoods of roughly 450 million of the world's poorest people are entirely dependent on managed ecosystem services. Climate change also affects forests both directly and indirectly through disturbance including forest fire. Increased warming and drying in the future is expected to have a significant impact on the risk of forest fire occurrence. A warmer, drier climate will lead to drier forest fuels that will in turn increase the chance of successful fire ignition and propagation. Schumacher and Bugmann (2006) assessed the interactions among forest dynamics, climate change and large-scale disturbances such as fire, wind and forest management. They projected that future climate change would cause extensive forest cover changes, beginning in the coming decades. Pitman et al. (2007) explored the impact of future climate change on the risk of forest and grassland fires over Australia in January using a high resolution climate model.

Table 2.5. Basic regional agricultural indicators and vulnerability

	Sub-Saharan Africa	Near East/ North Africa	South Asia	Southeast Asia	East Asia	Oceania	Former USSR	Europe	Latin America	USA, Canada
Ag. land (%)*	41	27	55	36	51	57	27	47	36	27
Cropland (%)*	7	7	44	13	11	6	10	29	7	13
Irrigated (%)*	5	21	31	21	11	4	9	12	10	8
Land area (106 ha)	2390	1 167	478	615	993	845	2227	473	2052	1 839
Climate	**tropical; arid, humid**	**subtropical, tropical; arid**	**tropical, subtropical; humid, arid**	**tropical; humid**	**subtropical, temperate oceanic, continental; humid**	**tropical, temperate, oceanic subtropical; arid, humid**	**polar, continental, temperate oceanic; humid, arid**	**temperate oceanic, some subtropical, humid, arid**	**tropical, subtropical; mostly humid**	**continental subtropical, polar, temp. oceanic, mid, arid**
Pop. (106)	566	287	1145	451	1 333	27	289	510	447	277
Ag. pop.(%)	62	32	63	49	59	17	13	8	27	3
Pop./ha cropland	3.6	3.4	5.4	5.7	12.6	0.5	1.3	3.7	2.9	1.2
Ag. prod. (106t)										
Cereals	57	79	258	130	433	24	180	255	111	388
Roots and tubers	111	12.5	26	50	159	3	65	79	45	22
Pulses	5.7	4.1	14.4	2.5	6.3	2	6	7	5.8	2.2
S. cane and beet	60	39	297	181	103	32	62	144	494	56
Meat	6.7	5.5	5.7	6.4	39.6	4.5	17	42	20.5	33.5
1991 GNP/cap.**	350	1 940	320	930	590	13780	2700	15300	2390	22 100
Annual growth**	-1.2	-2.4	3.1	3.9	7.1	1.5	N.A.	2.2	-0.3	1.7
Ag. (% of GDP)**	>30%	10-19%	>30%	20 to>30%	20-29%	<6%	10-29%	<6%	10-19%	<6%

* Agricultural land includes grazing and cropland, reported as a percentage of total land area. Cropland is reported as a percentage of agricultural land. Irrigated area is reported as a percentage of cropland.

** GNP is in 1991 USA dollars; annual growth, per cent per annum, is for the period 1980-1991. Source: Computed from FAO (1992); GNP per capita, GNP growth rates, and agriculture as a share of the economy are from World Development Indicators in World Bank (1993) and temperature and climate classes from Rötter et al. (1995).

Battles et al. (2008) reported that conifer tree growth declined under all climate scenarios and management regimes in the mixed-conifer forest of the Sierra Nevada, California, USA. The most extreme changes in climate decreased productivity, as measured by stem volume increment, in mature stands by 19% by 2100. More severe reductions in yield (25%) were observed for pine plantations. Climate change impacts on forests will result not only through changes in mean climate, but also through changes in seasonal and diurnal rainfall and temperature patterns (Zierl and Bugmann, 2005). Recently observed moderate climatic changes have induced forest productivity gains globally and possibly enhanced carbon sequestration, especially in tropical forests (Boisvenue and Running, 2006; Baker et al., 2006; Malhi and Phillips, 2004; Phillips et al., 2004; Phillips et al., 2006). The effects of drought on forests include mortality, a potential reduction in resilience and can cause major biotic feedbacks (Lloret et al., 2004; Hogg and Wein, 2005). Drought conditions further interact with disturbances such as insects (Hanson and Weltzin, 2000; Logan et al., 2003; Schlyter et al., 2006). Tree-defoliating insects, especially in boreal forests, periodically cause substantial damage forest ecosystems (Gitay et al., 2001; Logan et al., 2003).

2.9. Conclusion

In this chapter, I discussed the science and signs of climate change. Accumulation of greenhouse gases in the atmosphere since the beginning of industrial revolution is largely responsible for the current warming and changes to global climate that are witnessing today. Even those who dispute this and suggest natural factors as the reason for climate change, do agree that global climate has changed and the mean temperature of the planet has gone up and it continues to go up at an increasing rate. This can have unprecedented effects on agriculture, food supply, biodiversity and human health.

It can be seen that global warming is the byproduct of human development which has been and still largely driven by fossil energy. There has been a direct correlation between growth in GDP and emission of GHGs (Huang, 2007; Michael, 1995; Grossman. and Krueger, 1995; Holtz-Eakin and Selden, 1995). Thus, it can be seen that climate change is the environmental cost of economic development. Perhaps, it is not possible to have economic growth without a parallel environmental cost or damage, but keeping this damage minimum and reversible is the key to sustainable growth (OECD, 2011).

2.10. References

Baker, J.M., Ochsner, T.E., Venterea, R.T. and Grif's, T.J. (2006). Tillage and soil carbon sequestration- What do we really know? doi:10.1016/j.agee.2006.05.014.

Battles, J.J., Robards, T., Das, A., Waring, K., Gilless, J.K., Biging, G. and Schurr, F. (2008). Climate change impacts on forest growth and tree mortality: a data-driven modeling study in the mixed- conifer forest of the Sierra Nevada, California. Climatic Change. 87 (Suppl 1): S193–S213.

Blunden, J. and Arndt, D. S. (Eds). (2013). State of the Climate in 2012. Bulletin of American. Meteorological Society. 94 (8): S1–S238.

Bogdanova, E.G. and Mestcherskaya A.V. (1998). Influence of moistening losses on the homogeneity of annual precipitation time series. Russian Meteorology and Hydrology. 11: 88–99.

Boisvenue, C. and Running, S.W. (2006). Impacts of climate change on natural forest productivity - evidence since the middle of the 20th century. Global Change Biology. 12: 862-882.

Chinn, T.J.H., Winkler, S., Salinger, M.J. and Haakensen, N. (2005). Recent glacier advances in Norway and New Zealand: a comparison of their glaciological and meteorological causes. Geografiska Annaler. 87A(1): 141–157.

Church, J.A., and White, N.J. (2006). A 20th century acceleration in global sea-level rise. Geophysical Research Letters. 33: L01602, doi:10.1029/ 2005GL024826.

Church, J.A., White , N.J., Coleman, R., Lambeck, K. and Mitrivica, J.X. (2004). Estimates of the regional distribution of sea-level rise over the 1950 to 2000 period. Journal of Climate. 17(13): 2609–2625.

Cole, S. and Hansen, K. (2013). NASA study projects warming-driven changes in global rainfall. Available at http://www.nasa.gov/home/ hqnews/2013/may/ HQ_13-119_Rainfall_Response.html

Douglas, B.C. (2001). Sea level change in the era of the recording tide gauges. In: Sea Level Rise: History and Consequences [Douglas, B.C., Kearney, M.S., and S.P. Leatherman (eds.)]. Academic Press, New York, pp. 37–64.

Dowdeswell, J.A. (2006). A changing Greenland Ice Sheet and global sea-level rise. Science. 311: 963-964.

Ehrlich, P.R. and Holdren, J.P. (1971). Impact of population growth. Science. 171(3977): 1212-1217.

Etheridge, D. M., Steele, L. P., Langenfelds, R. L., Francey, R. J., Barnola, J.M. and Morgan, V. I. (1996). Natural and anthropogenic changes in atmospheric CO_2 over the last 1000 years from air in Antarctic ice and firn. Journal of Geophysical Research. 101(D2): 4115–4128.

FAO. (1992). Agrostat. FAO Statistics Division, Rome.

FAO. (2000). Global Forest Products Outlook Study: Thematic study on plantations by Brown, C. Working Paper No. GFPOS/WP/03. Food and Agriculture Organization of the United Nations, Rome, 129 pp.

Feulner G., Rahmstorf S., Levermann A., Volkwardt S. (2013). On the origin of the surface air temperature difference between the hemispheres in earth's present-day climate, Journal of Climate, 26(18): 7136-7150. doi:10.1175/JCLI-D-12-00636.1

Foley, J.A., Defries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. and Snyder, P.K. (2005). Global Consequences of Land Use. Science. 309(5734): 570-574.

Francey, R. J. and Farquhar, G. D. (1982). An explanation of $^{13}C/^{12}C$ variations in tree rings. Nature. 297: 28 – 31.

Gitay, H., Brown, S., Easterling, W., and Jallow, B. (2001). Ecosystems and their goods and services. In: Climate Change 2001: Impacts, adaptation, and vulnerability. McCarthy, J. J., Canziani, O.F., Leary, N.A., Dokken, D.J., and White, K.S. (Eds). Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK. pp. 235-341.

Graedel, T. E. and McRae, J. E. (1980). On the possible increase of the atmospheric methane and carbon monoxide concentrations during the last decade. Geophysical Research Letters. 7(11): 977-979.

Greene, A.M. (2005). A time constant for hemispheric glacier mass balance. Journal of Glaciology. 51(174): 353–362.

Groisman, P. Ya. and Rankova, E. Ya. (2001). Precipitation trends over the Russian permafrost-free zone: removing the artifacts of pre-processing. International Journal of Climatology. 21: 657-678. doi: 10.1002/joc.627.

Groisman, P.Y., Knight, R.W., Easterling D.R., Karl, T.R., Hegerl, G.C. and Razuvaev, V.N. (1999). Trends in intense precipitation in the climate record. Journal of Climate. 18: 1326-1350.

Grossman, G. M. and Krueger, A. B. (1995). Economic growth and the environment. Quartely Journal of Economics. 110: 353-377.

Gruza, G.V., Rankova, E.Ya., Razuvaev, V.N. and Bulygina, O.A. (1999). Indicators of climatic change for the Russian Federation. Climatic Change. 42: 219–242.

Hanson, P.J. and Weltzin, J.F. (2000). Drought disturbance from climate change: response of United States forests. The Science of the Total Environment. 262: 205- 220.

Haylock, M. and Nicholls, N. (2000). Trends in extreme rainfall indices for an updated high quality data set for Australia, 1910-1998. International Journal of Climatology. 20: 1533–1541.

Hays, J.D., Imbrie, J. and Shackleton, N.J. (1976). Variations in Earth's orbit: Pacemaker of the Ice Ages. Science, 194 (4270): 1121-1132.

HDR (Human Development Report). (2007/2008). Fighting climate change: Human solidarity in a divided world. Published for United Nations Development Programme by Palgrave Macmillan, New York.

Hennessy, K., Fitzharris, B., Bates, B.C., Harvey, N., Howden, S.M., Hughes, L., Salinger, J. and Warrick, R. (2007). Australia and New Zealand. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Parry, M.L., Canziani, O.F., Palutikof, J.P., Van der Linden, P.J. and Hanson, C.E. (Eds.). Cambridge University Press, Cambridge, UK, 507-540.

Hogg, E.H. and Wein, R. W. (2005). Impacts of drought on forest growth andregeneration following fire in southwestern Yukon, Canada. Canadian Journal of Forest Research. 35: 2141–2150.

Holgate, S.J. and Woodworth, P.L. (2004). Evidence for enhanced coastal sea level rise during the 1990s. Geophysical Research Letters. 31: L07305, doi:10.1029/2004GL019626.

Holtz-Eakin, D. and Selden, T. (1995). Stoking the fires? CO_2 emissions and economic growth. Journal of Public Economics. 57: 85-101.

Howat, I. M., Ahn, Y., Joughin, I., Van den Broeke, M. R., Lenaerts, J. T. M. and Smith, B. (2011). Mass balance of Greenland's three largest outlet glaciers, 2000–2010, Geophysical Research Letters. 38: L12501, doi:10.1029/2011GL047565.

Howat, I.M., Joughin, I., Tulaczyk, S. and Gogineni, S. (2005). Rapid retreat and acceleration of Helheim Glacier, east Greenland. Geophysical Research Letters. 32: L22502, doi: 10.1029/2005GL024737.

Huang,W., Lee, G. and Wu, C. (2007). GHG emissions, GDP growth and the Kyoto Protocol: A revisit of Environmental Kuznets Curve hypothesis. Energy Policy. 36:239-247.

Hulme, M., Osborn, T.J. and Johns, T.C. (1998). Precipitation sensitivity to global warming: comparisons of observations with HadCM2 simulations. Geophysical Research Letters. 25(17): 3379-3382.

Indermühle, A., Stocker, T. F., Joos, F., Fischer, H., Smith, H. J., Wahlen, M., Deck, B., Mastroianni, D., Tschumi, J., Blunier, T., Meyer, R. and Stauffer, B. (1999). Holocene carbon-cycle dynamics based on CO_2 trapped in ice at Taylor Dome, Antarctica. Nature. 398: 121 – 126.

IPCC First Assessment Report (1990). Climate Change. Houghton, J.T., Jenkins, G.J. and Ephraums, J.J. (eds.).

Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Melbourne, Australia 410 pp.

IPCC, Fourth Assessment Report (AR4), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

IPCC. (2001). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., et al. (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp.

Ishii, M., Kimoto, M., Sakamoto, K. and Iwasaki, Sin-Iti. (2006). Steric Sea Level Changes Estimated from Historical Ocean Subsurface Temperature and Salinity Analyses. Journal of Oceanography. 62: 155-170.

Jacob, J. (2005). The science, politics and economics of global climate change: Implications for the carbon sink projects. Current science. 89(3): 464-474.

Jones, P.D. and Hulme, M. (1996). Calculating regional climatic time series for temperature and precipitation: methods and illustrations. Journal of Climatology. 16: 361-377.

Kane, S., Reilly, J. and Tobey. J. (1992). An empirical study of the economic effects of climate change on world agriculture. Climatic Change. 21: 17-35.

Karl, T.R. and Knight, R.W. (1998). Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States. Bulletin of American. Meteorological Society. 79: 231–241.

Keeling, C.D. (1960). The concentration and isotopic abundances of carbon dioxide in the atmosphere. Tellus. 12(2): 200-203.

Keeling, R.F. and Shertz, S.R. (1992). Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle. Nature. 358:723-727.

Keeling, R.F., Najjar, R.P., Bender, M.L. and Tans, P.P. (1993). What atmospheric oxygen measurements can tell us about the global carbon cycle, Global Biogeochemical Cycles. 7(1): 37-67.

Kumar, K. K., Rajagopalan, B. and Cane, M. A. (1999). On the weakening relationship between the Indian Monsoon and ENSO. Science. 284: 2156–2159.

Kumar, K.R, Pant, G.B., Parthasarathy, B. and Sontakke, N.A.1992. Spatial and sub seasonal patterns of the long term trends of Indian summer monsoon rainfall. International Journal of climatology. 12: 257-268.

Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T. and Prather, M. (2007). Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Levitus, S., Antonov, J. I., Boyer, T. P., Locarnini, R. A., Garcia, H. E. and Mishonov, A. V. (2009). Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems. Geophysical Research Letters. 36: L07608, doi:10.1029/2008GL037155.

Levitus, S., Antonov, J. and Boyer, T. (2005). Warming of the world ocean, 1955-2003. Geophysical Research Letters. 32: L02604, doi:10.1029/2004GL021592.

Lloret, F., Peñuelas, J. and Estiarte, M. (2004). Experimental evidence of reduced diversity of seedlings due to climate modification in a Mediterranean-type community. Global Change Biology. 10: 248-258. - doi: 10.1111/j.1365-2486.2004. 00725.x

Logan, J.A., Régnière, J. and Powell, J.A. (2003). Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and Environment. 1: 130-137.

Malhi. Y. and Phillips, O.L. (2004). Tropical forests and global atmospheric change: a synthesis. Philosophical Transactions of the Royal Society B: Biological Sciences. 359(1443):549-55.

Mekis É. and Hogg, W.D. (1999). Rehabilitation and analysis of Canadian daily precipitation time series. Atmosphere Ocean. 37: 53-85.

Michael, T. (1995). Carbon dioxide emissions and global GDP. Ecological Economics. 15(3): 215–223.

Myhre, G. (1998). New estimates of radiative forcing due to well mixed greenhouse gases. Geophysical

Research Letters. 25(14): 2715-2718.

Neftel, A., Moor, E., Oeschger, H. and Stauffer, B. (1985). Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries. Nature. 315:45-47.

Nesje, A. and Dahl, S.O. (2003). The 'Little Ice Age' - only temperature? The Holocene. 13(1): 139–145.

New, M. (1998). Climate trend atlas of Europe based on observations 1891-1990. C.D.Schonwiese and J.Rapp. Kluwer Academic Publishers: Dordrecht, 1997. Pp. vii + 228. ISBN 0-7923-4483-9. Dfl 175.00, US$112.00, ú69.00. International Journal of Climatology. 18: 580-581. doi: 10.1002/(SICI) 1097-0088(199804)18:5<580::AID-JOC276>3.0.CO;2-4.

OECD (2011). Towards Green Growth - Monitoring Progress: OECD Indicators. Available at http://www.oecd.org/greengrowth/

Oerlemans, J. (2005). Extracting a climate signal from 169 glacier records. Science. 308: 675-677.

Ohmura, A., (2004). Cryosphere during the twentieth century. In: The State of the Planet: Frontiers and Challenges in Geophysics. Sparks, R.S.J. and Hawkesworth, C.J. (Eds.). Geophysical Monograph 150, International Union of Geodesy and Geophysics, Boulder, C.O. and American Geophysical Union, Washington, DC, pp. 239–257.

Parry, M.L., Duinker, P.N., Morison, J.I.L., Porter, J.H., Reilly, J. and Wright, L.J. (1990). Agriculture and forestry. In: Climate Change: The IPCC Impacts Assessment. McG. Tegart, W.J., Sheldon, G.W. and Griffiths, D.C. (Eds.). Australian Government Printing Office, Canberra. pp. 2-1 - 2-45.

Peltier, W.R. (2001). Global glacial isostatic adjustment and modern instrumental records of relative sea level history. In: Sea Level Rise: History and Consequences. Douglas, B.C., Kearney, M.S. and Leatherman, S.P. (Eds.). Academic Press, San Diego, pp. 65–95.

Philander, S. G. (1990). El Niño, La Niña, and the Southern Oscillation. ix + 293 pp. San Diego, New York, Berkeley, Boston, London, Sydney, Tokyo, Toronto: Academic Press (Harcourt Brace Jovanovich). Price £42.50 (hard covers). ISBN 0 12 553235 0. International Geophysics Series Vol. 46.

Philander, S. G. H., and Rasmusson, E. M. (1985). The Southern Oscillation and El Nino, In: Advances in Geophysics (28). A. Climate Dynamics, Saltzman, B. (Ed.), Academic Press, New York, 197-213,

Phillips, S.J., Anderson, R.P. and Schapire, R.E. (2006). Maximum entropy modeling of species geographic distributions. Ecological Modelling. 190: 231–259.

Phillips, S.J., Dud´ık, M. and Schapire, R.E. (2004). A maximum entropy approach to species distribution modeling. In: Proceedings of the 21st International Conference on Machine Learning, ACM Press, New York, pp. 655–662.

Pitman, A. J., Narisma, G. T. and Mc Aneney J. (2007). The impact of climate change on the risk of forest and grassland fires in Australia. Climatic Change. 84(3-4): 383-401.

Raj, S., Satheesh, P.R. and Jacob, J. (2011). Evidence for climate warming in some natural rubber growing regions of South India. Natural Rubber Research, 24(1): 10-17.

Rakesh Bhambri, R., Bolch, T. and Chaujar, R.K. (2012). Frontal recession of Gangotri Glacier, Garhwal Himalayas, from 1965 to 2006, measured through high-resolution remote sensing data. Current Science. 102(3): 489-494.

Ramaswamy. V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G.Y. and Solomon S. (2001). Radiative Forcing of Climate Change. IPCC second assessment report 2001. Climate Change 2001: The Scientific Basis. Joos, F. and Srinivasan, J. (Eds). Cambridge University Press, Cambridge, Great Britain, New York, NY, USA.

Raper, S.C.B. and Braithwaite, R.J. (2005). The potential for sea level rise: New estimates from glacier and ice cap area and volume distribution. Geophysical Research Letters. 32: L05502, doi:10.1029/2004GL021981.

Richard, M. A., Brian, H. H., Stephanie, L. and Neil, L. (1998). Effects of global climate change on agriculture: an interpretative review. Climate Research. 11: 19–30.

Rignot, E. and Kanagaratnam, P. (2006). Changes in the velocity structure of the Greenland Ice Sheet. Science. 311: 986–990.

Rosa, E. A. and Dietz ,T. (2012). Human drivers of national greenhouse-gas emissions. Nature Climate Change. 2: 581–586.

Rosenzweig, C. and Hillel, D. (1995). Potential Impacts of Climate Change on Agriculture and World Food Supply. Consequences (Summer):24–32.

Rosenzweig, C. and Liverman, D. (1992). Predicted effects of climate change on agriculture: A comparison of temperate and tropical regions. In Global climate change: Implications, challenges, and mitigation measures, ed. S. K. Majumdar, 342-61. PA: The Pennsylvania Academy of Sciences.

Rötter, R., Stol, W., Van de Geijn, S.C. and van Keulen, H. (1995). World Agro-climates. I. Current Temperature Zones and Drylands. AB-DLO, Research Institute for Agrobiology and Soil Fertility, Wageningen. 55 p.

Satheesh, P.R. and Jacob, J. (2011). Impact of climate warming on natural rubber productivity in different agro-climatic regions of India. Natural Rubber Research. 24 (1): 1-9.

Schlyter, P., Stjernquist, I., Bärring, L., Jönsson A.M. and Nilsson, C. (2006). Assessment of the impacts of climate change and weather extremes on boreal forests in northern Europe, focusing on Norway spruce. Climate Research. 31: 75-84.

Schumacher, S. and Bugmann, H. (2006). The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. Global Change Biology. 12: 1435-1450.

Stechikov, G.L., Ingo, K., Alan, R., Hans, F.G., Juan, C.A., Grainger, R.G., Alyn, L. and Larry, T. (1998). Radiative forcing from the 1991 Mount Pinatubo volcanic eruption. Journal of Geophysical Research, 103 (D12): 13837-13857.

Sutton, R. T., Dong, B. and Gregory, J.M. (2007). Land/sea warming ratio in response to climate change: IPCC AR4 model results and comparison with observations. Geophysical Research Letters. 34(2): L02701, doi:10.1029/2006GL028164.

Tobey, J., Reilly, J. and Kane, S. (1992). Economic Implications of Global Climate Change for World Agriculture. Journal of Agricultural and Resource Economics. 17(1): 195-204.

Trenberth, K.E., Dai, A., Rasmussen, R.M. and Parsons, D.B. (2003). The changing character of precipitation. Bulletin of American Meteorological Society. 84:1205-1217.

Trenberth, K.E., Fasullo, J. and Smith, L. (2005). Trends and variability in column-integrated water vapor. Climate Dynamics. 24:741–758.

Vincent, C., Le Meur, E., Six, D. and Funk, M. (2005). Solving the paradox of the end of the Little Ice Age in the Alps. Geophysical Research Letters. 32: L09706, doi:10.1029/2005GL022552.

Warren, Bruce A., (1981). Deep circulation of the world ocean. In: Evolution of Physical Oceanography, Scientific Surveys in Honor of Henry Stommel, Bruce A. Warren and Carl Wunsch, editors, The MIT Press, Cambridge, Massachusetts; pp. 6-41.

Willis, J.K., Roemmich, D. and Cornuelle, B. (2004). Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales. Journal of Geophysical Research. 109: c12036, doi:10.1029/ 2003jc002260.

Wolfe, J. (2000). Volcanoes and Climate Change. NASA Earth Observatory. Available at www. earthobservatory.nasa.gov/Features/Volcano

World Bank. (1993). World Development Report. Washington DC.

Zhai, P.M., and Ren, F.M. (1999). On change of China's maximum and minimum temperatures in 1951-1990. Acta Meteorologica Sinica. 13 (2): 278–290.

Zierl, B., and Bugmann, H. (2005). Global change impacts on hydrological processes in Alpine catchments, Water Resources Research. 41: W02028, doi:10.1029/2004WR003447.

CHAPTER 3

HISTORIC CLIMATE CHANGE THAT HAS HAPPENED IN THE PLANTATION GROWING REGIONS OF INDIA

"Men Argue Nature acts"

Voltaire

3.1. Introduction

In the previous chapters, I have discussed the agro-climatic requirements of various plantation crops and their distribution in India and the science behind climate change. I have shown how the remarkable economic growth achieved by the developed world since the industrial revolution fuelled by large scale consumption of fossil energy is related to accumulation of CO_2 in the atmosphere which is largely responsible for global warming and climate change (IPCC, 2007). In this chapter, historic climate change that has happened in the past one century in the country as a whole and in the various rainfall subdivisions and homogeneous (temperature) regions of the country where most of the plantation crops are grown is analyzed. Time series analyses of temperature, rainfall and extreme climatic events using data collected from different rubber growing regions in India are also discussed in this chapter.

Every plant species has an optimal climatic requirement for their growth and productivity. Plantation crops being perennial rainfed crops that grow for several decades, are exposed to remarkable variations in climatic parameters over their life cycle. In India, these crops are cultivated in diverse agro-climatic regions. Any change in the normal climatic requirements of a crop can seriously impact its growth and productivity directly or indirectly (Rosenzweig and Parry, 1994; Cynthia et al., 2001). It has been clearly shown that rising temperature and climate change have begun to adversely affect crops in various parts of the world (Ranade, 2009; Rosenzweig and Hillel,1995; Richard et al., 1998; Kang et al., 2009; Rosenzweig et al., 2000; Cynthia et al., 2000; Van et al., 2002; Murdiyarso, 2000; Singh and Lal, 2009; IFPRI, 2007; Jerry et al., 2012). Extreme weather events like droughts, floods, shifting rainfall pattern, severe storms and heat waves have a direct impact on agriculture. These changes can also cause incidence of outbreaks of pests and diseases seriously impacting crops (Cynthia et al., 2001).

A close look at published data suggest that climate has been changing in the major rubber growing countries in South and South East Asia (Manton et al., 2001; Raj et al. 2011; He Jin-Hai, 2009; Joseph et al., 2006; Pant and Kumar, 1997; Pearce and Mohanti, 1984). This part of the world has been known to be highly vulnerable to climate change (IPCC, 2007). Manton et al. (2001) reported that the number of rainy days decreased significantly in the rubber growing countries in South East Asia during 1961-1998. Number of hot days and warm nights also has gone up during this period. The changes in the climate extremes were consistent for all the countries studied. The frequency of warm nights was increasing faster in the western regions while the frequency of hot days was increasing faster in the eastern regions. They also reported that the extreme rainfall events did not show any significant spatial consistency, but the number of rainy days showed statistical significance.

Being mostly rainfed crops, spices and plantation crops are vulnerable to the adverse effects of climate change. Many of these crops are generally cultivated in the tropical regions where the average rainfall ranges from 1000-4000 mm per year. Temperature requirements also vary for different crops. For example, tea crop needs a lower daily mean temperature with a high annual rainfall but rubber needs a well distributed annual rainfall with a temperature ranging from 20-35 ^{0}C. Natural rubber has a rainfall requirement of 2000 mm or more and temperature requirement of 21 ^{0}C to 35 ^{0}C with a warm humid climate. A brief review of literature of precipitation and temperature have changed in India in general is given below.

3.2. Review of Literature

3.2.1. Historic changes in precipitation

Indian agriculture is mainly dependent on the quantum and distribution of seasonal rainfall over the country. Understanding the regional level of rainfall trend using long period data is of immense importance for countries like India, where the economy is dependent on rain fed agriculture. There are several studies that have examined the actual variability that has happened in the rainfall in India for the past several years and the trends were varied according to the period of study and the region (Rajeevan, 2001; Goswami et al., 2006; Guhathakurta and Rajeevan, 2006; Krishnamurthy and Shukla, 2000; Kumar et al., 1992; Lal et al., 2001; Mooley and Parthasarathy, 1984; Naidu et al.1999). Amount of annual rainfall increased over Central India and decreased over some parts of eastern India for the period 1901–1960 (Menon and Pandalai, 1960). There was an increasing trend in mean annual and south west monsoon (SWM) rainfall over the meteorological sub-divisions of Punjab, Haryana, west Rajasthan, east Rajasthan and west Madhya Pradesh during the period 1901–1982 (Pant and Hingane, 1988). Half of the meteorological subdivisions witnessed an increasing trend in annual rainfall. Annual and monsoon rainfall decreased, and pre-monsoon, post monsoon and winter rainfall increased over the years for the last 135 years from1871 to 2005. (Krishnakumar et al., 2007; Mooley and Parthasarathy, 1984). Guhathakurtha and Rajeevan, (2008) and Rajeevan et al. (2006) analysed the rainfall of a network of 1476 rain gauge stations in India for the period 1901–2003 and showed a significant decreasing trend in the monsoon rainfall for three sub-divisions such as Jharkhand, Chhattisgarh and Kerala. Subdivisions like Gangetic West Bengal, Western Uttar Pradesh, Jammuand Kashmir, Konkan and Goa, Madhya Maharashtra, Rayalseema, coastal Andhra Pradesh and North Interior Karnataka experienced a significant increasing trend. Goswami et al. (2006) found that showed that there were significant increasing trends in extreme rain events over central India during the monsoon season, at the same time there was a significant decreasing trend in the frequency of moderate events during the same period. But the annual mean rainfall showed no significant trend.

Rajeevan (2001) studied the periodicities of monsoon in India. The Indian monsoon rainfall is highly influenced by atmospheric factors such as sea surface temperature variations (Goswami et al., 2006). Parthasarathy and Dhar (1975) reported an increase of about 5% in the annual rainfall using data from 3000 rain gauges for the period from 1901 to 1960. But a study conducted by Kumar et al., (1992) showed that in India southwest monsoon seasonal rainfall did not had any significant trend. A significant variability in the spatial patterns of the rainfall over India on both daily and seasonal time scales was also reported by analysing the intra-seasonal and inter-annual variability of rainfall (Krishnamurthy and Shukla, 2000).

Mooley and Parthasarathy (1984) showed that the rainfall over India had no significant trend over the period of 1871-1978. Sarkar and Thapliyal (1988) and Srivastava et al., (1988) indicated no trend in all India summer monsoon rainfall. In terms of changes in rainfall over India, no clear trend of increase or decrease in average annual rainfall over India has been observed. The trends and periodicities of annual rainfall for 29 sub-divisions of India were studied using time series of data for 124 years and found that there was no remarkable change in the annual rainfall (Naidu, et al., 1999). Gadgil (1988) studied the intra-seasonal and inter-annual aspects of Indian summer monsoon in India. Borgoankar and Pant (2001) reported that there was no significant trend in Indian monsoon rainfall since the 17th century. Unlike in temperature trends, rainfall trends are uncertain at several locations (Kumar et al., 2002; Rao et al., 2008).

Several researchers have studied time to time the variability in Indian monsoon and found that there was not much variability in annual rainfall (Gadgil, 1988; Guhathakurta and Rajeevan, 2006; He Jin-Hai, 2009; Rajeevan, 2001; Kumar et al., 1992; Rao et al., 2008 and Yin, 1949). But SWM rainfall showed a decreasing trend in the spices and plantation crop cultivating areas of NE and SW regions of India (Sub-divisions like Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Sub –Himalayan West Bengal and Sikkim, Orissa, Chattisgarh, Tamil Nadu & Pondicherry, North interior Karnataka and Kerala) and increasing trend in sub-divisions like Gangetic West Bengal, Konkan & Goa, Coastal Andhra Pradesh, Telangana, Rayalaseema, Coastal Karnataka and South Interior Karnataka (Guhathakurta and Rajeevan, 2006). Almost all the spices and plantation growing sub-divisions showed an increasing trend in the pre and post monsoon rainfall except a decreasing trend in pre and post monsoon of Tamil Nadu & Pondicherry, pre monsoon of Assam & Meghalaya and post monsoon of Orissa sub-division (Bhat, 2009). Thus in general, we can see a shift in the normal rainfall pattern all over the plantation crop cultivating regions in India.

Kerala is considered as the 'farm land' for almost all plantation crops because geographically Kerala has got different agro-climatic conditions suited for cultivating different types of spices and plantation crops (Jacob, 2013). In Kerala, southwest monsoon (SWM) rainfall contributes about 70% of the annual rainfall in three to four months. Contribution of pre, post and winter rainfall to the annual rainfall is 14.0, 15.8 and 2.3% respectively (Krishnakumar et al., 2009). Thus in Kerala all the crops have a major dependence on SWM. Kerala is considered as the gateway of SWM.

There was no significant reduction in the amount of annual rainfall for the period of 1871 to 2005 in Kerala. But, there was a significant reduction of 232.6 mm in SWM and an increase of 93.9 mm in northeast monsoon (NEM) during the last 135 years (Krishnakumar et al., 2009). Pre monsoon and winter rainfall did not show any significant trend. Percentage departure of the decadal mean rainfall from the normal indicated that the excess rainfall years during SWM were more frequent in the recent decades when compared to the earlier decades from 1871 to 2005. (Krishnakumar et al., 2009). Krishnakumar et al., (2007) have observed that monthly rainfall in Kerala during June and July was decreasing while the same was increasing in August and September, indicating that there was a shift in the pattern of monthly rainfall. Joseph et al., (2004) analyzed time series of daily rainfall of south Kerala using data from a network of 39 to 44 rain gauge stations for the summer monsoon season of 95 year to study the inter-annual variation in rainfall and found that a large inter-annual variability of 23 to 46 days. Raj and Azeez (2010) reported that annual rainfall in the Palakkad Gap in the Western Ghats showed variation with altitude and that the annual rainfall in the region was comparatively lesser than that of the entire State.

Simon and Mohankumar (2004) showed that the altitude and rainfall in Kerala were not correlated. Soman et al. (1988) reported a fall in the annual rainfall in the southern part of Kerala. This study also examined the long term trends in rainfall of 75 rain recording stations over Kerala for the 80 year period from 1901 to 1980 and reported a significant decreasing trend in the rainfall over the eastern high lands and adjacent areas which are home to several spices and plantation crops. Ananthakrishnan et al., (1979) reported that the pre-monsoon season accounted for several thunderstorm incidences in the State and winter (December-February) minimum clouding and rainfall. Rajeevan and Dubey (1995) developed a regression model for long range prediction of monsoon onset over Kerala using April mean surface temperature and winter snow cover over Eurasia. Ananthakrishnan et al., (1991); Pearce and Mohanty (1984); Ananthakrishnan and Soman (1988); Soman and Krishnakumar (1993); Joseph et al., (1994 and 2006) reported that large scale changes occur in the circulation features in association with the onset phase of Indian monsoon. Rao and Krishnakumar (2005) carried out statistical analysis using the long series of data on onset of monsoon and rainfall over Kerala for the period from 1870 to 2004. This study showed that there was no change in the date of onset of monsoon in Kerala over a period of time.

3.2.2. Historic changes in surface temperature

The temperature over a given region varies seasonally and annually depending upon latitude, longitude and altitude. Indian subcontinent is also not an exception for the changes in surface temperature due to climate change. Temperature variability across the country was studied by Kumar and Hingane (1988); Pant and Hingane (1988); Kumar and Parikh (1998); Singh et al. (1989); Kumar et al. (2002); Gadgil and Dhorde (2005); Kothawale and Kumar (2005) and Ramakrishna et al. (2003).It has been shown that the rate of increase in temperature varied depending upon the data set, location, region and season. Overall, a warming trend was evident across the country and the rate of increase in temperature was high in recent years though some locations showed a cooling trend. A clear upward trend in surface air temperature along the West coast was noticed between 1961 and 2003. This rise was about 0.8 ^{0}C in maximum and 0.2 ^{0}C in minimum temperature, with an increase in average surface air temperature of 0.6 ^{0}C. India Meteorological Department (IMD) reported that the maximum, minimum and mean temperature over Kerala had increased by 0.8 ^{0}C, 0.2 ^{0}C and 0.5 ^{0}C respectively during the period 1961-2003. The maximum temperature over Kerala increased by 0.64 ^{0}C while the minimum temperature rose 0.23 ^{0}C during the period 1956 to 2004 (Rao et al., 2009).

Pant and Kumar (1997) showed a significant warming trend of 0.57 ^{0}C per 100 years in India for 1881–1997, seasonally and annually. The magnitude of warming was higher in the post-monsoon and winter seasons. The monsoon temperature did not show a significant trend in any major parts of the country, except for a significant negative trend over northwest India. Mean annual temperature was found to be increasing in all India basis, in the west coast, interior peninsula, north central and north-eastern regions during the period 1901–1982 (Hingane et al.1985). Trend analyses of maximum and minimum temperature data at 121 stations in India for 1901–1987 by Rupa Kumar et al. (1994) showed increasing maximum temperature, minimum temperature did not show any pattern, resulting in rise in mean and diurnal range of temperature. For the last 100 years, there was an increase of 0.42 ^{0}C in the annual mean temperature, 0.92 ^{0}C in the mean maximum temperature and 0.09 ^{0}C in the mean minimum temperature. There was a rise of 1.1 ^{0}C in mean winter temperature, 0.94 ^{0}C in mean post-monsoon temperature, and a decline of 0.40 ^{0}C in mean pre-monsoon temperature for the last century in India (Arora et al., 2005). Frequency of occurrence of hot days and hot nights showed an increasing trend, whereas cold days and cold nights showed a decreasing trend during the period 1970–2005 in India as a whole and seven homogeneous regions. For the last 100 years in India, the annual mean, maximum and minimum temperatures showed significant warming trends of 0.51 °C, 0.72 °C and 0.27 °C, respectively. Indian mean annual and seasonal temperatures also showed a significant warming trend in all seasons. (Kothawale et al., 2010).

3.3. Data and Methodology

3.3.1. Data used

3.3.1.1. Temperature and rainfall data over India

Temperature data for homogeneous Indian regions and sub-divisional rainfall data over India were obtained from Indian Institute of Tropical meteorology (IITM, www.tropmet.res.in/Data%20Archival-51-Page). Anomaly and trend analyses were done for surface temperature over homogeneous Indian regions like All India, Western Himalaya, Northwest India, North Central India, Northeast India, Interior Peninsular India, East coast of India and West coast of India. These homogeneous regions have been prepared based on their distinct climatic and geographical peculiarities (Kothawale and Kumar, 2005). The period of data used for the analysis was 1901 to 2007.

Sub-divisional rainfall datasets for the period of 1871 to 2011 were analysed for for all India and 15 other rainfall sub-divisions in which natural rubber is cultivated. The rainfall subdivisions are prepared from 306 rain gauge stations by giving weightage to the district area where these stations are running. All these stations are almost uniformly distributed In India and rainfall data are available from 1871 (Mooley et al., 1981; Parthasarathy et al., 1987). The rainfall sub-divisions used for the study are All India, Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura, Sub Himalaya and West Bengal, Gangetic West Bengal, Odisha, Konkan and Goa, Madhya Maharashtra, Coastal Andhra Pradesh, Thelangana, Rayalaseema, Tamil Nadu & Pondicherry, Coastal Karnataka, North Interior Karnataka, South Interior Karnataka and Kerala.

3.3.1.2. Temperature and rainfall data from different rubber growing regions

Long term daily temperature and rainfall data for different rubber growing regions of India were collected from the Regional Research Stations (RRSs) of the Rubber Research Institute of India (RRII) and subjected to anomaly and trend analyses. The different regional stations from where the data was collected and the general climatic conditions of these regions given in Table 3.1.

Table 3.1. Mean climatic characteristics of different Regional Research Stations of RRII, India.

RRS	State	Lattitude (⁰N)	Longitude (⁰E)	Data Period	Altitude (m)	Mean Annual Temperature (⁰C)		Mean Annual rainfall (mm)
						Max.	Min.	
Traditional Region								
Kottayam	Kerala	09⁰32′	76⁰36′	1960-2010	73	31.3	22.8	3000
Chethackal	Kerala	09⁰22′	76⁰50′	1987-2010	80	32.6	21.8	3500
Padiyoor	Kerala	11⁰58′	75⁰36′	1998-2010	20	32.8	22.0	3700
Parliar	Tamil Nadu	08⁰26′	77⁰36′	1994-2010	33	32.3	22.9	2000
Nettana	Karnataka	12⁰45′	75⁰32′	1989-2010	110	32.0	19.4	4700
Non-traditional region								
Dapchari	Maharashtra	20⁰04′	72⁰04′	1986-2010	48	33.1	20.5	2500
Agarthala	Tripura	23⁰53′	91⁰15′	1984-2012	20	30.5	20.0	2000
Tura	Meghalaya	25⁰31′	90⁰14′	1995-2012	600	29.1	16.5	2500
Nagrakata	West Bengal	28⁰54′	88⁰25′	1995-2012	229	29.6	17.8	3812
Guwahati	Assam	56⁰11′	91⁰45′	1989-2012	105	30.0	18.2	1500
Dhenkanal	Odisha	20⁰67′	85⁰60′	1998-2012	80	33.5	20.6	1250

3.3.2. Methodology

Temperature and rainfall data were analyzed annually and seasonally. For seasonal analysis of temperature, each year was divided into four periods ie. JF (January – February), MAM (March – May), JJAS (June – September) and OND (October - December) which roughly represent winter, summer, monsoon and autumn seasons. For seasonal analysis of rainfall data of sub-divisions, each year was divided into three main rainy seasons like pre-monsoon (March – May), southwest monsoon or SWM (June – September) and post-monsoon (October – December). Rainfall data were divided into 30 years groups and monthly distribution was analyzed for all sub-divisions. Trend analyses were also done to estimate the change in the time series annually and seasonally.

For the analysis of the data of regional stations of RRII, the same method was followed. Additionally, analyses of extreme weather events were also done for each station annually and seasonally. To detect the frequency of occurrence of maximum temperature extremes, number of warm winter and hot summer days per year were analyzed. A hot day is one in which the temperature is more than the sum of the long term mean temperature and one standard deviation (Henderson and Muller, 1997).

$$Hd = \frac{\sum Tx}{N} + SD \qquad \text{Eqn. (1)}$$

were *Hd* is the hot day, *Tx* is annual or seasonal maximum temperature, *N* is the number data points and *SD* is the standard deviation.

Like maximum temperature, the frequency of minimum temperature extremes were also calculated as warm winter and summer nights by replacing the maximum temperature with minimum temperature.

$$Wn = \frac{\sum Tn}{N} + SD \qquad \text{Eqn. (2)}$$

were *Wn* is the hot day, *Tn* is annual or seasonal minimum temperature, *N* is the number data points and *SD* is the standard deviation.

Mean daily datasets for the maximum and minimum temperatures were calculated for the earlier and recent decade and plotted for all the stations to detect the behavior of daily temperature throughout the year.

3.3.2.1 Trend analysis

Time series analyses were carried out to detect the trends in annual, seasonal means for temperature and rainfall. In this study linear regression method (parametric) and Sen's estimator method (non-parametric) were used to determine the trend in the time series. In these methods, it assumes that a linear trend in the time series. Regression analysis is conducted with time as the independent variable and the climatic parameter as the dependent variable. After putting the linear trend, the change in time series was computed by the equation;

$$y = ax + b \qquad \text{Eqn. (3)}$$

were *a* is the slope or trend, *x* is the time or year and *b* is the intercept.

Sen's estimator is a non parametric regression method used to detect the magnitude of trend in a time series (Lettenmaier et al., 1994; Yue and Hashino, 2003; Partal and Kahya, 2006). In this method, the slopes (Ti) of all data pairs are first calculated by

$$Ti = \frac{Xj - Xk}{j - k} \quad for\ i = 1, 2, \ldots\ldots N, \qquad \text{Eqn. (4)}$$

where *Xj* and *Xk* are data values at time *j* and *k* ($j > k$) respectively. The median of these N values of *Ti* is the Sen's estimator of slope (β) which is calculated as;

$$\beta = \begin{cases} T_{\frac{N+1}{2}} & N \text{ is odd} \\ \frac{1}{2}\left(T_{\frac{N}{2}} + T_{\frac{N+2}{2}}\right) & N \text{ is even} \end{cases} \qquad \text{Eqn. (5)}$$

β represents the upward and downward trend in a series. If the value of β is positive, it indicates the increasing trend and if it is negative, indicates decreasing trend in a time series.

3.3.2.2. Mann-Kendall trend test for significance of a trend

Mann-Kendall test is used for testing the statistical significance of the trend in a time series (Mann, 1945; Kendall, 1975). The Mann- Kendall test checks the null hypothesis of no trend (H_0) versus the alternative hypothesis (H_a) of the presence of trend in the time series. In this study the null hypothesis was tested at 95% confidence level.

The test statistic *S* is then computed as (Salas, 1993);

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \text{sign}(X_j - X_i) \qquad \text{Eqn. (6)}$$

where *N* is the number of data points. Assuming (Xj – Xi) = θ,the value of sgn(θ) is computed as ;

$$\text{sign}(\theta) = \begin{cases} 1 \ \text{if} \ \theta > 0 \\ 0 \ \text{if} \ \theta = 0 \\ -1 \ \text{if} \ \theta < 0 \end{cases} \qquad \text{Eqn. (7)}$$

The *S* statistic represents the number of positive differences (Xj > Xi) minus the number of negative differences (Xj < Xi) for all the differences considered. When *S* is a positive number, the later values tend to be larger than the earlier values and show an upward trend in the time series. If *S* is a negative number, a downward trend is indicated and if zero there is no trend. Then the Variance *S* is computed as;

$$VAR(S) = \frac{1}{18}\left[N(N-1)(2N+5) - \sum_{p=1}^{g} t_p(t_p-1)(2t_p+5)\right] \qquad \text{Eqn. (8)}$$

Were *N* is the number of data points, *g* is the number of tied groups (a tied group is a set of sample data having same value), *tp* is the number of data points in the p[th] group. Finally with *VAR(S)* standardized test statistic *Z* will be computed as;

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if} \ \theta > 0 \\ 0 & \text{if} \ \theta = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if} \ \theta < 0 \end{cases} \qquad \text{Eqn. (9)}$$

The trend is said to be decreasing if *Z* is negative and the computed probability is greater than the level of significance (|Z|> $Z\alpha/2$) in a two-tailed test. The trend is said to be increasing if the *Z* is positive and the computed probability is greater than the level of significance. If the computed value is less than the alpha level of significance, the alternate hypothesis (H_a) is rejected and there is no trend.

3.4. Results and Discussion

From the preceding chapter and the description given above in this chapter, it can be seen that climate change is a highly complex and variable phenomenon, the expression of which can be seen around us as unprecedented warming of the atmosphere, altered rainfall patterns, extreme weather events such as floods, heat waves, droughts etc. As IPCC reported in its Fourth Assessment Report (AR4), the rate of warming in global temperature is much higher in the recent decades than before. The planet has been warming at an increasing rate and 11 out of the 12 warmest years on record have occurred during the period of 1993-2005. Regional climate is also changing with global climate and the extent also varies regionally. Regional climate is much more relevant than global climate when it comes to the impact of climate change on agriculture. Agriculture of a region is ultimately dependent on regional climate. Historic climate change that has occurred in the rubber growing regions of India were analyzed in the present study and the results of the same are given below. The ultimate objective of this analysis is to examine how these changes would impact growth and productivity of rubber in the country which is discussed in the following chapter.

3.4.1. Trends in temperature and rainfall over India

3.4.1.1. Temperature

Analysis of temperature data of India showed that the surface maximum temperature over the country has significantly increased annually and seasonally during the last 107 years (Figure.3.1). Annual increase in mean temperature was 0.8 ^{0}C in the last 100 years and the maximum increase was 1.2 ^{0}C noted during October-December (OND) season. When all the homogeneous India regions were considered together, maximum increase were noted in January-February (JF) and October-December (OND) seasons which was 1.1 ^{0}C for the last 100 years. Among the regions, West coast of India showed maximum warming of more than 1 ^{0}C in all seasons for the past century. Minimum temperature also showed a significant increasing trend annually except in Northwest India region. Interior Peninsular India region showed a significant increasing trend in all seasons, but rest of the regions did not show a consistent trend in all seasons. The trend was positive or negative in some seasons and most of the cases it was not significant also (Table 3.2). The rate of increase was relatively high in OND and JF seasons, both in maximum and minimum temperatures.

Results of the analyses of seasonal and annual temperature anomaly (relative to 1961-1990 mean) and trend of maximum and minimum temperatures over all India, Western Himalaya and West coast of India for the period 1901-2007 were given in the Figure 3.1-3.3. Most of the plantation crops are coming under these homogeneous temperature regions. There was a significant change in the maximum temperature for all the seasons Northeast India region, where the non- traditional rubber cultivating regions of the NE parts of India coming under. Minimum temperature did not show any significant change except for annual temperature. West coast region, where most of the traditional rubber cultivating areas are present, showed a significant warming trend in the maximum temperature for all season, but the minimum temperature showed significant changes only for MAM, JJAS and OND seasons (Table. 3.2).

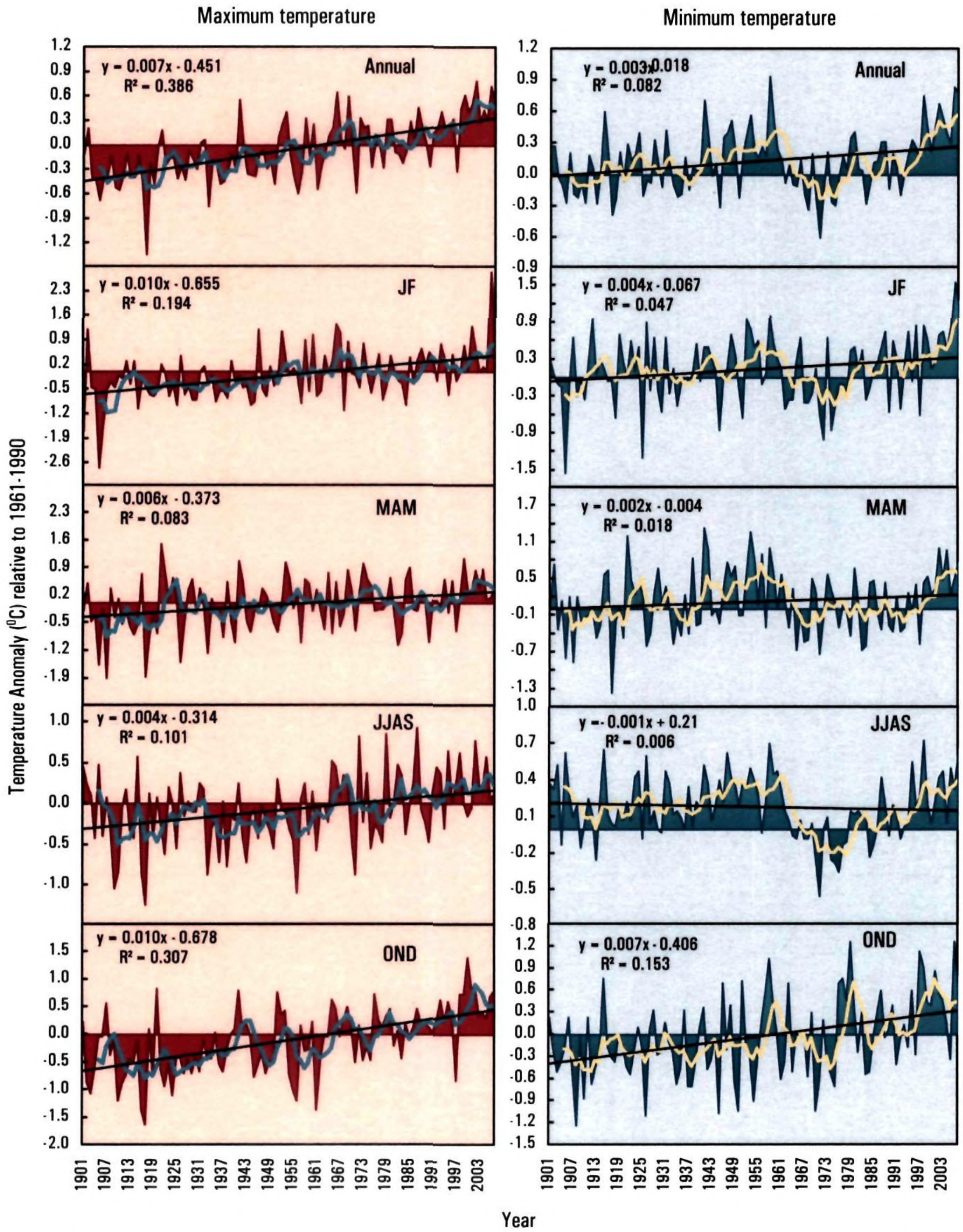


Figure 3.1. Annual and seasonal trend in maximum an minimum temperature over all India for the period 1901-2007. Black straight line represents the long term trend and the blue thick line represents the 5 year smoothed average.

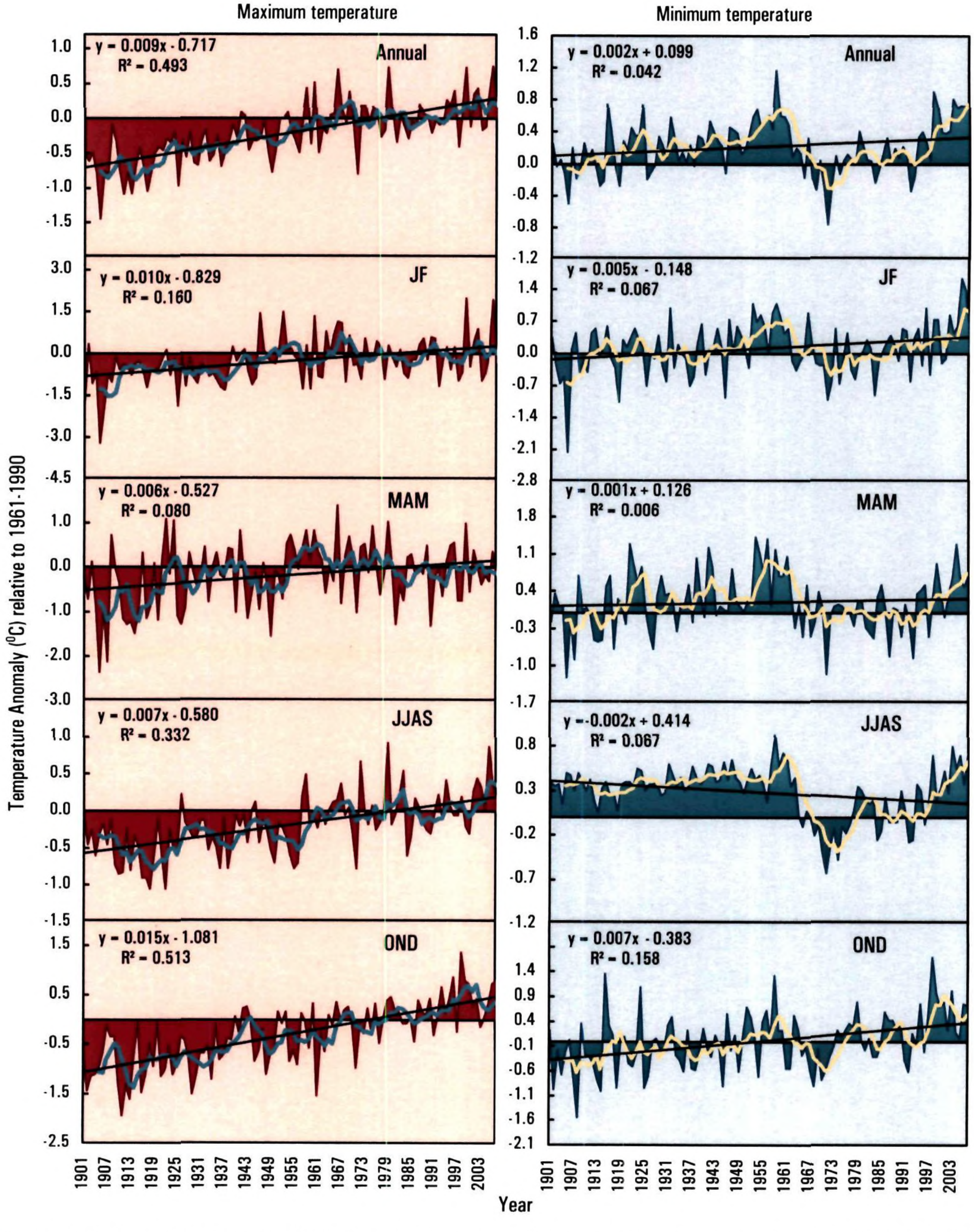


Figure 3.2. Annual and seasonal trend in maximum an minimum temperature over Northeast India for the period 1901-2007. Black straight line represents the long term trend and the blue thick line represents the 5 year smoothed average.

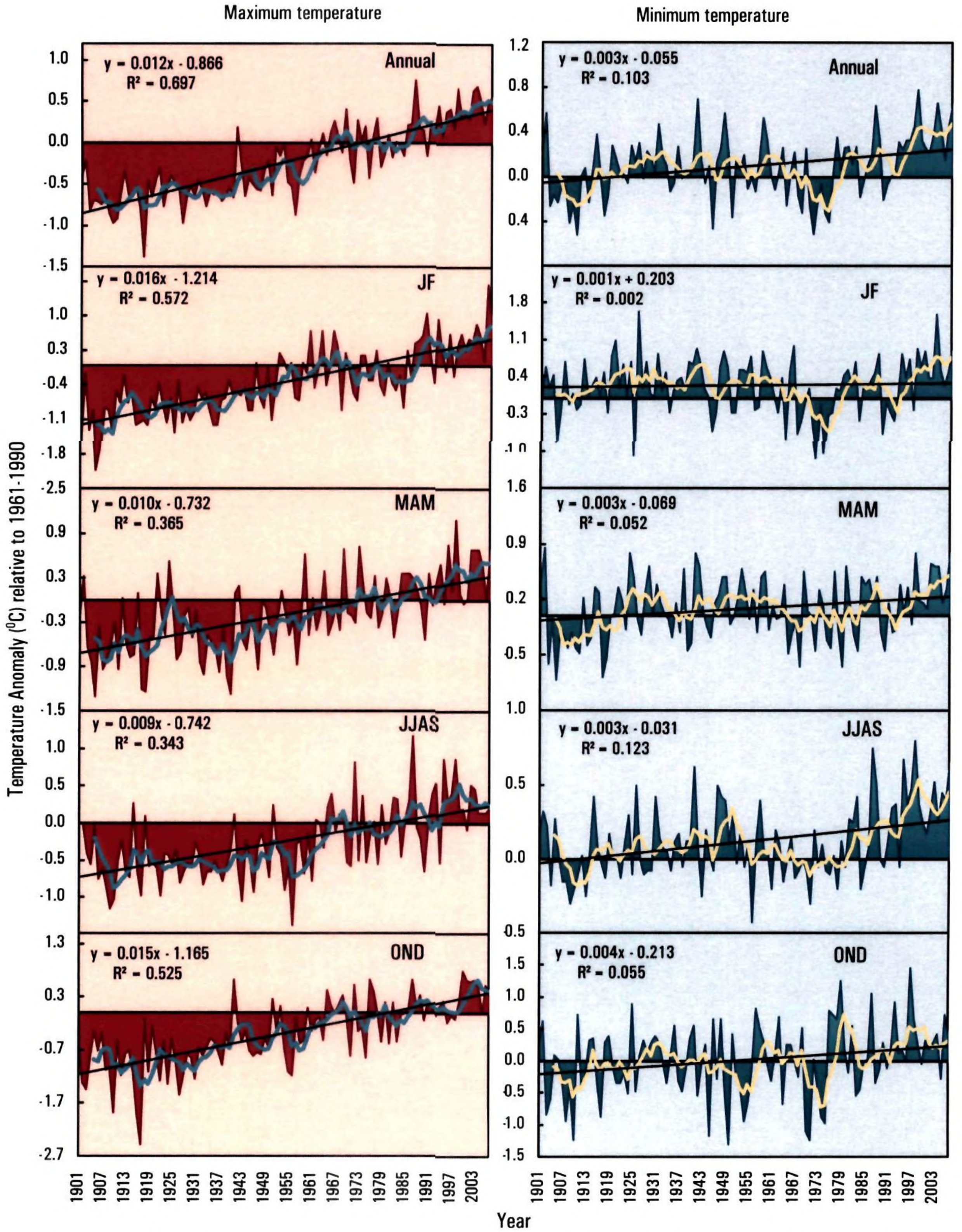


Figure 3.3. Annual and seasonal trend in maximum an minimum temperature over Westcoast of India for the period 1901-2007. Black straight line represents the long term trend and the blue thick line represents the 5 year smoothed average.

Table 3.2. Sen's estimator of slope for annual and seasonal maximum and minimum temperature (⁰C) for all India and homogeneous India regions.

Region	Temperature Maximum (⁰C)					Temperature Minimum (⁰C)				
	Annual	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND
All India	**0.008**	**0.008**	**0.006**	**0.005**	**0.012**	**0.003**	**0.004**	0.002	0.000	**0.007**
Western Himalaya	**0.010**	**0.027**	**0.012**	**0.004**	**0.008**	**0.006**	**0.010**	**0.005**	**0.001**	**0.011**
Northwest India	**0.006**	**0.006**	**0.005**	**0.003**	**0.009**	-0.001	-0.003	0.000	**-0.003**	0.000
North central India	**0.007**	**0.003**	**0.005**	**0.005**	**0.013**	**0.003**	0.004	0.002	-0.002	**0.010**
Northeast India	**0.009**	**0.008**	**0.006**	**0.007**	**0.015**	**0.002**	0.004	0.001	-0.002	0.008
Interior Peninsular India	***0.006***	***0.009***	***0.004***	***0.003***	***0.009***	***0.005***	***0.006***	***0.003***	***0.003***	***0.006***
Eastcoast of India	**0.007**	**0.010**	**0.005**	**0.003**	**0.010**	**0.004**	**0.006**	**0.004**	0.001	**0.005**
Westcoast of India	**0.012**	**0.016**	**0.010**	**0.010**	**0.015**	**0.003**	0.000	**0.003**	**0.003**	**0.004**

Values in bold are significant at 95% confidence level.

In general, it can be concluded that India as a whole has been warming in recent years, although in some places and in some seasons this trend was not always consistent. However, the predominant evidence is for a gradual warming trend and the rate of warming has been increasing over the years.

3.4.1.2. Rainfall

Study on all India annual and seasonal rainfall showed no significant changes over the past 141 years (Figure 3.4). Analysis of rainfall data for sixteen IMD rainfall subdivisions in the rubber growing tract in India also showed no trend in the amount of annual rainfall for the period from 1871-2011. Sub-divisions like Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura registered a significant decreasing trend in the annual and monsoon rainfall. The rate of reduction in the annual rainfall was -1.129 mm $year^{-1}$ and -1.141 mm $year^{-1}$ for Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura respectively and the rate of reduction in the monsoon rainfall was -1.094 mm $year^{-1}$ and -1.301 mm $year^{-1}$ for Assam & Meghalaya and Nagaland, Manipur, Mizoram & Tripura respectively. Sub-divisions like Gangetic West Bengal (1.002 mm $year^{-1}$), Konkan and Goa (2.092 mm $year^{-1}$) and Coastal Karnataka (2.527 mm $year^{-1}$) showed a significant increasing trend in the annual rainfall. Rayalaseema sub-division showed an increasing trend of 0.183 mm $year^{-1}$ and Kerala sub-division showed an increasing trend of 0.714 mm $year^{-1}$, both were statistically significant at 5% level (Table 3.3). Results of the trend analysis of rainfall over all India and Assam & Meghalaya, Madhya Maharashtra and Kerala subdivisions are given in the Figure 3.4 & 3.5.

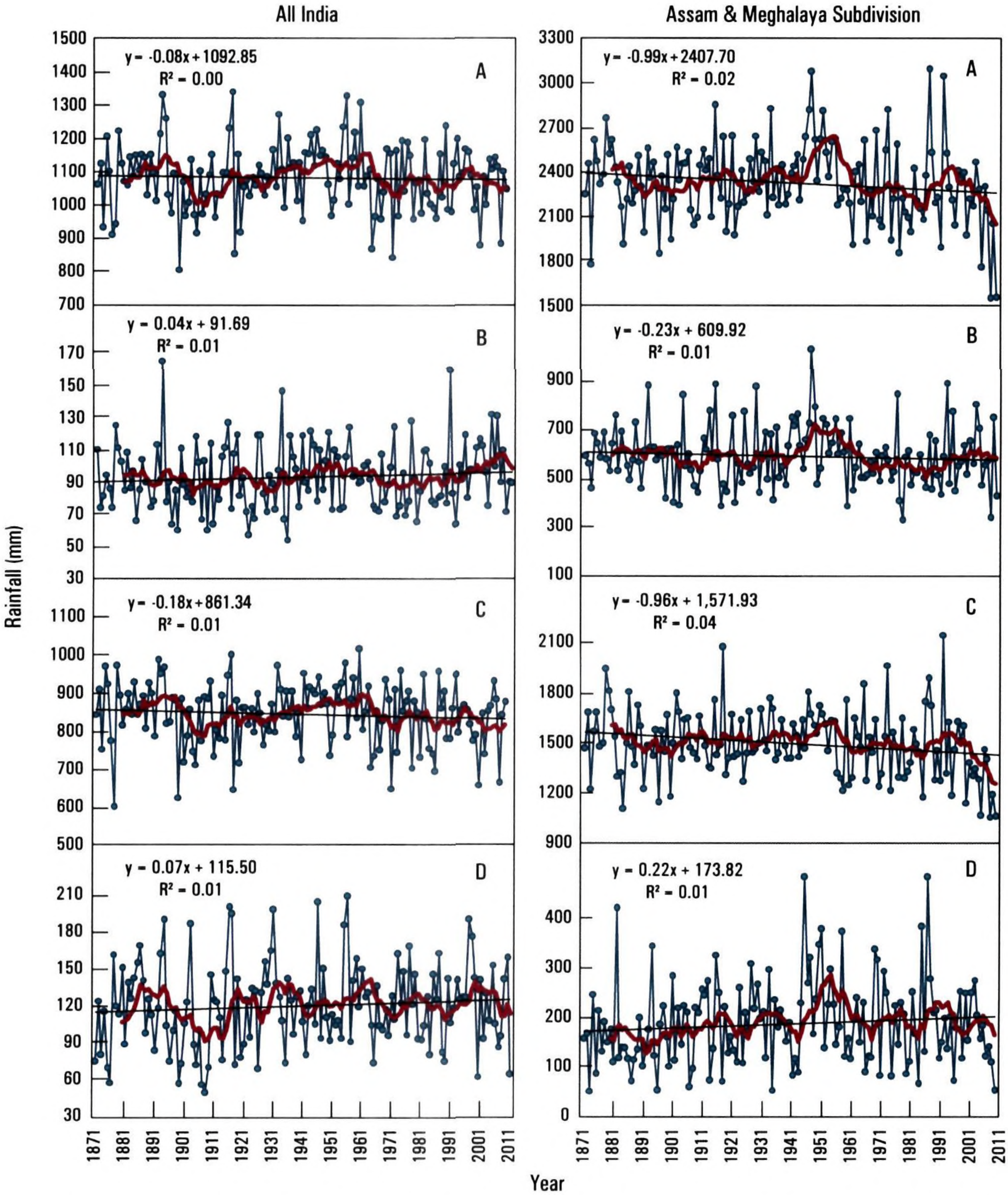


Figure 3.4. Annual and sesonal trend of rainfall over all India and Assam & Meghalaya sub-division for the period 1871-2011. (A) Annual rainfall, (B) Pre-monsoon, (C) Monsoon and (D) Post-monsoon. Black straight line represents the long term trend and the red thick line represents the 5 year smoothed average.

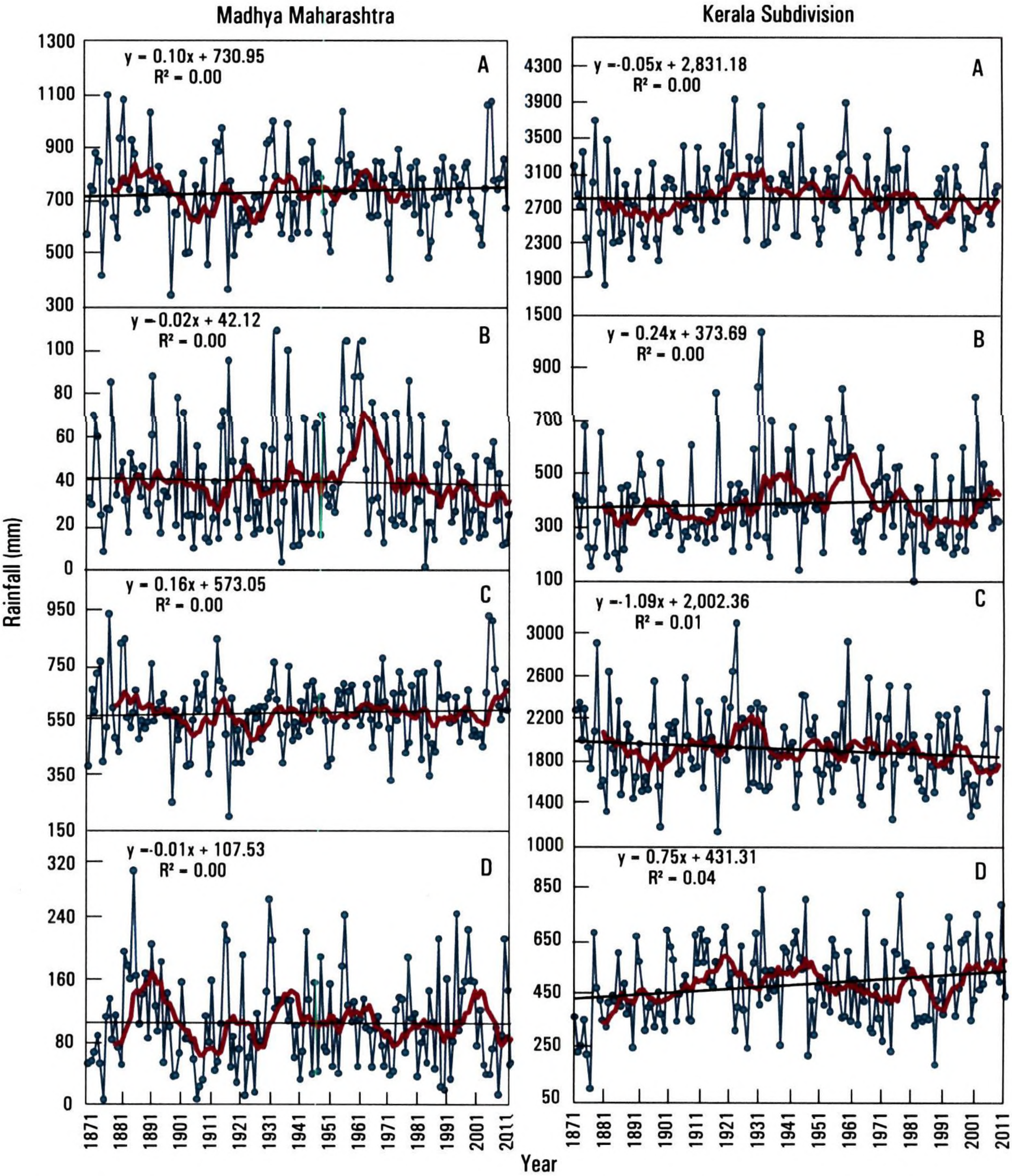


Figure 3.5. Annual and sesonal trend of rainfall over Madhya Maharashtra & Kerala sub-division for the period 1871-2011. (A) Annual rainfall, (B) Pre-monsoon, (C) Monsoon and (D) Post-monsoon. Black straight line represents the long term trend and the red thick line represents the 5 year smoothed average.

Table 3.3. Sen's estimator of slope for annual and seasonal rainfall (mm) for all India and IMD rainfall sub-divisions in the rubber growing tracts in India.

Subdivision	Rainfall (mm)			
	Annual	Pre-monsoon	Monsoon	Post-monsoon
All India	-0.053	0.047	-0.211	0.062
Assam & Meghalaya	**-1.129**	-0.314	**-1.094**	0.197
Nagaland, Manipur, Mizoram & Tripura	**-1.141**	-0.020	**-1.301**	0.055
Sub-himalayan West Bengal & Sikkim	-0.347	0.080	-0.727	0.304
Gangetic West Bengal	**1.002**	0.160	0.681	0.146
Orissa	-0.303	0.100	-0.320	-0.249
Konkan & Goa	**2.092**	0.034	1.658	0.238
Madhya Maharashtra	0.036	-0.029	0.114	-0.026
Coastal Andhra Pradesh	0.675	0.046	0.375	-0.039
Thelangana	0.548	0.080	0.173	0.167
Rayalaseema	0.500	**0.183**	0.201	0.087
Tamil Nadu & Pondicherry	0.287	-0.031	-0.005	0.375
Coastal Karnataka	**2.527**	0.362	1.645	0.257
North Interior Karnataka	0.280	0.116	0.016	-0.010
South Interior Karnataka	0.191	-0.008	0.253	-0.029
Kerala	0.148	0.252	-0.961	**0.714**

Values in bold are significant at 95% confidence level.

3.4.1.3 Tri-decadal analyses of sub-divisional rainfall

Tri-decadal mean monthly rainfall was analyzed for two periods (1871-1900 and 1982-2011) for all India and all sub-divisions to understand the changes in the distribution of rainfall throughout the months in a year (Figure 3.6). The changes were very prominent in the case of Assam & Meghalaya, Nagaland, Manipur, Mizoram & Tripura and Kerala sub-divisions. In the Assam & Meghalaya sub-division, June and September rainfall showed a marked reduction in the quantum, while the amount of rainfall during the month of August showed an increase. Lowering of peak amounts of rainfall during the southwest monsoon period with increase in peak amounts during the northeast monsoon was observed for the long-term data over the Kerala subdivision. Even as the quantum of annual rainfall did not show any significant change in the last several decades, there was a shift in the rainfall pattern in Kerala sub-division. The amount of rain received during southwest monsoon (SWM) decreased whereas the same for the northeast monsoon (NEM) increased (Figure 3.6).

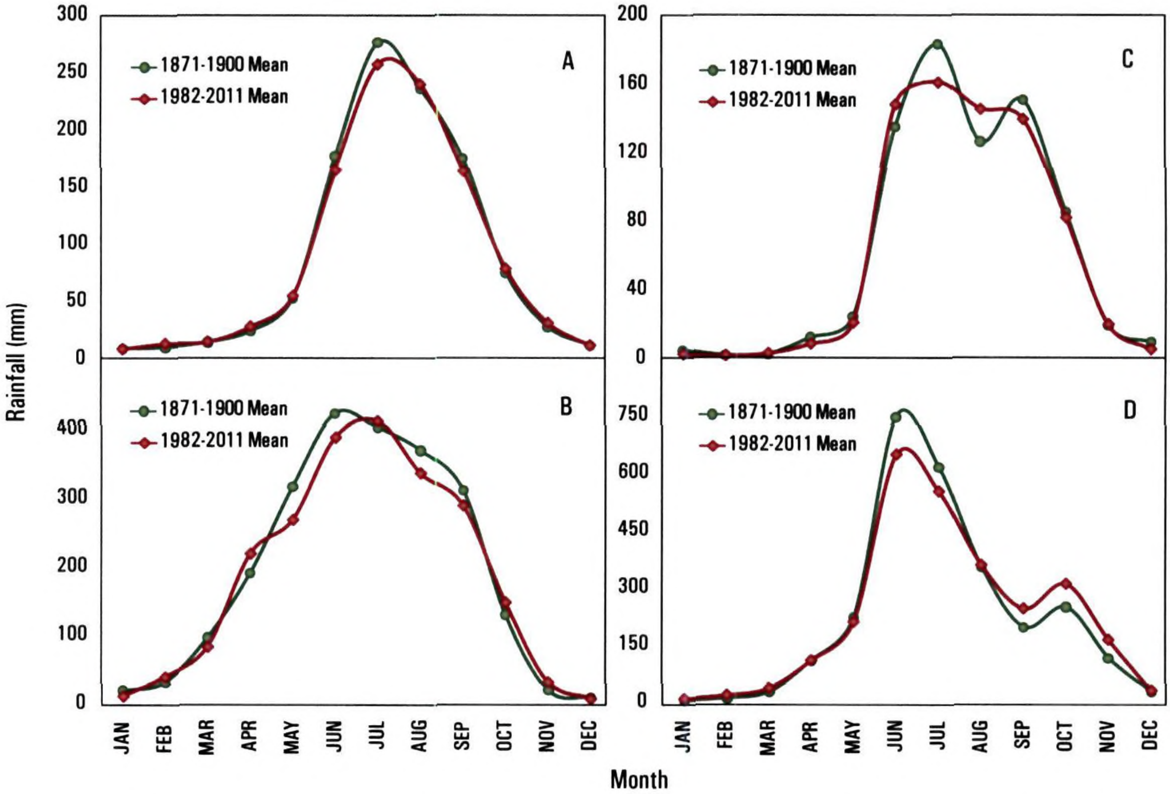


Figure 3.6. Tri-decadal mean monthly rainfall distribution for the tri-decadal periods of 1871-1990 and 1982-2011. (A) All India, (B) Assam & Meghalaya, (C) Madhya Maharashtra and (D) Kerala Sub-divisions.

3.4.2. Trends in temperature and rainfall over natural rubber growing regions of India

3.4.2.1. Temperature

There was an increasing trend in mean annual maximum temperature for all rubber growing regions for which data were available. There was no significant trend in temperature during MAM season in Chethackal, JF season in Agarthala, JF and OND seasons in Padiyoor, OND season in Tura and Nagrakata. In Kottayam, maximum temperature showed an increasing trend for all seasons and was significant at 5% level (Figure 3.7). Mean maximum temperature rose by was 0.043 ^{0}C yr-1, 0.049 ^{0}C yr^{-1}, 0.048 ^{0}C yr^{-1}, 0.043 ^{0}C yr^{-1}, and 0.045 ^{0}C yr^{-1}, in annual, JF, MAM, JJAS and OND seasons, respectively in Kottayam (Table 3.4). Tmax in Chethackal showed a significant increasing trend of 0.049 ^{0}C yr^{-1} in winter (JF) season. Seasons like JJAS and OND showed maximum significant increase in maximum temperature.

All seasons taken together, annual maximum temperature at Dapchari, Maharashtra showed a significant increasing trend. Minimum temperature did not show a consistent increasing or decreasing trend in any station for any season. Out of the 55 Sen's slope values for mean minimum temperature, 20 were negative (decreasing trend) (Table 3.4). In Kottayam, all the seasons showed positive trend (increasing trend) but only MAM and JJAS showed significant change (Figure 3.7). Padiyoor, Dapchari and Nagrakata stations showed an increasing trend in minimum temperature for all seasons taken together. In Padiyoor except JF season the minimum temperatures for all other seasons increased were significant at 5% level. In Dapchari the trend was significant only at MAM. Nagrakata station showed significant increasing trend in minimum temperature for all seasons except JJAS. Dhenkanal and Chethackal showed decreasing trend for all seasons, but in Dhenkanal the trends were not significant while in Chethackal annual and JJAS were showed a significant decreasing trend in minimum temperature (Table 3.4).

The mean daily maximum and minimum temperature for the five year period of 2006-2010 was well above the daily means for an earlier period of 1960-1964 (Figure 3.8). The changes were very prominent in the case of Kottayam, Parliar Dapchari and Guwahati. In Kottayam maximum temperature of every day of the recent five year mean was approximately two degrees celsius above the mean maximum temperature during 1960-1964 (Figure 3.8). Minimum temperature also showed the same daily trend (1.5 ^{0}C), but the days in January and February did not show a remarkable increase in the latter period. In Parliar, the increase was around 0.5 ^{0}C for maximum temperature while no marked difference was observed in minimum temperature between the two study periods. In Chethackal around 0.7 ^{0}C warming was noticed in minimum temperature during the same period. Rest of the stations did not show any remarkable difference in both maximum and minimum temperature between these two periods.

3.4.2.2. Rainfall

There was large variation in annual and seasonal rainfall between the stations, but variations in annual rainfall over time were not significant within most stations. There were significant reductions in seasonal rainfall in many places during some seasons such as during the pre-monsoon and post-monsoon seasons. In most stations the magnitude of trends was large but they were not significant due to large variations in the data. Even as changes in temperature were very prominent in Kottayam, annual rainfall did not register any change (Figure 3.9). Since the available period datasets were quite short, it was inadequate to predict the actual change in rainfall.

Significant changes were observed in the pre-monsoon rainfall over Chethackal and pre-monsoon and post monsoon rainfall over Dhenkanal. In Chethackal the pre-monsoon rainfall increased by 21. 7 mm and in Dhenkanal the pre and post monsoon decreased by 41.9 and 21.2 mm yr^{-1}, respectively (Table 3.4).

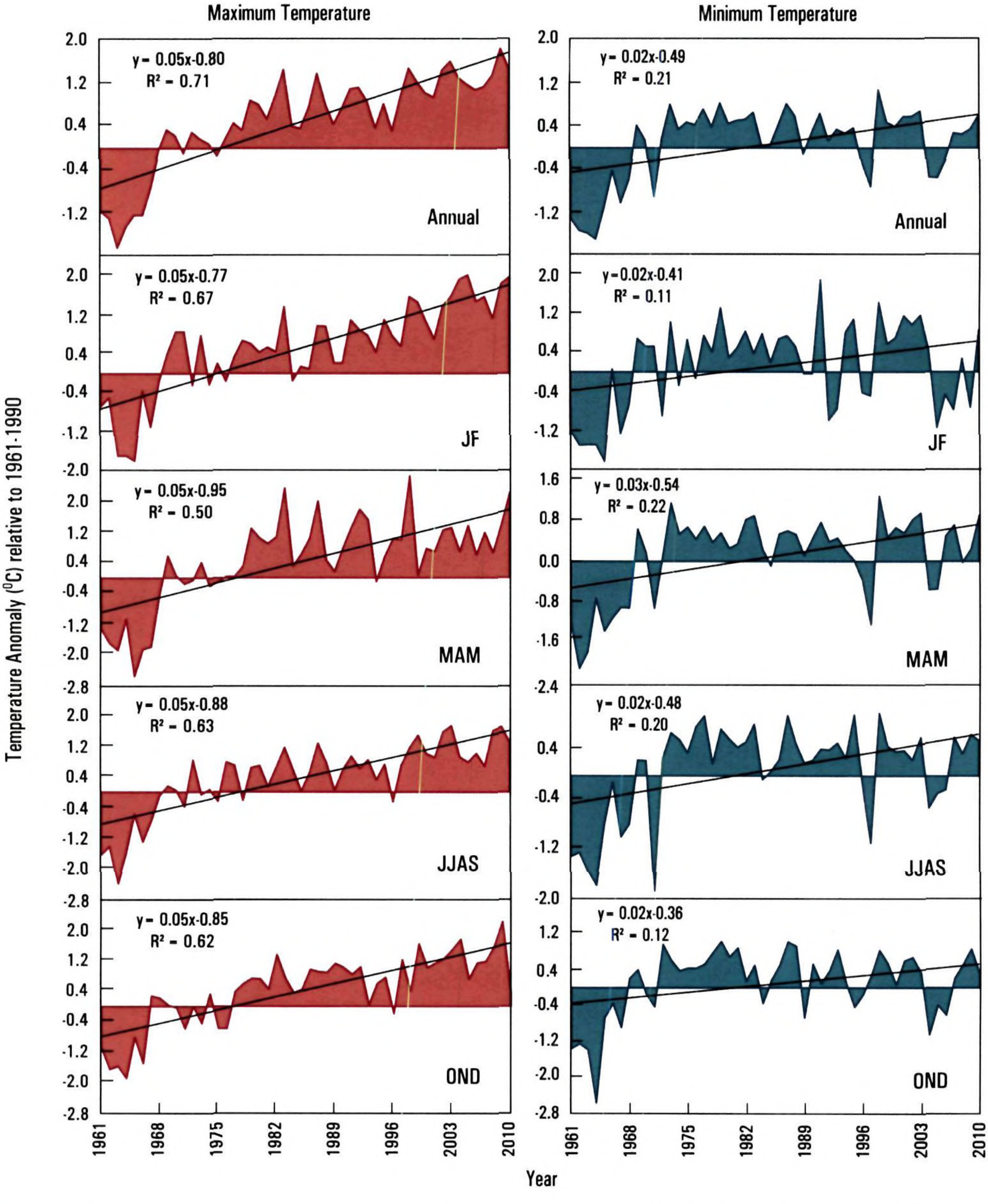


Figure 3.7. Annual and seasonal trend in maximum and minimum temperature over Kottayam for the period 1960-2010. Black straight line represents the long term trend in the time series.

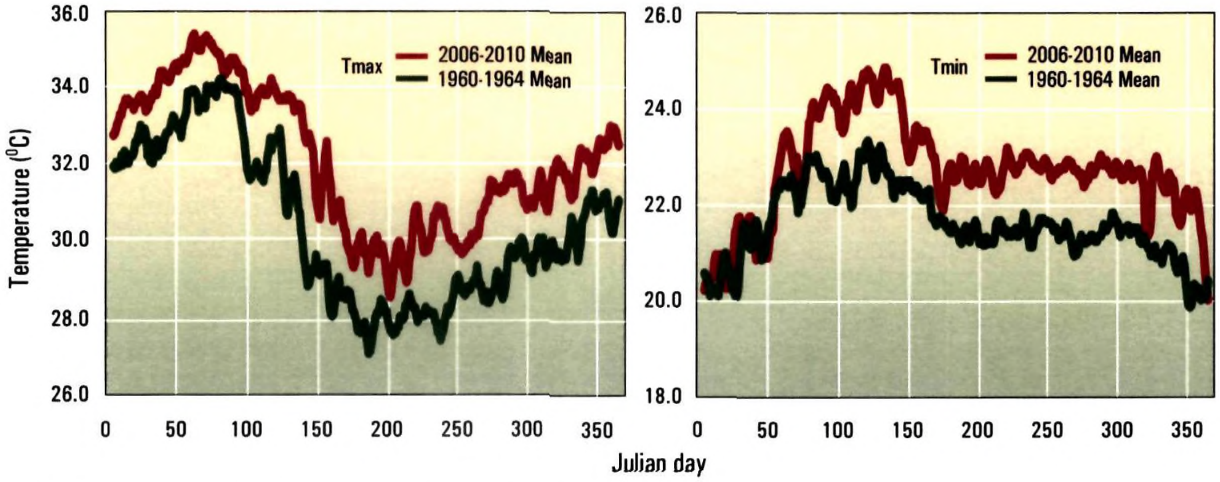


Figure 3.8. Variation in recent five year mean (2006-2010) daily maximum and minimum temperature over Kottayam compared to the earlier records (1960-1964).

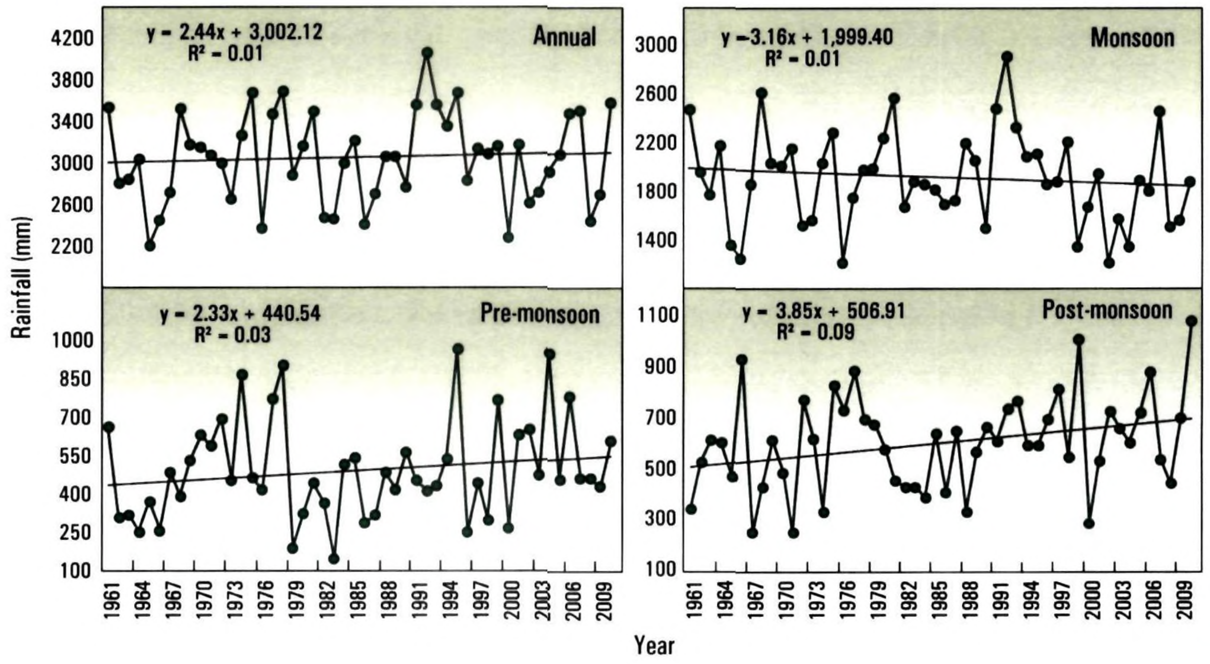


Figure 3.9. Annual and seasonal trends in rainfall over Kottayam for the period 1960-2010. Black straight line represents the long term trend line.

Table 3.4. Sen's estimator of slope for annual and seasonal temperature (°C) and rainfall (mm) for the datasets from all Regional Research Stations (RRSs) of Rubber Board, India.

Station	Temperature Maximum (°C)					Temperature Minimum (°C)					Rainfall (mm)			
	Annual	JF	MAM	JJAS	OND	Annual	JF	MAM	JJAS	OND	Annual	Pre-monsoon	Monsoon	Post-monsoon
RRII Kottayam, Kerala	**0.043**	**0.049**	**0.048**	**0.043**	**0.045**	**0.011**	0.016	**0.016**	**0.012**	0.009	3.819	2.837	-2.997	3.018
CES Chethackal, Kerala	0.021	**0.049**	-0.006	0.021	0.012	**-0.036**	-0.030	-0.029	**-0.035**	-0.015	13.950	**21.707**	-14.769	6.744
RRS Padiyoor, Kerala	0.015	-0.026	0.070	0.040	-0.013	**0.130**	0.015	**0.135**	**0.158**	**0.194**	107.694	-14.593	110.760	28.008
RRS Parliyar, Tamil Nadu	**0.065**	**0.079**	0.011	**0.083**	**0.078**	-0.007	-0.052	0.014	-0.013	0.025	-5.954	-14.400	3.100	8.580
RRS Nettana, Karnataka	**0.084**	0.077	0.023	**0.084**	**0.136**	0.057	0.141	0.028	0.018	-0.005	3.180	7.155	-6.642	-5.899
RRS Dapchari, Maharashtra	**0.101**	**0.136**	**0.122**	**0.086**	**0.082**	0.022	0.009	**0.059**	0.006	0.017	20.443	0.000	23.730	-0.930
RRS Agarthala, Tripura	0.013	-0.016	0.031	0.024	0.005	**0.026**	-0.009	0.021	**0.025**	**0.045**	-10.336	-2.401	2.513	-3.715
RRS Tura, Meghalaya	0.032	0.048	0.060	0.045	-0.018	0.004	0.011	-0.004	0.034	-0.020	55.329	18.958	40.672	-0.333
RRS Nagrakata, West Bengal	0.039	0.055	0.026	**0.065**	-0.017	**0.089**	**0.159**	**0.104**	0.026	**0.145**	23.351	-2.046	32.752	-4.456
RRS Guwahati, Assam	**0.057**	0.072	**0.060**	**0.042**	**0.056**	-0.012	-0.046	0.007	-0.014	-0.036	-13.919	-4.633	-5.009	-0.567
RRS Dhenkanal, Orissa	**0.134**	0.094	0.063	**0.221**	**0.127**	-0.061	-0.008	-0.078	-0.038	-0.092	-36.257	**-41.900**	50.100	**-24.717**

Values in bold are significant at 95% confidence level

TTable 3.5. Sen's estimator of slope for annual and seasonal extreme climatic events like hot days, warm nights, heavy rainy days and rainfree days for the datasets from all Regional Research Stations (RRSs) of Rubber Board, India.

Station	Temperature						Rainfall (mm)							
	Hot Days (days year^{-1})			Warm Nights (days year^{-1})			Heavy rainy days (days year^{-1})				Rainfree days (days year^{-1})			
	Annual	Summer	Winter	Annual	Summer	Winter	Annual	Pre monsoon	Monsoon	Post monsoon	Annual	Pre monsoon	Monsoon	Post monsoon
RRII Kottayam, Kerala	**2.586**	**0.691**	**0.625**	**0.897**	**0.500**	**0.283**	0.045	**0.029**	0.000	0.000	-0.109	-0.092	0.107	-0.050
CES Chethackal, Kerala	1.000	-0.300	**1.000**	**-2.000**	-0.500	-0.308	0.000	0.133	-0.143	0.000	-0.143	-0.231	0.000	-0.222
RRS Padiyoor, Kerala	0.550	0.367	0.236	**9.938**	**2.414**	0.292	1.000	-0.143	1.000	0.000	-1.633	0.464	-1.000	**-0.789**
RRS Parliyar, Tamil Nadu	**2.000**	-0.250	1.143	-1.667	-0.200	-0.750	-0.111	0.000	0.125	-0.100	0.667	0.200	0.600	0.000
RRS Nettana, Karnataka	0.667	-0.283	0.000	-0.568	-0.236	0.325	-0.162	0.000	-0.333	0.000	0.000	-0.106	-0.369	0.118
RRS Dapchari, Maharashtra	**2.813**	**1.143**	**0.750**	0.000	0.095	0.133	0.278	0.000	0.286	0.000	0.286	0.000	0.059	0.063
RRS Agarthala, Tripura	**1.806**	0.474	0.144	**1.303**	0.571	0.019	0.000	0.000	0.051	0.000	0.406	0.100	0.076	0.000
RRS Tura, Meghalaya	2.323	1.045	0.442	1.000	0.371	0.000	**0.618**	**0.226**	0.385	0.000	-0.523	-0.417	-0.171	0.000
RRS Nagrakata, West Bengal	**2.809**	0.375	0.299	**2.000**	0.250	**0.760**	0.155	0.000	0.191	0.000	0.414	0.155	0.000	0.408
RRS Guwahati, Assam	**2.313**	0.714	0.714	-1.500	-0.231	-0.353	-0.053	0.000	0.000	0.000	0.273	0.308	0.050	0.000
RRS Dhenkanal, Orissa	2.231	0.000	0.625	-1.750	-0.571	0.200	**0.143**	0.000	**0.143**	0.000	**4.600**	**5.800**	-2.000	**0.250**

Values in bold are significant at 95% confidence level

3.4.2.3 Extreme climatic events

Extreme weather events like hot days, warm nights, heavy rainy days and rain-free days were analyzed for estimating their long term trends. All the stations showed an increasing trend in the frequency occurrence of hot days per year except in summer season in Chethackal, Parliar and Nettana. As the mean maximum temperature increases, there is a high probability of occurrence of many hot days per year. Hot days in Kottayam significantly increased in summer, winter and annually (Table 3.5) (Figure 3.10). In Dapchari also number of hot days per year showed significant increasing trend and the magnitude was higher than that of Kottayam. In the case of warm nights also most of the stations showed an increasing trend. In Padiyoor the number of warm nights per year showed a huge increase (10 days yr-1) and this was significant at 5% level. Kottayam also showed a consistent significant increasing trend in the frequency of warm nights for all seasons (Figure 3.10), while in Chethackal the trend was negative. Extreme rainfall events did not show any trend in most of the stations in any season. Trend analysis showed that annual rainfall in rubber growing regions was not much affected. Kottayam showed a significant increasing trend in the frequency of heavy rainy days in the pre-monsoon period (Figure 3.11). In Tura this increased in pre-monsoon and annually while in Dhenkanal in monsoon season and annually. Frequency of rain-free days did not register a significant trend in any stations except in Dhenkanal, Nagrakata and Padiyoor (Table 3.5). In Dhenkanal except in monsoon season, all the seasons showed a significant increasing trend in the frequency of rain-free days. In Padiyoor post-monsoon season showed a significant decreasing trend in rain-free days while in Nagrakata this showed a significant increasing trend.

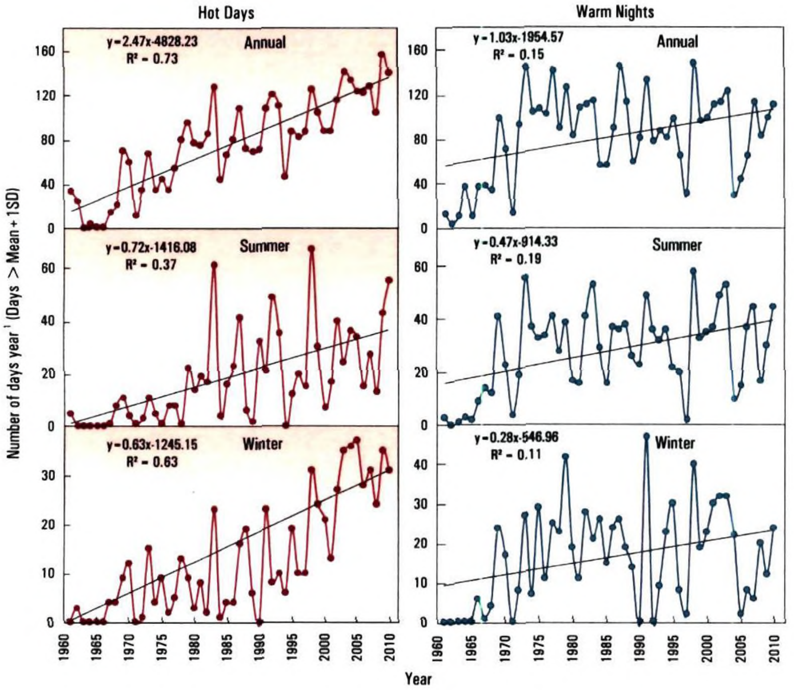


Figure 3.10.

Annual and seasonal trends in the frequency of hot days and warm nights over Kottayam for the period 1960-2010. Black straight line represents the long term trend line.

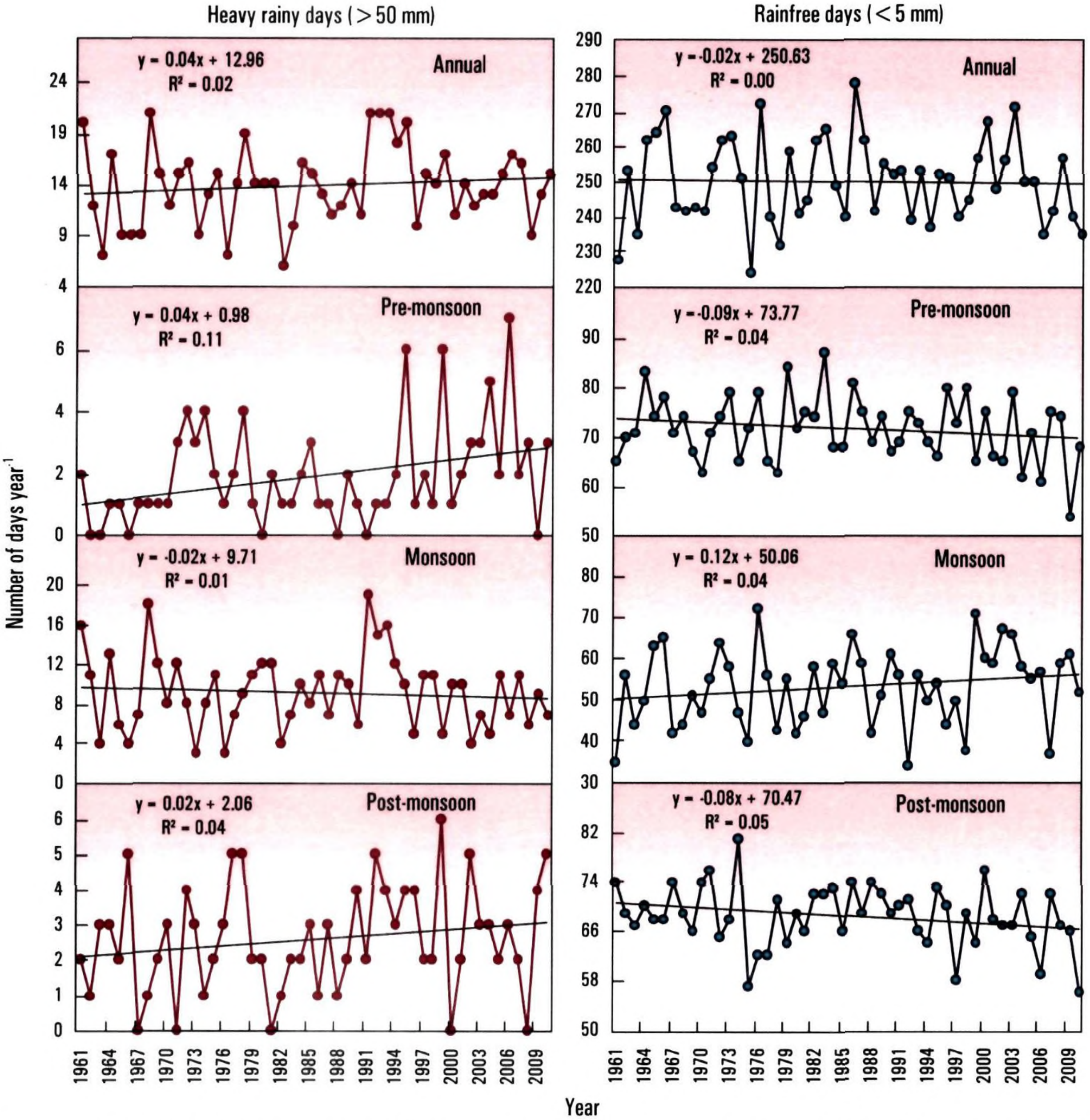


Figure 3.11. Annual and seasonal trends in the frequency of heavy rainy days and rainfree days over Kottayam for the period 1960-2010. Black straight line represents the long term trend line.

3.4.2.4. Long term temperature trends

Liner regression analyses showed that the mean annual maximum temperature ($Tmax_{ann}$) and minimum temperature ($Tmin_{ann}$) have been increasing at the rate of 0.05 and 0.03 °C per year, respectively since 1957 at RRII (Table 3.4). At the Regional Research Station of RRII in Agartala, Txann and Tnann increased at the rate of 0.02 and 0.06 °C per year, respectively since 1986. In every study location there was a warming trend, but the extent of the warming was different (Table 3.6).

Table 3.6. Climate warming trends based on liner regression analysis in different locations of the study representing different agro-climatic regions where NR is cultivated in India.

Station	Period of data used for trend analysis	Annual mean temperature (°C)		Intercept	R^2	Warming rate (°C/year)
Tura	1995-2009	Tmax	29.3	29.3	0.30	0.15
		Tmin	16.9	16.9	0.30	0.05
Agarthala	1984-2009	Tmax	30.6	30.6	0.07	0.02
		Tmin	19.9	19.9	0.30	0.06
Padiyoor	1998-2009	Tmax	32.8	32.8	0.05	0.01
		Tmin	21.8	21.8	0.60	0.11
Dapchari	1987-2009	Tmax	33.2	33.2	0.40	0.16
		Tmin	20.6	20.6	0.16	0.03
Kottayam	1957-2009	Tmax	31.2	30.0	0.66	0.05
		Tmin	22.7	21.9	0.31	0.03

3.5. Conclusion

The results from the present analyses clearly indicate that the climate is changing in the country as a whole and also in the rubber growing tracts in India. Both maximum and minimum temperatures have been increasing throughout all India, West Coast (Kerala & Konkan were rubber is mostly grown) and Northeast India in the past more than 100 years. While temperature showed a clear increasing trend, changes in rainfall were more irregular. Generally temperature has been increasing at an increasing rate. Quantum and distribution of annual rainfall on an all India scale did not change substantially. In Kerala also, the quantum of annual rainfall has not changed much, but there has been a reduction in the amount of SW monsoon rainfall and increase in NE monsoon rainfall. This shifting pattern of rainfall can have important implications for rubber cultivation in Kerala. For example, the planting process in rubber plantations is usually done with the onset of SWM. A decline in the quantum of SWM rainfall may seriously affect the success of rubber planting in the field. The availability of soil moisture during first year of planting is one of the factors that determine the success of initial establishment of the crop in the field and also duration of immaturity period of rubber plants. Occurrence of extreme heavy rainfall may cause soil erosion and soil deterioration and also will affect the growth and productivity of the crop indirectly. Kottayam has been warming faster than the country as a whole, the West Coast or Northeast. In Kottayam, nearly all the days of the year have been consistently warmer by about 2.0 °C during 2006-2010 compared to 1960-1964. The case was similar in the rubber growing regions of the country, but the extent varied. Each plant species has its own growing degree-days (GDD) for its optimum growth and reproduction. If the temperature increases, the required degree-days will attain earlier, and as a result the flowering and fruit set will happen unseasonal.

In conclusion, it is evident that the rubber growing regions of India has become warmer in recent decades, even as the rainfall did not show such a clear pattern of change. These changes that have happened in the past would have certainly impacted cultivation, growth and productivity of this crop in the past and they will also impact the crop in future which is addressed in the next chapter.

3.6. References

Ananthakrishnan, R. and Soman, M.K. (1988). The onset of southwest monsoon over Kerala for the period 1801-1980. Journal of Climatology. 8: 283-296.

Ananthakrishnan, R. Pathan, J.M. and Aralikatti, S.S. (1991).The onset phase of monsoon; Current Science. 52(7): 447-453.

Ananthakrishnan, R., Parthasarathy, B. and Pathan, J. M. (1979). Meteorology of Kerala. Contributions to Marine Sciences, 123-125.

Arora, M., Goel, N. K. and Singh, P. (2005).Evaluation of temperature trends over India. Hydrological Sciences Journal. 50 (1): 81–93.

Bhat, M. G. (2009). Cashew research in India- an overview. In: Cashew Research and Development in humid Tropics with emphasis on cashew apple processing. p. 26-36. Mathew, J., Mini, C and Abraham, M. (Eds). Kerala Agricultural University, Vellanikkara, Thrissur-680656.

Borgaonkar, H.P. and Pant, G.B. (2001). Long term climate variability over monsoon Asia as revealed by some proxy sources. Mausam. 52(1):9-22.

continental United States, 1948-1988. Journal of Climatology. 7: 586-607.

Cynthia, R., Ana Iglesias, X.B. Yang, Paul R. Epstein, and Eric Chivian. (2001). Climate change and extreme weather events: Implications for food production, plant, and pests. Global Change & Human Health. 2 (2): 90-104.

Cynthia, R., Ana, I., Yang, X.B., Epstein, P.R. and Chivian, E. (2000). Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases, and Pests. Published by: Centre for health and the global Environment. Harvard Medical School, 260 Longwood Avenue, Room 262A, Boston, MA 02115.

Gadgil, A. and Dhorde, A. (2005). Temperature trends in Twentieth Century at Pune, India. Atmospheric Environment. 39: 6550-6556.

Gadgil, S. (1988). Recent advances in monsoon research with particular reference to the Indian monsoon. Australian Meteorological Magazine. 36: 193-204.

Goswami, B.N., Venugopal, V., Sengupta, D. and Madhusoodhanan, M.S.(2006). Increasing trend of extreme rain events over India in a warming environment. Science. 314 (5804); 1442-1445.

Guhathakurta, P. and Rajeevan, M. (2006). Trends in the rainfall pattern over India. National Climate Centre Report No.2. India Meteorological Department.

Guhathakurta, P. and Rajeevan, M. (2008). Trends in the rainfall pattern over India. International Journal of Climatology. 28: 1453–1469.

He Jin-Hai. (2009). A Review of the Asian-Pacific Monsoon. Atmospheric and Oceanic Science Letters. 2(2): 91-96.

Henderson, K.G. and Muller, R.A. (1997). Extreme temperature days in the south-central United States. Climate Research. 8: 151-162.

Hingane, L.S., Kumar, K.R. and Murthy, B.V.R. (1985). Long term trends of surface air temperature in India. Journal of Climatology. 5: 521-528.

International Food Policy Research Institute (2007). Climate change impact on food security in Sub-Saharan Africa: Insights from comprehensive climate change scenarios. Ed. Ringler. C., Zhu, T., Cai, X., Coo, J. and Wang, D. Cambridge and New York, Cambridge University Press.

IPCC, Fourth Assessment Report (AR4), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Jacob, J. (2013). Chlorophyll fluorescence-based non-invasive techniques to detect and quantify climate stress on plants. Journal of Plantation Crops. 41(1): 1-7.

Jerry, K., Tim, H., Andre, D. and Tim, W. (2012). Climate change impacts on crop productivity in Africa and South Asia. Environmental Research Letters. doi:10.1088/1748-9326/7/3/034032. 7 (2012) 034032 (8pp).

Joseph P.V., Simon, A. Nair, V.G. and Thomas, A. (2004). Intra-seasonal oscillation (ISO) of south Kerala rainfall during the summer monsoons of 1901-1995. Proceedings of Indian Academy of Science. 113: 139-150

Joseph, P.V., Sooraj, K.P. and Rajan, C.K. (2006). The summer monsoon onset process over South Asia and an objective method for the date of monsoon onset over Kerala. International Journal of climatologyl. 26: 1871-1893.

Kang, Y., Khan, S. and Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security–A review. Progress in Natural Science, 19(12): 1665-1674.

Kendall, M. G. (1975). Rank Correlation Methods, 4th ed. Charles Griffin: London. 202 p.

Kothawale, D. R., Munot, A. A. and Kumar, K.K. (2010). Surface air temperature variability over India during 1901–2007, and its association with ENSO. Climate Research. 42: 89–104.

Kothawale, D.R., and Kumar, K.R. (2005). On the recent changes in surface air temperature trends over India. Geophysical Research Letters. 32: L18714, doi:10.1029/2005GL023528r.

Krishnakumar, K.N., Rao, G.S.L.H.V.P. and Gopakumar C.S. (2009). Rainfall trends in twentieth century over Kerala, India. Atmospheric Environment. 43 (11): 1940-1944.

Krishnakumar, K.N., Rao, G.S.L.H.V.P., Gopakumar. C.S and Mohan, H.S.R. (2007). Rainfall variability during southwest monsoon over Kerala (India):1871-2005. Indian Journal of Polar Scence. 1 (1): 81-87.

Krishnamurthy, V. and Shukla, J. (2000). Intra-seasonal and inter-annual variability of rainfall over India. Journal of Climate. 13: 4366-4377

Krishnamurthy, V. and Shukla, J. (2000). Intra-seasonal and inter-annual variability of rainfall over India. Journal of Climate. 13: 4366-4377

Kumar, K .R., Kumar, K. K., Ashrit, R. G., Patwardhan, S. K. and Pant, G. B. (2002). Climate change in India: Observation and Model Projections. Chapter 2. In: Shukla, P.R., Sharma, K.S. and Ramana, P.V. (Eds.). Climate Change and India: Issues, Concern and Opportunities. Tata McGraw-Hill Publishing Company Limited, New Delhi. pp. 317.

Kumar, K.R, Pant, G.B., Parthasarathy, B. and Sontakke, N.A. (1992). Spatial and sub seasonal patterns of the long term trends of Indian summer monsoon rainfall. International Journal of climatology. 12: 257-268.

Kumar, K.R, Pant, G.B., Parthasarathy, B. and Sontakke, N.A. (1992). Spatial and sub seasonal patterns of the long term trends of Indian summer monsoon rainfall. International Journal of climatology. 12: 257-268.

Kumar, K.R, Pant, G.B., Parthasarathy, B. and Sontakke, N.A.1992. Spatial and sub seasonal patterns of the long term trends of Indian summer monsoon rainfall. International Journal of climatology. 12: 257-268.

Kumar, K.R. and Hingane, L.S .(1988). Long term variations of surface air temperature at major industrial cities of India. Climatic change. 13: 287-307.

Kumar, K.S.K and Parikh, J. (1998). Climate change impacts on India agriculture. The Ricardian approach. In: Measuring the impacts of Climate Change on Indian Agriculture, Technical paper No.402.World Bank, Washington, D.C.

Lal, M., Nozawa, T., Emori, S., Harasawa, H., Takahashi, K., Kimoto, M., Abe-Ouchi, A., Nakajima, T., Takemura, T. and Numaguti, A. (2001). Future climate change: Implications for Indian summer monsoon and its variability. Current Science. 81(9): 1196-1207.

Lettenmaier, D.P., Wood, E.F., Wallis, J.R. (1994). Hydro- climatological trends in the

Manton, M.J., Della-marta, P.M., Haylock,M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I. and Yee, D. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998. International Journal of Climatology. 21: 269–284.

Mann, H. B. (1945). Non-parametric tests against trend. Econometrica. 13: 245-259.

Menon, K.P.V. and Pandalai, K.M. (1960). The Coconut Palm- a Monograph. Indian Central Coconut Committee,Ernakulam.

Mooley, D. A. and Parthasarathy. B. (1984). Fluctuations of All India summer monsoon rainfall during 1871-1978. Climatic Change. 6: 287–301.

Mooley, D. A., Parthasarathy, B., Sontakke, N. A., and Munot, A. A. (1981). Annual rain-water over

India, its variability and impact on the economy. Journal of Climatology. 1:167-186.

Murdiyarso, D. (2000). Adaptation to Climatic Variability and Change: Asian Perspectives on Agriculture and Food Security. Environmental Monitoring and Assessment 61(1): 123-131.

Naidu, C.V., Rao., B.R.S. and Rao, B.D.V. (1999). Climatic trends and periodicities of annual rainfall over India. Meteorological Applications, 6: 395-404.

Pant, G. B. and Kumar, K.R. (1997). Climates of South Asia, John Wiley & Sons Ltd.,West Sussex, UK. 320 pp.

Pant, G.B and Hingane, L.S. (1988). Climatic change in and around the Rajasthan desert during the 20th Century. Journal of Climatology. 8:391-401.

Partal, T. and Kahya, E. (2006). Trend analysis in Turkish precipitation data. Hydrological Process. 20: 2011-2026.

Parthasarathy, B. and Dhar, O.N. (1975). Trend analysis of annual Indian rainfall. Hydrological Sciences - Bulletin , XX, 26/1975. 257-260.

Parthasarathy, B., Sontakke, N. A., Munot, A. A. and Kothawale, D. R. (1987). Droughts/floods in the summer monsoon rainfall season over different meteorological subdivisions of India for the period 1871-1984. Journal of Climatology. 7: 57-70.

Pearce, R.P. and Mohanti, U.C. (1984). Onsets of the Asian summer monsoon 1979-82. Journal of Atmospheric Science. 41: 1620-1639.

Raj, P.P.N. and Azeez, P.A. (2010). Changing rainfall in the Palakkad plains of South India. Atsosfera. 23(1): 75-82.

Raj, s., Satheesh, P.R. and Jacob, J. (2011). Evidence for climate warming in some natural rubber growing regions of South India. Natural Rubber Research, 24(1): 10-17.

Rajeevan, M. (2001). Prediction of Indian summer monsoon: Status, problems and prospects. Current Science. 81(11): 1451-1457.

Rajeevan, M. and Dubey, D. P. (1995). Long range prediction of monsoon onset over Kerala, Mausam. 46: 287-290.

Rajeevan, M., Pal., D.S., Kumar, R.A. and Lal, B. (2006). New statistical models for long-range forecasting of southwest monsoon rainfall over India. Cli. Dynamics. 28(7-8), 813-828.i: 10.1007/s00382-006-0197-6.

Ramakrishna, Y.S., Singh, H.P. and Rao, N. (2003). Weather based indices for forecasting foodgrains production in India. Journal of Agrometeorology. 5(1):1-11.

Ranade, P.S. (2009). Impact of climate change on agriculture. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 183-185.

Rao, G.S.L.H.V.P and Krishnakumar, K.N. (2005). Monsoon onset over Kerala (India): 1870- 2004. Journal of Agrometeorology. 7(2): 161-167.

Rao, G.S.L.H.V.P., Rao, AVRK., Krishnakumar, K.N. and Gopakumar, C.S. (2009). Climate change projections and impacts on plantations in Kerala. In: Proceedings of Climate change Adaptation Strategies in Agriculture and Allied Sectors-invited papers. pp.158.

Rao, GSLHVP., Mohan, H.S.R., Gopakumar, C.S and Krishnakumar, K.N. (2008). Climate change and cropping systems over Kerala in the humid tropics. Journal of Agrometeorology. (Special issue-Part 2): 286-291.

Richard, M. A., Brian, H. H., Stephanie, L. and Neil, L. (1998). Effects of global climate change on agriculture: an interpretative review. Climate Research. 11: 19–30.

Rosenzweig, C. and Hillel, D. (1995). Potential Impacts of Climate Change on Agriculture and World Food Supply. Consequences (Summer):24–32.

Rosenzweig, C. and Liverman, D. (1992). Predicted effects of climate change on agriculture: A comparison of temperate and tropical regions. In Global climate change: Implications, challenges, and mitigation measures, ed. S. K. Majumdar, 342-61. PA: The Pennsylvania Academy of Sciences.

Rosenzweig, C., and M. L. Parry. (1994). Potential impact of climate change on world food supply. Nature, 367:133- 138.

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R. and Chivian, E. (2000). Implications of Climate Change for U.S. Agriculture: Extreme Weather Events, Plant Diseases, and Pests. Cambridge, Massachusetts: Center for Health and the Global Environment, Harvard Medical School. Cambridge, MA. 56 pp.

Rupakumar, K., Kumar, K.K. and Pant, G.B. (1994). Diurnal asymmetry of surface temperature trends over India. Geophysical Research Letters. 21, 677–680.

Salas, J.D. (1993). Analysis and Modeling of Hydrologic Time Series. In: The McGraw Hill Handbook of Hydrology. Maidment, D.R. (Ed.) Chapter 19 : 72 p.

Sarkar, R.P. and Thapliyal, V. (1988). Climatic change and variability. Mausam. 39(2):127-138.

Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. Journal of the American Statistical Association. 39: 1379-1389.

Simon, A. and Mohankumar, K. (2004). Spatial variability and rainfall characteristics of Kerala. Proceedings of Indian Academy of Science (Earth Planet. Sci.), 113, June 2004. pp.211-221.

Singh, J.P. and Lal, S.S. (2009). Climate change and potato production in India. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 115-117.

Singh, N., Krishnakumar, K. and Soman, M.K. (1989). Some features of the periods contributing percentages of rainfall to annual total in Kerala, India. Theoretical and Applied Climatology. 39:160-170.

Soman, M.K. and Krishnakumar, K. (1993). Space - time evolution of meteorological features associated with the onset of the Indian summer monsoon. Monthly Weather Review. 121: 1177-1194.

Soman, M.K., Krishnakumar, K and Singh, N. (1988). Decreasing trend in the rainfall of Kerala. Current Science. 57 (1): 7-12.

Srivasthava, H.N., Sinha, R. K.C., Dikshit, S.K. and Mukhopadhyay, R.K. (1988). Trends in rainfall and radiation over India. Vayu Mandal. 28(1-2):41-45.

Van, D.N., Abdoussalam, S. and Ben M.A. (2002). Impact of climate change on agricultural production in the Sahel - Part 2. Case study for groundnut and cowpea in Niger. Climatic Change 54(3):349-68.

Yin, M. T. (1949). A synoptic-aerologic study of the onset of the summer monsoon over India and Burma. Journal of Meteorology. 6: 364-400.

Yue, S. and Hashino, M. (2003). Long term trends of annual and monthly precipitation in Japan. Journal of the American Water Resources Association. 39: 587-596.

CHAPTER 4

IMPACT OF CLIMATE CHANGE ON NATURAL RUBBER PLANTATIONS OF INDIA

"Whatever kind of seed is sown in a field, prepared in due season, a plant of that same kind, marked with the peculiar qualities of the seed, springs up in it"

Guru Nanak

4.1. Introduction

In the last chapter, I have analyzed temperature and rainfall data of India for the past one century with special reference to the regions where plantation crops are grown. These data collected form the various rubber growing parts of India were also analyzed. A warming trend was evident throughout the country, but changes in the rainfall were less consistent. It was evident that all rubber growing regions were warming significantly and this can impact productivity of this crop which is addressed in this chapter. Supply and demand of natural rubber and the various factors that affect production of this crop are also discussed before analyzing how a warming climate will impact rubber yield in the different agro-climatic regions of India.

4.2. Production and consumption of natural rubber: Global and Indian perspectives

Use of natural rubber, an industrial raw material of strategic importance has a direct association with economic growth. Per capita consumption of rubber (natural + synthetic) is high in the developed world than in developing countries (IRSG, 2013; Indian Rubber Statistics, 2012). India has a very low per capita rubber consumption of hardly 1.2 kg/person/year whereas this is as large as 6.5 kg/person/year in China and 8.6 and 13.3 kg/person/year in the USA and Japan, respectively. Developed world has perhaps already reached a saturation point in terms of their rubber consumption and in these countries the GDP growth is also very small. Fast growing countries such as India, Brazil, South Africa etc. where the per capita rubber consumption is small will continue to consume increasingly more rubber as its economy grows further.

According to the International Rubber Study Group (IRSG), globally there will be short supply of natural rubber in the coming years (Aravindan, 2006). Estimates made by the Indian Rubber Board also indicate that the country may not be able to produce enough natural rubber to meet its growing industrial demand. Indian economy is the 10th largest in the world and 4th largest among developing countries (World Bank, 2012). India's economy grew by 143.15 billion US \$ yr^{-1} from 2002 to 2011 (IMF, 2012 available at www.imf.org). As the Indian economy grows, more rubber will be consumed.

Indian economy is largely an agriculture economy, because around 17% of its economic growth is dependent on agriculture (CIA, 2012 available at www.cia.gov) and more than 55% of the population is dependent on agriculture as the main means of their livelihood. Indian agrarian GDP has shown a growth rate of about 2.8% during 2012 and this is highly dependent on the monsoon rains. The total area cultivated with natural rubber in India is 0.76 million ha which accounts for only 0.005% of the total arable land in the country (158.1

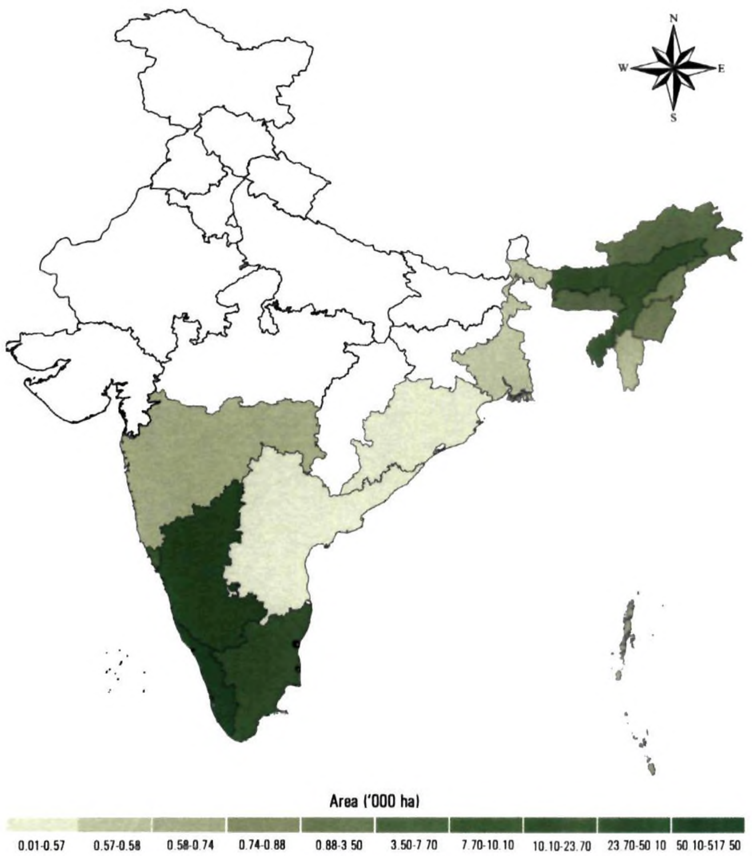
million ha, World Bank, 2010). Natural rubber is not a major crop in India as a whole, yet this is such an important strategic produce that the Indian government has always given priority for increasing its supply within the country. In those states and regions where this is a major crop, it contributes substantially to the local economy, ecology and socio-economic development of the people. For example, in the state of Kerala where this crop has been traditionally grown for over a century now, it occupies 36.2 % of the total cultivated lands and contributes roughly 45% of the state's agriculture GDP (DES India, 2012; DES Kerala, 2012). India ranks fifth in total area of rubber cultivation in the world (IRSG, 2013).

In India commercial rubber cultivation started in 1870s and the first rubber plantation was established in 1902 in Thattekadu, Kerala. Now in India around 0.76 million hectares of land area is under rubber cultivation (Indian Rubber Statistics, 2012). Of this, around 78% is in Kerala and Tamil Nadu (traditional region) and the rest 22% in non-traditional regions like Tripura, Assam, Meghalaya, Nagaland, Manipur, Mizoram and Arunachal Pradesh, Karnataka, Goa, Maharashtra, Orissa, West Bengal, Andhra Pradesh and Andaman Nicobar Islands (Figure 4.1). In the North Eastern of Tripura, there is a total of 59285 ha which accounts for 18.7% of the state's cultivated area (Indian Rubber Statistics, 2012). In this state which has a considerable native population, natural rubber cultivation has led to remarkable socio-economic development resulting in tangible reduction in insurgency activities and restoration of denuded ecosystems.

Global coverage of natural rubber cultivation is around 12.23 million hectares (IRSG, 2013). Indonesia, Thailand and Malaysia are the top natural rubber growing countries in the world which together has 265.1 million hectare of land area (1.7 % to the world total) (Figure 4.2).

Between 1998 and 2011, consumption of NR in the world increased at the rate of 349.7 thousand tons yr-1 while the production increased by 346.7 thousand tons yr^{-1} (IRSG, 2012). In India this increased at the rate of 30.4 thousand tons yr-1 while its supply increased by 24.7 thousand tons yr^{-1} (IRSG, 2012). Almost all studies show that in the years ahead, this kind of harmony between demand and consumption may not continue to exist even as consumption of NR is expected to increase at a faster rate than its supply, both nationally and globally, provided there is sustained economic growth (Figure 4.3).

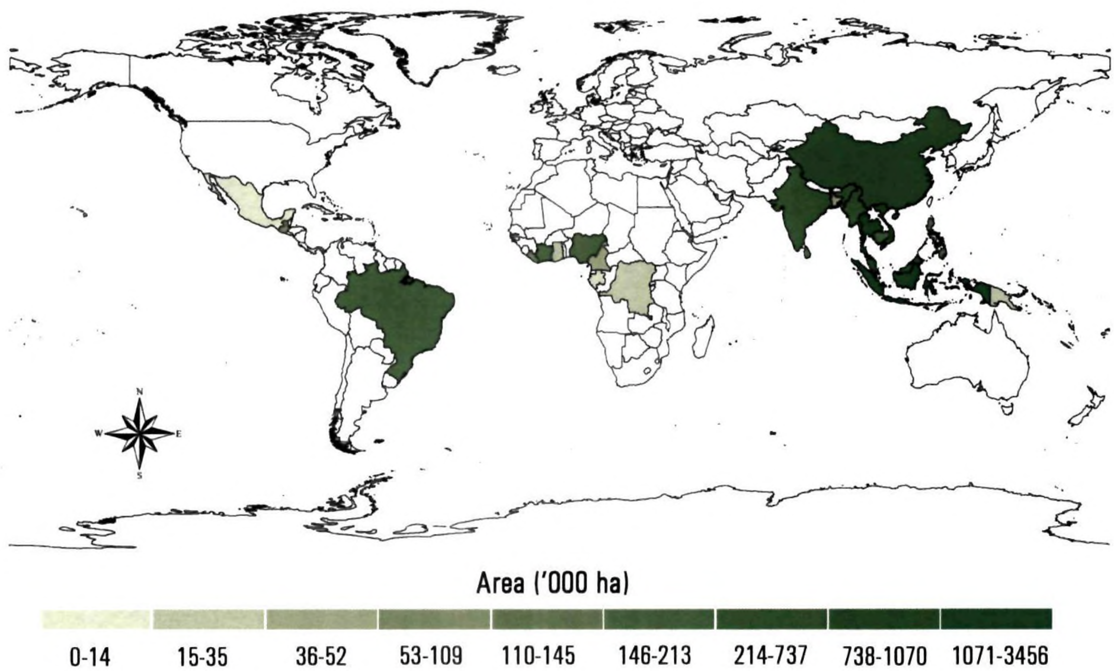
As discussed earlier, climate change can affect the productivity of the crop whether it is plantation crop, spices or agriculture crop (Rosenzweig and Parry, 1994). Change in rainfall pattern, temperature, soil moisture and temperature, relative humidity, sunshine hours etc. can affect the productivity of a crop directly. Changes in weather pattern can impact incidence of pests and diseases and thus it can indirectly affect productivity of crops (Cynthia et al., 2001). We know that climate change is happening and the global temperature has risen substantially in recent decades and this is likely rise further (Rao et al., 2009).



Data source: Indian Rubber Statistics, 2012

Figure 4.1.

Map showing the natural rubber growing states in India with area of cultivation. (The shaded area does not mean that the state has rubber cultivation all over its geographical area.)



Data source: IRSG, 2013

Figure 4.2. Map showing major natural rubber growing countries in the world with area of cultivation.

(The shaded area does not mean that the country has rubber cultivation all over its geographical area.)

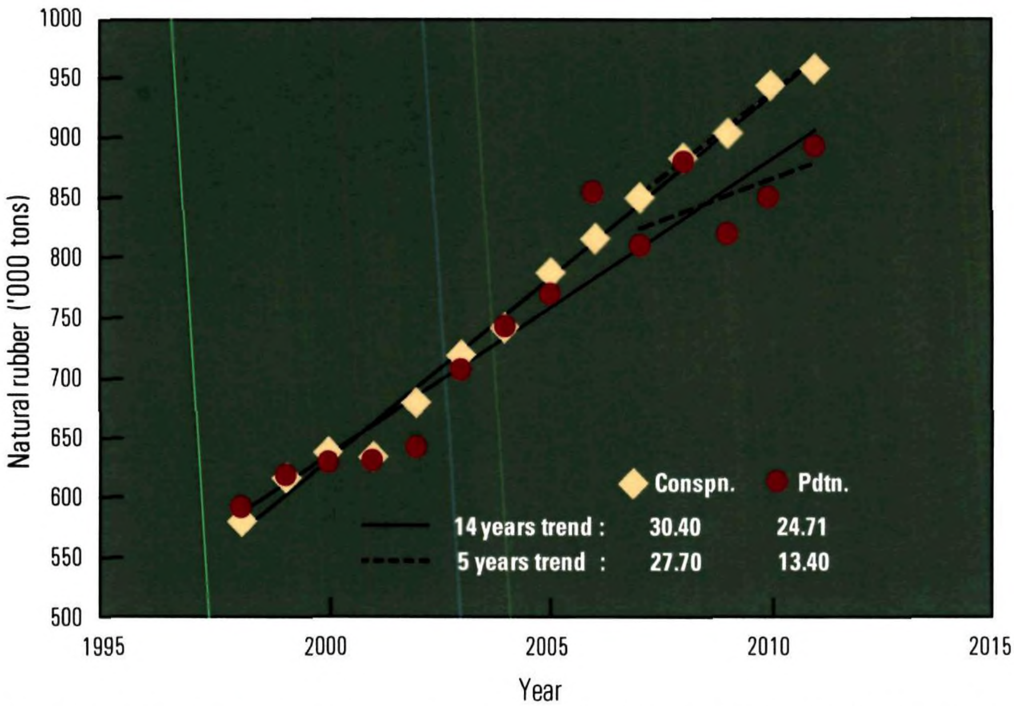


Figure 4.3. Production and consumption of natural rubber in India during 1998 to 2011. There was a perfect harmony between the production and consumption in the last 14 years, while coming to the recent years the difference between the consumption and the supply was much higher than the long term trend.

Natural rubber is mostly grown in South and South East Asian countries like Indonesia, Thailand, Malaysia, Vietnam, India, China, the Philippines, Sri Lanka, Cambodia etc. South East Asian countries are most vulnerable to climate change (IPCC, 2007a). Studies have shown that temperatures have generally gone up in this part of the world in the recent decades (Manton et al., 2001). Number of rainy days and number of cool nights per year showed a declining trend while that of hot days per year increased. While we may be able to understand and appreciate to what extent climate has changed in the traditional rubber growing regions of the world in the recent past, it is extremely difficult to predict how exactly these changes will continue in the years ahead and how these changes will affect growth and productivity of NR. Thus the impact of change in future climate on natural rubber growth, productivity and supply will be complex and difficult to predict.

Since 2006 India ranks first in the world in terms of NR productivity. Despite the recent global economic crisis, India remained reasonably buoyant and the Indian economy is expected to grow at impressive rates in the coming years and thus the demand for NR also will be on the rise. But climate change is one important factor that may seriously jeopardize NR availability in India and other major NR producing countries in South and South East Asia, a region particularly vulnerable to the adverse impact of climate change (Manton et al., 2001).

In this chapter, I examine how rising temperature may influence natural rubber productivity in different agro-climatic regions of India where this is cultivated.

4.3. Factors determining natural rubber production

There are several factors which affect yield of any crop, such as weather, agronomic constraints, agricultural practices and farm characteristics which are briefly reviewed here.

4.3.1. Agro-climatic conditions

Agro-climatic conditions prevailing in the region are the main determinants of crop production in any agricultural system. Rubber plants require an optimum amount of rainfall, temperature, relative humidity, sunshine etc. (see chapter 1). Precipitation is a key determinant of crop growth and yields in rain-fed areas and water stress s a major limiting factor for crops in many parts of the world (Lawlor, 2002; Winch, 2006). Rubber plants need an equally distributed rainfall of 125 mm month-1, which is considered as the optimum. An annual rainfall of 2000-4000 mm is best for its growth and yield. Temperature influences plant growth as it affects physiological processes such as photosynthesis, transpiration, respiration, germination, and flowering (Went, 1953). Air temperature is more important for crop growth than soil temperature (Mavi and Tupper, 2004). In the case of rubber plants minimum and maximum temperature are equally important. A mean monthly temperature of 20-25 ^{0}C is considered as the optimum for its optimum performance. An optimum minimum temperature will enhance yield. Optimum day temperature will enhance the photosynthetic rate resulting in accumulation of more carbohydrates. A very low or high temperature may injure the rubber plant (Chandrasekhar et al., 1990). A relatively high humidity will enhance the turgor pressure in the latex vessels and increases the latex yield. An increase in sunshine hours will increase photosynthesis and help increase latex yield. But a prolonged sunshine with low soil moisture will have a negative effect on photosynthesis. Evapotranspiration (ET) is the combination of the loss of water from soils (by evaporation) and from crops (by transpiration). The water lost through the evapotranspiration has to be compensated by equivalent amount water through rainfall or irrigation, known as the crop water requirement. If rainfall or irrigation does not meet crop water requirement, plants will experience a water stress, which reduces crop yields (Maman et al., 2003). It is generally felt that a warmer future world may see increasing incidences of drought (Dai, 2013; NOAA, 2011) seriously affecting crops more in the tropics than in the temperate regions (IPCC, 2007a).

4.3.2. Agronomic management

Selection of clones suited for the area of cultivation is an important factor which determines the productivity. Tapping is another important management factor that determines sustainable yield. Tapping frequency, stimulation and the skill of rubber tapper are also important yield determining management practices. Biotic factors such as weeds, pests and diseases and abiotic factors like soil quality, soil pH, soil nutrients etc. are the main agronomic constraints which affect crop growth and yield. Weeds absorb the water and nutrients from the soil which are essential for growth or rubber plants. Competition from weeds should be avoided in rubber plantations, especially young rubber plantations for good growth and yield. Crop yields can suffer from pests and disease as they impede crop growth or damage plants (Winch, 2006). A number of insects, pests and diseases which attack different parts of rubber plants, result in the biotic stress leading to a reduction of latex yield. Abnormal leaf fall, Shoot rot, Powdery mildew, *Corynespora* leaf fall, *Colletotrichum* leaf disease, Pink disease, Patch canker, Brown and White root disease etc. are the main diseases of rubber. White grubs, bark feeding caterpillars, termites, mealy bugs, slugs, snails and mites are the major insects and pests which attack rubber plants. Rubber trees can grow in a wide range of soils. Highly weathered lateritic type soils are most suitable for rubber cultivation. Soils with pH of around 6.5 are considered as most suitable for the growth and yield. Both in the immature and mature phases of the growth of rubber plants, good availability of nutrients is required. After testing the soil, supplementing the deficient minerals is essential for ensuring good performance of rubber trees. Several fertilizer recommendations are available for rubber plantations depending on the soil profile of the area of cultivation.

4.4. Review of literature

4.4.1. Impact of climate change on agriculture

Global warming and climate change as a result of accumulation of greenhouse gases in the atmosphere (IPCC, 2007b) is affecting agriculture in many parts of the world. Several studies have been made to understand and quantify the impact of these changes on agriculture in different regions in the world (IPCC, 2007b; Ranade, 2009; Rosenzweig and Hillel,1995; Richard et al., 1998; Kang et al., 2009; Rosenzweig et al., 2000; Cynthia et al., 2000; Van et al., 2002; Murdiyarso, 2000; Singh and Lal, 2009; Jerry et al., 2012). But the uncertainties in the prediction of exact change in the climate do not permit the scientific community to work out a precise estimation of its impact on agriculture. The impacts of climate change on agriculture may be positive or negative (Satheesh and Jacob, 2011). For example, an increase in the temperature generally reduces the crop yield in the tropics, but temperate crop yields may increase with increasing temperature because currently they might be experiencing a temperature below its threshold level (IPCC, 2007b). Similarly, the extended growing season as a result of shortened winter and early arrival of spring as a result of climate change will help increase yields in the Northern hemisphere (IPCC, 2007b). It is also known that rising

CO_2 concentration in the atmosphere will have different effects on warming in different regions of the world. For example, in the humid tropics, there may be more warming (due to the presence of more water vapor molecules in the atmosphere) than in the less humid temperate regions for the same level of rise in CO_2 in the atmosphere (Rosenzweig and Liverman, 1992; Acock and Allen, 1985). Thus tropical agriculture may suffer more than temperate regions from the adverse effects of rising temperature.

Apart from the rising temperature, changes in rainfall would have even greater adverse effect on yields in tropical countries. In addition, degradation of soil and a decrease in water resources resulting from climate change are likely to have negative impacts on global agriculture. Grains produced in a future world with elevated CO_2 may have less proteins and nutritive value (Roslyn et al., 2010; Gleadow et al., 2009; Gleadow, 2010; Taub et al., 2008; Lobell et al., 2008; Wall et al., 2001; Achanta, 1993; Aggarwal and Sinha, 1993; Baker et al., 1989; Rosenzweig, 1985). Therefore, a good understanding of the changes in regional climate is essential for future projection of their impacts rather than the understanding of climate change in a global scale.

Quantifying the economic impact of climate change on agriculture is also receiving greater attention these days. It has been estimated that with an increase in temperature, there would be a decline in crop yields and that will result in the increase of food prices. Growth in global food demand is faster than the global food production (Parry et al., 1999). Therefore, climate change not only will have an effect on the productivity of agricultural products but will also have economic consequences also (Kaiser and Drennen, 1993).

4.4.1.1 Global scenario

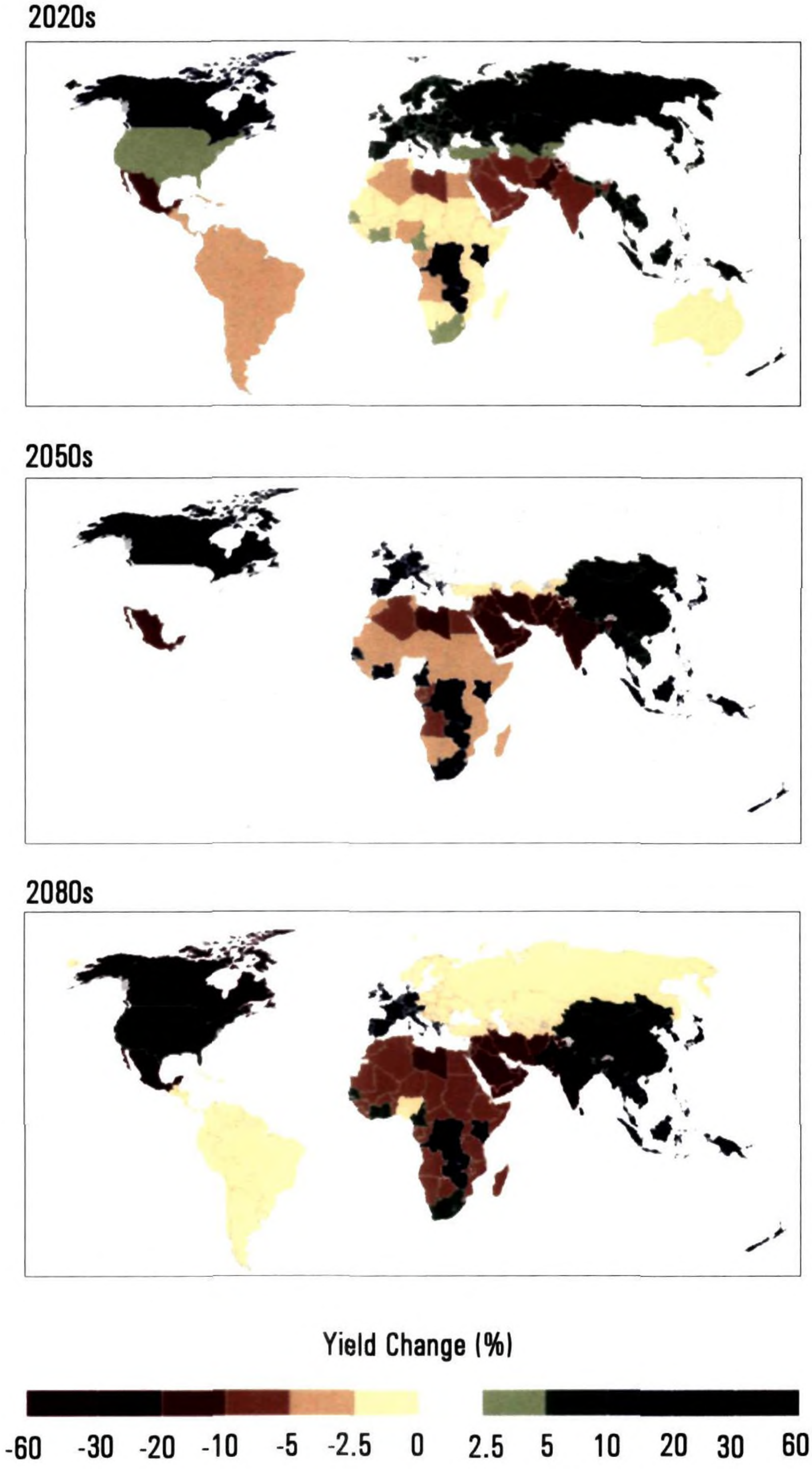
Several studies have indicated that the changes in climate and the accumulation of atmospheric CO_2 have significant effects on the growth and productivity of agricultural crops around the world. Elevated CO_2 in the atmosphere may increase the photosynthetic rate and finally the crop productivity (Kimball, 1983; Cure and Acock, 1986; Allen et al., 1987), especially in plants with the C_3 photosynthetic pathway because C_3 photosynthesis will respond more to elevated CO_2 concentration that C_4 photosynthesis (Kimball et al., 1993; Poorster and Navas, 2003; Sage, 1995). Enhanced levels of atmospheric CO_2 concentration will increase the net primary productivity of the forest ecosystems (Mingkui and Woodard, 1998) by stimulating photosynthesis, but the tissues may have less proteins (Tuchman et al., 2002; Jacob et al., 1995; Drake et al., 1997; Long et al., 1994). Extreme weather events associated with global warming and climate change can reduce crop productivity substantially (Long, 1991).

In addition to stimulating photosynthesis, elevated CO_2 will cause closure of stomata and thus will reduce transpiration loss of water from plants. (Rosenzweig, 1985; Morison, and

Gifford, 1984; Long et al., 1994; Drake et al., 1997; Jacob et al., 1995). Thus more biomass (and yield) will be produced with better water use efficiency in a future world with elevated CO_2. It was reported that transpiration was reduced by 30 percent in some crop plants with elevated CO_2 (Kimball, 1983). However, stomatal response to CO_2 is affected by many environmental factors like temperature, light intensity, atmospheric vapour pressure) and plant factors (age, hormones), so predicting the effect of elevated CO_2 on the stomata response is very difficult (Rosenzweig and Hillel, 1995). It can be said that a world with slightly elevated CO_2 concentration in its atmosphere would have been beneficial for agriculture, provided nothing else changed. But that is not the case. CO_2 being a greenhouse gas will increase the temperature which brings about marked changes in the climate, often in unpredictable ways and thus becomes a major concern for agriculture.

The actual response to CO_2 changes differs among crops and regions. Hence, the local climate condition of an area and the type of crop actually determine the exact effect of increased CO_2 concentration in the atmosphere. Effects of climate change and elevated CO_2 on agricultural yields in North and Latin America as estimated by the IPCC (IPCC, 1995) is given in Table 4.1. Most of the commercial crops in the United States, including wheat, rice, barley, oats, potatoes, and most vegetable crops, tend to show an increase in the yield (15-20%) with a doubling of CO_2, while tropical or warm-weather crops like corn, sorghum, sugar cane, and many tropical grasses, are less responsive with a doubling of CO_2 (increased by 5% only).

Many studies reported that climate change can alter global patterns of food supply and demand. Changes in the average national grain crop yield throughout the world for the Hadley Center climate change scenario HadCM2 for 2020s, 2050s, and 2080s were modelled for the crops like wheat, maize, and rice (Rosenzweig et al., 2000) The direct effects of higher CO_2 levels on crops are taken into account (Figure 4.4). As CO_2 concentration in the atmosphere increases, the rate of photosynthesis and water-use efficiency of plants also increase. Crop productivity improved in some regions, while in others it decreased as a result of climate warming and climate change. In general crop yields increased in high and mid-latitudes while yield decreased in the arid and sub-humid tropics (Acock and Allen, 1985; Kimball et al., 1995; Parry et al., 2005). Thus people living in the tropics that made little contribution to emissions and climate change will be affected the most as their food security is threatened by global warming.



Source: Cynthia et al., 2001

Figure 4.4. Percentage change in crop yields for the Hadley Centre global climate change scenario (HadCM2). Direct physiological effects of CO_2 and crop adaptation are taken into account.

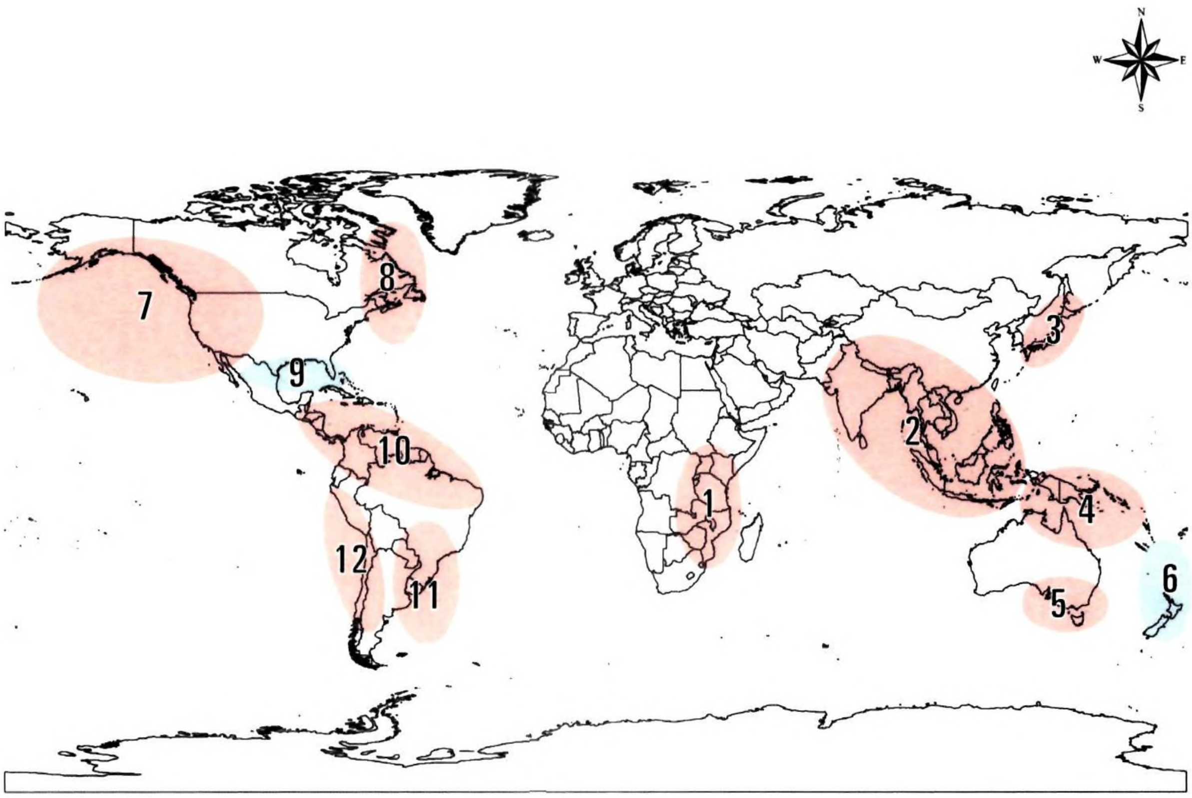
Table 4.1. Ranges of estimated climate change effects on selected crop yield in North and Latin America

Location of Study Site	Impact (Crop: Percent Change in Yield)	Climate Change Scenario
North America		
Canada (Alberta, Manitoba, Saskatchewan, Ontario)	Wheat: -40% to +234% (results varied widely by site and scenario)	GISS, GFDL, UKMO, Incremental* with CO_2
United State (Average of total based on selected sites)	Wheat: -20% to -2% Corn: -30% to -15% Soybean: -40% to +15%	GISS, GFDL, UKMO with CO_2
Latin America		
Argentina	Corn: -36% to -17%	GISS, GFDL, UKMO, Incremental* with and without CO_2
Argentina	Wheat: +3% to +48% Corn: -4% to -18% Sunflower: +14% to +23% Soybean: -3% to -8%	GISS, GFDL, UKMO with CO_2
Brazil	Wheat: -50% to -15% Corn: -25% to -2% Soybean: -61% to -6%	GISS, GFDL, UKMO Incremental* with CO_2
Mexico	Corn: -61% to -6%	GISS, GFDL, UKMO Incremental* with CO_2

*Incremental Scenario = +2 ^{0}C and +4 ^{0}C; +20% precipitation and -20% precipitation

As the indirect effect of climate change, changes in spatial and temporal distribution and proliferation of insects, weeds, and pathogens were reported in several studies. Its distribution and proliferation is determined mainly by climate, because temperature, light, and water are major factors controlling their growth and development (Rosenzweig and Hillel, 1998; Sutherst, 1990). There are reports showing that global production of major crops and their estimated losses due to pathogens, insects and weeds (Table 4.2). Studies show that in a warmer climate, pests may become more active than at present and may expand their geographical range. This will finally result in the increased use of insecticides, pesticides etc. and thus resulting crop loss and associated economic losses (Patterson, 1993; Coakley et al., 1999; Oerke et al., 1995). There is also the apprehension that a warmer future world with elevated levels of CO_2 will make weeds more competitive and use of pesticides may also increase (Ziska and Dukes, 2011; Ziska et al., 2004).

Halpert and Ropelewski (1992) studied the effect of El Niño on agriculture. The effect of El Niño varies seasonally in different regions of different countries (Figure 4.5). Every case the effect observed would be climate extremes, which may adversely affect the growth and productivity of crops. It was reported that crop yields affected by climate change are different in various areas, in some areas crop yields will increase, and for other areas it will decrease depending on the latitude of the area and management practices. An increase in precipitation will increase crop yield because crop yield is more sensitive to the precipitation than temperature (Kang et al., 2009).



1. Warm (Oct-Jun). Wet (Northern area, Oct-Apr) and wet (Southern area, Nov-May)
2. Warm (Oct-Jun). Dry (Most of the area (Jun-Sep), wet (Southern most India) (Oct-Dec)
3. Warm (Oct-Feb)
4. Warm (Northern area and cool (Southern area) ((Dec-Jun), Dry (Nov-May)
5. Warm (Nov-Jun). Dry (Nov-May)
6. Cool (Jan-Nov)
7. Warm (Dec-Mar). Limited wet areas in the U.S. (Apr-Oct)
8. Warm (Dec-Mar)
9. Cool (Oct-Mar). Wet (Oct-Mar)
10. Warm (Jul-Jun). Dry (Jul-Oct)
11. Warm May-Apr). Wet in the Southern area (Nov-Feb)
12. Warm (May-Apr). Wet in the Northern area (Nov-Apr)

Figure 4.5. The effect of El Niño in different parts of the world in different season, which may directly impact the crop growth around the world.

Table 4.2. Global production of eight major crops and estimated losses for the eight crops by pest and region, 1988-1990.

Crop	Actual Crop Production (bUS$)	US$ (billions) Losses due to			
		Pathogens	Insects	Weeds	Total
Rice	106.4	33.0	45.4	34.2	112.5
Wheat	64.65	14.0	10.5	14.0	38.5
Barley	13.7	1.9	1.7	2.0	5.7
Maize	44.0	7.87	10.4	9.3	27.4
Potatoes	35.1	9.8	9.6	5.3	24.8
Soybean	24.2	3.2	3.7	4.7	11.6
Cotton	25.7	4.7	6.3	4.9	15.5
Coffee	11.4	2.8	2.8	2.0	2.6
Region					
Africa	13.3	4.1	4.4	4.3	12.8
N. America	50.5	7.1	7.5	8.4	22.9
Latin America	30.7	7.1	7.6	7.0	21.7
Asia	162.9	43.8	57.6	43.8	145.2
Europe	42.6	5.8	6.1	4.9	16.8
Former Soviet Union	31.9	8.2	7.0	6.7	22.1
Oceania	3.3	0.8	0.6	0.5	1.9

The effect of extreme climatic events on crops may be either direct or indirect and may finally affect crop yields. Plants in the early stages of development are most vulnerable to these extreme weather events (Cynthia et al., 2000). When the temperature exceeds the optimal range of the crops, the crops tend to respond negatively, resulting in the reduction in crop yield. The optimal temperature varies for different crops. For example, corn pollen loses its viability if the temperature rises beyond 36 °C. In potato, the tuber initiation and bulking will be reduced while temperatures cross 20 °C (Paulsen, 1994). In soybeans, Ferris et al., 1998 reported that high temperatures at the time of flowering or early seed filling, and water deficit during the reproductive stage, reduces photosynthesis and seed yield of soybean. Because pod development and seed filling are the most sensitive phases of crop development in soybean. High temperatures and low moisture stress tend to decrease the yield, while increased atmospheric CO_2 concentration results in the overall increase in the yield in soybean (Jane et al., 2002).

Mohamed et al. (2002) examined the impact of inter-annual rainfall variability over 30 years and future climate change scenarios on millet production in Niger. Results from the study indicated that sea surface temperature anomalies, the amount of rainfall, the number of rainy days and the wind erosion are the significant determinants of millet productivity. The authors estimated that the production of millet will be about 13 percent lower by 2025, as a result of reduction of rainfall with an increase in temperature. Similarly, Van et al. (2002) studied the impact of climate change on groundnut and cowpea production. They estimated a reduction of 11 and 25 percent yield of groundnut and cowpea, respectively by 2025. In a recent study, Murdiyarso (2000) estimated the potential impact of climate change on rice production in Asia, taking into account CO_2 effects. The results indicated that the rice production will decrease by 7.4% per degree increase in temperature.

International Food Policy Research Institute (IFPRI, 2007) projected a negative impact of climate change on several food crops like wheat, sweet potato, cassava, maize, rice, sugarcane, millet and sorghum in Sub-Saharan Africa. Of these, wheat and sweet potato showed maximum reduction in yield of more than 20 and 13%, respectively. In a recent study, Jerry et al. (2012) projected the impact of climate change on eight major crops in Africa and South Asia. They show that the mean change in yield of eight crops is about -8% by 2050 in both regions. In Africa, mean yield changes of wheat, maize, sorghum and millet were -17, -5, -15 and -10%, respectively. Across South Asia the yield reduction of -16 and -1% were estimated for maize and sorghum (Table 4.3).

Tonkaz et al. (2010) studied the impact of changing temperature and elevated CO_2 on winter wheat grown under semi-arid conditions. They found that the temperature had significant influence in the yield and several physiological parameters of the crop. Results indicated that when both temperatures increased by 6 ^{0}C, yield decreased 30%, while 6 ^{0}C decrease in temperatures increased yield by 37%. Elevated CO_2 levels had a positive effect on yield, grain number, leaf area, and biomass. They showed that every 40 ppm increase in CO_2 level increased yields by 150 kg ha^{-1}. In a study, Rosenzweig and Liverman (1992) compared the effects of climate change on agriculture in temperate and tropical regions. These regions differ significantly in their biophysical characteristics of climate and soil. They studied the impacts of higher levels of carbon dioxide in the atmosphere and associated global warming. The projected changes differ for the temperate and tropical regions.

A number of studies have attempted to quantify impacts of recent climate trends on crop production. In a recent study, historic climate changes from 1980 to 2008 period were estimated. The authors reported that these changes have lowered wheat and maize yields by roughly 6 and 4%, respectively. Global soybean and rice yields were relatively unaffected by changes. Yields for barley, maize, and wheat all increased substantially since 1980 (Lobell et al., 2011).

Table 4.3. Summary of reported impacts of climate change on yield (mean and median changes %) for all crops, by sub-region in Africa and South Asia.

Crop	n	Mean change (%)	Median change (%)	Crops with significant variation	n	Mean change (%)	Crops with non-significant variation*	n
All crops	257	-7.7	-7.0	Wheat	37	-12.1	Rice	43
				Maize	12	-7.2	Cassava	8
				Sorghum	9	-13.0	Sugarcane	7
				Millet	23	-*8.8		
Africa	163	-7.7	-10.0	Wheat	20	-17.2	Rice	5
				Maize	10	-5.6	Cassava	7
				Sorghum	6	-14.6	Sugarcane	3
				Millet	13	-9.6		
Southern Africa	33	-11.0	-15.1	Maize	24	-11.4	Wheat	2
							Sorghum	3
							Sugarcane	2
Central Africa	14	-14.9	-12.1	Maize	8	-13.1	Wheat	2
East Africa	35	0.4 (NS)	-2.3	--	--	--	Wheat	2
							Maize	29
West Africa	34	-12.5	-8.4	Maize	19	-7.4	Wheat	3
							Sorghum	5
							Cassava	4
Sahel	24	-11.3	-11.5	Maize	13	-12.6	Sorghum	3
				Millet	6	-10.6		
North Africa	28	0.8 (NS)	-7.3	--	--	--	Wheat	10
							Maize	12
S. Asia	94	-7.7	-5.0	Maize	23	-15.9	Rice	38
				Sorghum	10	-10.8	Wheat	17
							Sugarcane	4
South Asia	74	-8.7	-8.4	Maize	21	-17.6	Rice	26
				Sorghum	10	-10.8	Wheat	13
							Sugarcane	3
South East Asia	20	-3.6 (NS)	-2.5	--	--	--	Rice	12
							Wheat	4
							Maize	2

*only crops with more than one observation included

n = Number of reported mean yield changes, which may include several from the same source for different countries or time slices; NS = not significant

Source: Jerry et al., 2012

4.4.1.2. Indian Scenario

Almost all developing countries are located in tropical belt with hot climate and these are more vulnerable to the potential impact of climate change. The agricultural systems in developing countries are much less capital and technology intensive than in the developed world. Therefore, the impact of climate change on agriculture in developing countries will be higher than that of developed countries (Ranade, 2009). Limited attempts were made to relate the effect of climate change on agriculture or crop growth and productivity in India. Lal et al. (2001) reported a 5-25% decline in the winter rainfall and 10-15% increase in the monsoon rainfall over India by 2080. This may lead to severe drought in dry season or flood in monsoon season and ultimately results in the crop loss for large areas. Bhoomiraj et al. (2010) reported the yield decline in Indian mustard (*Brassica juncea*) using the INFOCROP, a dynamic crop simulation model. The crop was sensitive to changes in carbon dioxide and temperature. The analysis showed that mustard yields were likely to reduce in both irrigated and rain-fed conditions. However, these reductions have spatial variation in different mustard growing region of India. In both irrigated and rain-fed conditions, yield reduction would be higher in eastern India (57-67%) followed by central India (14-48%) and northern India (21.4-40.3%).

Singh and Lal (2009) estimated the impact of climate change on potato production in India. The results showed that potato yield may decline by 3.16 and 13.72 % in the year 2020 and 2050, respectively. Rosenzweig and Parry (1994) found that a rise in temperature of 4 ^{0}C could result in grain yields in India reducing by 25–40 percent. Under doubled atmospheric CO_2 and increased temperature, the rice production may increase in Uttar Pradesh State of northern India provided there was no nutrient and water limitations (Achanta, 1993).

Recent studies revealed that climate change may seriously affect the growth and yield of rice in Andhra Pradesh. It was reported that the anthesis in rice was delayed by 4 and 7 days, when temperature was increased by 1 ^{0}C and 2 ^{0}C, respectively. The maturity of the crop was delayed by 7 and 12 days when temperatures were elevated to 1 ^{0}C and 2 ^{0}C. It was noticed that there was no change in yield with elevated CO_2 levels up to 450 and 600 ppm. The influence of temperature was also projected and was found that the yield decreased was by 7.3 and 13.7% when the temperature rose by 1 ^{0}C and 2 ^{0}C, respectively. However, the grain yield of rice was increased by 31 and 38.2% when the CO_2 concentration was increased to 450 ppm and 600 ppm, respectively (Reddy et al., 2009).

North East India occupies 30% of total rice cultivation in India spread over about 3.5 million hectare of land area. Of these over 60% of the area is under rainfed agriculture. Using INFOCROP crop simulations Model, the yield of rice in 64 districts of Northeast India were estimated. The results showed that the yield increased in 21 districts and decreased in 43 districts by 10%. Highest decrease in yield was noticed for North Sikkim District of Sikkim (Ravindranath et al., 2011). With the same dynamic modelling system, Srivani et al. (2007) projected the yield, duration of the crop and days to anthesis of rice in Tamil Nadu for 2020, 2050 and 2080. The simulated results of the model showed that there was a progressive reduction in the crop duration and days to anthesis for all the study regions. The economic yield loss due to changing climate for all study area was estimated as an average of 7.08% for 2020, 17.5% for 2050 and 14.4% for 2080. Several studies projected that the decreased yield in rain-fed and dry land wheat and rice and loss in farm net revenue between 9 to 25 per cent for a temperature increase of 2 to 3.5 ^{0}C. Sinha and Swaminathan (1991) showed that an increase of 2 ^{0}C in temperature could decrease rice yield by about 0.75 tons/ha in the high yield areas and a 0.5 ^{0}C increase in winter temperature would reduce wheat yield by 0.45 ton/ha. Saseendran et al. (2007) showed that for every one degree rise in temperature the decline in rice yield would be about 6%.

As a result of human activities, the concentration of CO_2 in the atmosphere is likely to be doubled by the end of 21st century (Keeling et al., 1995). Several studies being conducted to understand the effect of elevated CO_2 in the atmosphere using open top chambers and Free Air Carbon Dioxide Enrichment (FACE) experiments. Almost all studies showed an increase in the photosynthetic rate and crop yield (Kimball, 1983). In an experiment, Uprety et al. (2003) observed increase in rice grain yield due to increase in CO_2 concentration. The increased net photosynthetic rate and greater accumulation of sugar contributed significantly to the accelerated development of leaves and tillers and finally grain yield.

In India there are two major crop growing seasons, the 'Kharif' (summer season) and the 'Rabi' (winter season). Kharif season coincides with the south-west monsoon and the rabi season begins after the summer monsoon, and continues through to the following spring or early summer. The major kharif crops are rice, maize, sugarcane, cotton, jute, groundnut, soybean and Bajra etc. and major rabi crops are wheat, mustard, barley, potato, onion and gram etc. Southwest monsoon is critical for kharif crops while summer monsoon is critical for rabi crops. Any change in the monsoon rainfall may seriously affect crop productivity in these two seasons. The inter-annual monsoon rainfall variability in India leads to large-scale droughts and floods, resulting in a major effect on Indian food grain production (Parthasarathy and Pant, 1985; Kumar et al., 2004) and on the economy of the country (Gadgil et al., 1999). Mall and Singh (2000) observed that small changes in the growing season temperature over the years appeared to be the key aspect of weather affecting yearly wheat yield fluctuations in India. Pathak et al. (2003) showed that the negative trends in solar radiation and an increase in minimum temperature, resulting in declining trends of potential yields of rice and wheat in the Indo-Gangetic plains of India. In Delhi the minimum and maximum temperature show a rising trend both in summer or 'Kharif' season as well as winter or 'rabi' season starts after summer monsoon. There was also a small declining trend in solar radiation during rabi and Kharif season after 1980. Solar radiation is closely related to crop growth. Any decrease in this will significantly reduce agricultural productivity. The accompanied increase in minimum temperatures increases respiration of the crops and thus further reduces net growth and productivity (Agarwal, 2003).

In India, a few studies have been carried out to understand the impact of elevated atmospheric CO_2 and associated climatic change on the nature and magnitude of yield gains or losses of crops (Mall et al. 2006). Agarwal and Sinha (1993) reported that at 425 ppm CO_2 concentration and no rise in temperature, wheat grain yield increased significantly. In northern India, a 1 ^{0}C rise in mean temperature had no significant effect on potential yields. An increase of 2 ^{0}C in temperature reduced potential wheat yields in most places. Gangadhar and Sinha (1994) studied the impact of climate change on wheat performance of India and showed that wheat yields decreased due to the adverse effects of temperature during grain filling and maturity stages of the crop.

Gangadhar et al. (1995) studied the impact of climate change on productivity of Sorghum in three diverse growing regions in India (Hyderabad, Akola and Solapur). The results indicated a decrease in yield and biomass of rainy season sorghum at Hyderabad and Akola. But the adverse effects of increasing temperature were masked by the positive effects of increased CO_2 resulting in shortened crop growing seasons. Chatterjee (1998) showed a consistent decrease in the sorghum yields while the temperature increased from the present day conditions. Increase in temperature by 1 and 2 ^{0}C sorghum decreased the grain yields by 7 to 12%. A further increase in temperature drastically reduced the potential yields by 18 to 24%. Lal et al. (1999) projected 50% increased yield for soybean for a doubling of CO_2 in central India. However, a 3 ^{0}C rise in temperature almost nullified the positive effects of doubling of carbon dioxide concentration. Soybean crops in central India are found to be more vulnerable to increase in maximum temperature than in minimum temperature. A decline in daily rainfall amount by 10% restricts the grain yield to about 32%.

Most of the simulation studies have shown a decrease in duration and yield of crops as temperature increased in different parts of India. In north India, irrigated wheat yields decreased as temperature increases. Saseendran et al. (2000) reported that in Kerala, an increase in CO_2 concentration leads to the increase in rice yield due to its fertilization effect and also enhance the water use efficiency. The results showed that if the temperature rise up to 5 ^{0}C, there is a continuous decline in the rice yield and after that it decreased suddenly. They found that one-degree rise in temperature resulted in the decline of yield by 6%. A 2 ^{0}C increase in temperature resulted in 17% decrease in grain yield but beyond that the decrease was very high. These decreases were compensated by CO_2 fertilizing effect on crop growth. CO_2 concentration has to rise to 450 ppm to nullify the negative effect of 1 ^{0}C increase in temperature (Aggarwal, 2003), but 450 ppm CO_2 concentration may produce more than 1 ^{0}C rise in temperature and thus the net result may be a decline in yield. Impact of climate change on Indian agriculture is already substantial and this has the potential to become catastrophic in years ahead unless appropriate strategies are not put in place.

4.4.2. Impact of climate change on plantation crops

Studies on the impact of climate change on plantation crops are very few compared to food crops and annual crops. In a study, Rao et al. (2009) reported that cashew production was reduced in Kerala in the recent years and likely go down further. This yield decline was due to the reduction in the area of cultivation and occurrence of weather aberrations during the reproductive phase of the crop. Some crop yield projection models developed outside India showed that the area under tea and coffee will be adversely affected when the temperature increased to 2 ^{0}C. Increase in maximum temperature of 1-3 ^{0}C during summer of the year 2004 adversely affected crops like pepper and cocoa (Rao et al., 2008). Studies by Kumar and Aggarwal (2013) indicated that climate change is projected to increase coconut productivity in western coastal region, Kerala, parts of Tamil Nadu, Karnataka and Maharashtra, North-Eastern states, Andaman and Nicobar and Lakshadweep, provided current level of water and management is made available in future also and also. Decline in the yield were projected for Andhra Pradesh, Orissa, West Bengal, Gujarat and parts of Karnataka and Tamil Nadu. Even with current management practices, all India coconut productivity was projected to increase by 4.3% in A1B 2030, 1.9% in A1B 2080, 6.8% in A2 2080 and 5.7% in B2 2080 scenarios compared to the mean productivity of 2000–2005. Improved agronomic practices and genetic adaptation measures like growing improved local tall cultivars and hybrids under improved crop management can increase the productivity by about 33% in 2030, and by 25–32% in 2080 climate scenarios. They stated that the productivity can be improved by 20% to almost double if all plantations in India are provided with above mentioned management even in current climates. Lutze et al. (1998) reported that crop growth under elevated CO_2 led to spring frost damage in field-grown seedlings of snow gum (Eucalyptus pauciflora Sieb, ex Spreng), a usually frost-tolerant eucalyptus. Their result suggests that an increase in frost susceptibility may lower likely gains in productivity from CO_2 fertilization. Another study by Akossou et al. (2012) showed that the radial growth of teak (Tectona grandis) was influenced by the changes in the conditions of humidity like evaporation and rain. The impact of climate variability in the productivity of oil palm was studied by World Bank (2010). Malaysia experiences hot and wet tropical climate, with atypical daily surface temperature in the range of 20-30 ^{0}C. Increase in air temperature over Malaysia without CO_2 fertilization will expected to decrease the oil palm yield by 10-20% by 2050.

4.5. Materials and Methods

In the previous chapter, historical climate data of the rubber growing regions of India have been presented. These data and the corresponding national mean yield data (productivity) could have been regressed to find out how far changes in the climate have affected the latter. However, several external variables that cannot be exactly quantified (for including in a statistical model) also might have occurred during the same period. For example, recent decades have seen increasing extents of area coming under high yielding clones of rubber. There have been considerable improvements in various agro-management practices, including tapping practices such as adoption of rain guarding and yield stimulation which have a direct and immediate bearing on productivity. Some of these factors are quantifiable and several others cannot be quantified, but all have certainly contributed to increasing productivity of rubber in India in recent years which is today the highest in the world (IRSG, 2013). Thus, over the recent decades, when climate of the rubber growing regions have undergone significant warming (as described in chapter 3), the same period also witnessed remarkable improvement in productivity; thanks to the widespread adoption of high yielding clones and better agro-management practices adopted by the growers. Therefore, regressing the historic climate data with corresponding data of national productivity will not correctly address the question of the impact of climate warming on rubber productivity. In such an analysis, the impact of climate warming on rubber yield will be masked; if not wrong conclusions will be arrived at.

Therefore, I depended on round-the-year daily weather data from the diverse agro-climatic regions of India where rubber is being cultivated. These regions represented very wide variations in climate which have been well documented (Jacob et al., 1999; George and Jacob, 2000). The weather data and yield data were collected for different clones grown in the research farms under the Rubber Research Institute of India where the agro-management practices adopted were similar. Therefore, it is assumed that any variation in daily yield may be attributable to corresponding variations in the prevailing agro-climatic conditions; soil factors being constant in a given farm.

Long term daily weather data (details in chapter 3) and yield data (ie. gram dry weight of rubber produced per tree per tapping day, g t^{-1} t^{-1}) were collected from weather stations at the Rubber Research Institute of India (RRII) located in Kottayam which is a typical traditional rubber growing region in Kerala and from the Regional Research Stations (RRSs) of RRII at Agarthala, Tura, Dapchari (non-traditional) and RRS, Padiyoor (traditional) representing diverse agro-climatic regions in India where NR is cultivated in the country (Jacob et al., 1999). Daily weather data which is corresponding to the daily yield data collected from different RRSs. For the traditional region daily weather and yield data collected for the period 2003-2008 for Kottayam and 2007-2008 for Padiyoor. For Dapchari, which is a non-traditional hot region, daily yield and weather data collected from 2007-2008. For Tura and Agarthala (Northeastern non-traditional cold regions) data for the period of 2003-2008 were collected from the respective RRSs. Monthly per hectare productivity data were collected for Kottayam, Kanjirapally and Thaliparamba from different rubber plantations in these regions for the period of 2008 to 2009. Linear regression analyses were done to estimate the magnitude of long term trend in the temperature time series (see chapter 3).

The climatic conditions in these regions ranged from extreme dry and hot conditions in Dapchari to severe winter conditions in NE. Dapchari is situated at 20^0 04'N, 72^0 04'E with an average elevation of 48 m above MSL in the North Konkan region of Maharashtra. During the monsoon season this region gets around 2400 mm rainfall. During peak summer days the maximum temperature goes above 38 ^{0}C (Jacob et al., 1999).

Agarthala and Tura are situated in NE India, at 23^0 50'N, 91^0 16'E and 25^0 30'N, 90^0 13'E with an altitude of around 30 and 1100 m above MSL, respectively. The annual rainfall in these regions ranged from 2000-2400 mm (Jacob et al., 1999; George and Jacob, 2000). During peak winter, the minimum temperature may be as low as 5 0C or less. Compared to these two non- traditional regions, the weather conditions in the traditional NR growing regions of India are more moderate. The traditional regions are situated at a latitudinal range of 8^0 15'N to 12^0 5'N and longitudinal range of 74^0 5'E to 77^0 30'E with an altitude of 20-840 m above MSL and are represented by RRII, Kottayam and RRS, Padiyoor. Mean annual rainfall in these regions ranged from 2000-4500 mm (Jacob et al., 1999; George and Jacob, 2000). The mean maximum and minimum temperatures during summer months were 33 ^{0}C and 25 ^{0}C and for winter days, 31 ^{0}C and 22 ^{0}C, respectively. India is perhaps the only major NR growing country where NR is cultivated in such extremely diverse agro-climatic conditions.

Each of the above stations has its own experimental farm. The management practices adopted everywhere were the same and as recommended by Rubber Board. For the yield data, fields with the same clone, age and tapping were selected. Daily yield data (with same tapping frequency) and the corresponding daily data on minimum temperature (Tmin), maximum temperature (Tmax), mean annual temperature (T_{ann}.), mean annual maximum temperature

(Tmaxann), mean annual minimum temperature ($Tmin_{ann}$), mean annual rainfall (RF_{ann}) and mean number of annual rainy days (RFD_{ann}) were used in regression analyses to determine the quantitative effect of each parameter on yield.

Three different approaches were adopted in regressing the weather data with yield as described below. It may be noted that long term data on weather and yield as available in the different regional stations for different clones and periods only could be used in the analyses.

4.5.1. Approach 1

In the first approach, we regressed mean annual productivity in these diverse agro-climatic regions together with the prevailing weather parameters (annual means). Multiple linear regression (MLR) was done using the statistical software SPSS v11.0.1. In the multiple regression model, we used weather parameters like mean annual temperature (T_{ann}.), mean annual maximum temperature ($Tmax_{ann}$), mean annual minimum temperature ($Tmin_{ann}$), mean annual rainfall (RF_{ann}) and mean number of annual rainy days (RFD_{ann}) as independent variables and mean annual yield of a tree per day i.e. $g\ t^{-1}\ t^{-1}$ as the dependent variable. In the first approach, variables from all the different experimental locations representing the diverse agro-climatic regions were regressed together so as to get maximum variability in the independent (weather) variables. After the competition of backward MLR analysis, it was found that only maximum temperature, minimum temperature, annual rainfall have significant impact on the yield. In that the rainfall has only a small impact on per tree yield of rubber. Hence the next two approaches were carried out only using the temperature data.

4.5.2. Approach 2

In the second approach, daily per tree yield ($g\ t^{-1}\ t^{-1}$) for several years was regressed with the corresponding maximum and minimum temperature for these years separately for the different agro- climatic regions, but pooling all clones grown in one location together. In a separate analysis, clone-wise impacts of climate variables were separately analyzed for each station. For Agarthala and Padiyoor, data on RRII 105, RRII 414, RRII 417, RRII 422, RRII 429, RRII 430 and RRIM 600 were used. In the case of Dapchari, data on RRIM 600 was only available and clones like RRII 105, RRII 414, RRII 417, RRII 422, RRII 429 and RRII 430 were used for Kottayam. For RRS Tura, yield data of several clones such as GL1, GT1, PB 235, PB 260, PB 310, PB 311, PB 5/51, PB 86, PR 225, RRIC 102, RRIC 105, RRII 105, RRII 118, RRII 203, RRII 208, RRII 5, RRIM 600 and RRIM 605 were considered for the MLR modelling.

4.5.3. Approach 3

In a third approach, we regressed the per hectare productivity with maximum and minimum temperatures for three locations from within the traditional areas, namely Kottayam, Kanjirapally and Thaliparamba and estimated the impact of rising temperatures on productivity. In this approach monthly per hectare productivity data were regressed with the monthly mean maximum and minimum temperature for all the three regions. MLR models were prepared for each location separately. After getting a model for each location, we predicted the yield for 1 degree rise in Tmax and Tmin. Per hectare productivity were predicted up to the year 2030. Trend analysis was done with the actual productivity data calculated from the area and production data taken from the rubber statistical bulletin of IRSG (2012). Trends in the projected per hectare yield and the actual per hectare productivity were compared to understand the future rubber production in a warming climate and for understanding the urgency to release of highly productive, efficient and environmental stress tolerant clones.

4.6. Results and Discussion

4.6.1. Approach 1: Combined regression analyses of yield (per tree, per year) and weather parameters for different agro-climatic regions

Mean annual weather data (T_{ann}, $Tmax_{ann}$, $Tmin_{ann}$, RF_{ann} and RFD_{ann}) for the period 2003 to 2009 were used as independent variables (X variables) and mean annual productivity of the tree during the same period were taken as dependent variable (Y variable) to work out a multiple liner regression model in which data from all study locations were pooled together in order to catch maximum variations in the independent variables (see approach 1 in materials and methods). In the last step of MLR, only three independent variables were left in the model, namely, $Tmax_{ann}$, $Tmin_{ann}$ and RF_{ann} with an R^2 of 0.25 (Table 4.4) as the other independent variables were eliminated as they did not explain the variability in the dependent variable (yield per tree per year) any better than these three variables. Thus, the model that best explained variability in yield in terms of the climatic parameters was as follws:

$$Y = 96.94 - 7.05\ Tmax_{ann} + 7.45\ Tmin_{ann} + 0.008\ RF_{ann} \quad R^2 - 0.25 \qquad \text{Eqn. (1)}$$

According to this model, rising Tmax has a negative while increasing Tmin and rainfall have a positive impact on yield per tree per year. Using this equation, the mean yields per tree per year were predicted for the prevailing Tmax, Tmin and RFann at the different argo-climatic regions where rubber is grown in India (Table 4.5). The results showed an increase in the per day productivity of 6.2% for the regions together. Agarthala region showed a negligible reduction of yield (1.05%) in the future (2020). From these results it can be interpreted that the analysis of stations altogether is not a good way to study the impact of climate parameters on the yield, because each of these stations are situated in the different agro-climatic condition in India. The meaning of one weather parameter in one region may not be the same for another. Hence the approach one was rejected and MLR for individual regions carried out separately as discussed in the approach 2.

Table 4.4. MLR (Backward) models obtained between the annual yield and different weather parameters for all stations together.

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig.
		B	Std. Error	Beta		
1	(Constant)	-26.4	152.224		-0.173	0.871
	T_{ann}	2.787	2.628	0.284	1.061	0.349
	Tx_{ann}	-4.922	6.459	-0.607	-0.762	0.488
	Tn_{ann}	6.203	5.56	1.145	1.116	0.327
	RF_{ann}	5.68E-03	0.009	0.449	0.625	0.566
	RFD_{ann}	8.94E-02	0.305	0.21	0.293	0.784
2	(Constant)	-0.195	111.345		-0.002	0.999
	T_{ann}	2.642	2.333	0.269	1.132	0.309
	Tx_{ann}	-6.419	3.572	-0.791	-1.797	0.132
	Tn_{ann}	7.647	2.327	1.412	3.286	0.022
	RF_{ann}	8.13E-03	0.003	0.643	2.58	0.049
3	(Constant)	96.938	72.647		1.334	0.23
	Tx_{ann}	-7.053	3.61	-0.869	-1.954	0.099
	Tn_{ann}	7.452	2.375	1.376	3.138	0.02
	RF_{ann}	8.11E-03	0.003	0.641	2.515	0.046

Table 4.5. Present and future mean annual temperature, annual rainfall and per day productivity (g/t/t) calculated using the MLR model obtained from the approach 1.

Station	2010			2020			Productivity (g/t/t)		
	$Tmax_{ann}$	$Tmin_{ann}$	RF_{ann}	$Tmax_{ann}$	$Tmin_{ann}$	RF_{ann}	2010	2030	% Change
Tura	29.6	17.1	2500	31.1	18.6	3606.58	35.66	45.11	9.45
Agarthala	30.77	20.11	2500	32.27	21.61	2293.28	49.83	48.78	-1.05
Padiyoor	32.96	22.06	3700	34.46	23.56	5853.88	58.52	76.35	17.83
Dapchari	33.51	20.78	2500	35.01	22.28	2908.86	35.51	39.38	3.87
Kottayam	31.4	22.88	3000	32.9	24.38	3076.38	70.03	71.24	1.21

4.6.2. Approach 2: (i) Separate regression models for yield (per tree, per day) for individual regions with all clones pooled together

The above model (approach 1) in which the independent variables from various agro-climatic regions were pooled and incorporated in one MLR model had a fundamental flaw. It would not be possible to know from it, if the different independent variables had qualitatively and quantitatively different impacts on yield in the different regions. In order to decipher this point, it was necessary to do the regression analysis for the different agro-climatic regions separately. It is expected that in the NE where very low winter temperatures prevail, an increase in Tmax may have a a positive effect on yield unlike in other places where the effect of the already prevailing high Tmax may be negative. Such differential effects are masked in the above model. Therefore MLR analysis was made separately for the different regions and also for different clones and the results are discussed below.

For obtaining variations in daily yield per tree (Y) and weather (X), daily data were collected round the year as in approach 1 above. MLR models were made for the different regions and the different available clones in these regions separately. The final MLR models obtained for the individual regions had only two independent variables in them, namely daily maximum temperature (Tmax) and daily minimum temperature (Tmin). Unlike in approach 1, RFann got eliminated at the last step in approach 2. The MLR models for the different study locations are given below.

Y = *433.43 - 7.87Tmax - 4.83Tmin* (Kottayam, 9^0 26'N to 76^0 48'N) Eqn. (2)

Y = 171.01 - 2.54Tmax - 1.71Tmin (Padiyoor, 11^0 58'N to 75^0 36'N) Eqn. (3)

$Y = 204.98 - 1.01Tmax - 5.51Tmin$ (Dapchari, 20^0 04'N, 72^0 04'E) Eqn. (4)

$Y = 41.25 + 0.67Tmax - 1.13Tmin$ (Agarthala, 23^0 50'N, 91^0 16'E) Eqn. (5)

$Y = -24.85 + 3.58Tmax - 2.59Tmin$ (Tura, 25^0 30'N, 90^0 13'E) Eqn. (6)

Out of the five stations studied, two regions (Kottayam and Padiyoor) in this study represented the traditional areas in Kerala. Kottayam is considered as the cradle of rubber cultivation in the country where more than 0.11 million ha is under this crop (Indian Rubber Statistics, 2012), which constitutes more than 10% of the total cultivated area in this district (GIS data of RRII-unpublished). Padiyoor in North Kerala is also a traditional area, but agro-climatically this region in Malabar is generally a little less congenial than Kottayam. In both these stations, both Tmax and Tmin had a negative impact on yield indicating that with a warming climate yield may go down. The extent of impact on yield per tree per day was more for Tmax than Tmin. Both these parameters had a stronger impact in Kottayam than in Padiyoor (equations 2 and 3) indicating that a warming climate can decrease productivity more in Kottayam than in Padiyoor.

In Dapchari, a nontraditional region in the north Konkan characterized by high summer temperature and relatively cooler winter temperatures (compared to Kottayam and Padiyoor), both Tmax and Tmin had a negative impact on yield per tree per day, but Tmin had a stronger impact than Tmax (equation 4). In Agartalla and Tura, the two nontraditional areas in NE characterized by very cold winter and reasonably warm summer, Tmax had a positive impact and Tmin had a negative impact on yield per tree per day (equations 5 and 6). This indicates that a warming climate will increase rubber yield in NE, provided Tmax warms more than Tmin in this part of the country. Thus, it can be seen that Tmax and Tmin had qualitatively and quantitatively different impacts on rubber yield in the different agro-climatic regions of the country. In the cold NE, a warming climate may positively impact rubber yield where low winter temperature is presently a limiting factor for growth and productivity of rubber. In the traditional regions, future warming may reduce yields and this impact appears to be more in the most traditional parts of Kerala (Kerala) than in Malabar or North Konkan.

Even though the relative impact of warming may be more in Kottayam than in Malabar or the Konkan, the absolute yields may still remain high in Kottayam region for the time being. But if the present warming trends continue, this scenario also can undergo significant changes making productivity in Kerala (and by extrapolation in the more traditional parts of Kerala) taking a dip in coming years.

From the above five models (approach 2), the change in yield per tree per day when both Tmax and Tmin concomitantly increased by 1^{0}C was calculated for the different regions (Table 4.6). Reduction in yield per tree per day in Kottayam was to the tune of 16% for

1 °C rise in Tmax and Tmin. In Dapchari the yield (per tree per day) reduction for 1 °C rise in Tmax and Tmin was 11.25% followed by 8.43% in Padiyoor. But in the other two regions, namely Agarthala and Tura in NE India where winter temperatures are very low, the impact of warming was found to be negligible on yiled per tree per day. In Agarthala the yield per tree pre day decreased by about 1.17% and in the case of Tura there was an increase in the yield per tree per day by almost 2.72% for 1 °C rise in Tmax and Tmin. Thus, small rise in temperature in this region may not have much adverse impact on rubber yield. Sometimes climate warming may increase the yield just like what happened in the Tura region. In addition to the mild or stimulatory impact of climate warming on yield, it is likely that more regions of the NE where cold winter is presently a limiting factor for further expansion of rubber cultivation may become congenial for rubber planting in future.

Table 4.6. Percentage change in NR productivity (on a per tree per day basis) for one degree Celsius rise in Tmax and Tmin and predicted yield for the next 10 years with the current warming trends.

Region	Data priod	Parameter	MLR Coeff.	MLR Intercept	MLR R^2	% Change (for 1 °C rise)	% Change (for next 10 year)	Estimated productivity from MLR ($gt^{-1}t^{-1}$)
Tura	2000-08	Tmax	3.58	-24.85	0.23	**2.72**	**11.25**	**35.8**
		Tmin	-2.60					
Agarthala	2003-08	Tmax	0.67	41.25	0.07	**-1.17**	**-1.10**	**37.9**
		Tmin	-1.13					
Kottayam	2003-08	Tmax	7.87	433.43	0.29	**-16.23**	**-6.88**	**73.0**
		Tmin	4.83					
Padiyoor	2007-08	Tmax	-2.54	171.01	0.19	**-8.43**	**-4.23**	**48.6**
		Tmin	-1.71					
Dapchari	2006-09	Tmax	-1.01	204.98	0.50	**-11.25**	**-4.69**	**57.7**
		Tmin	-5.51					

During the last 52 years (1957-2009) Tmax and Tmin in RRII have increased at the rate of 0.05 °C yr^{-1} and 0.03 °C yr^{-1}, respectively (Table 3.6). Extrapolating this data, the rise in Tmax and Tmin in the next 10 years (ie until 2020) was calculated and the same was used to estimate the expected productivity (yield per tree per day) after 10 years at Kottayam using the MLR models developed for Kottayam and similarly for the other study locations (Table 4.6). The yield (per tree per day) decrease after 10 years will be about 6.88% in Kottayam.

In Padiyoor the rate of increase in Tmax and Tmin during the period 1998-2009 was 0.01 and 0.11 $^{0}C\ yr^{-1}$, respectively and this may result in the reduction of yield per tree per year by 4.23% after 10 years based on the MLR model. In the case of Dapchari, during the period 1994-2009 the rate of increase in Tmax was much higher (0.16 $^{0}C\ yr^{-1}$) but the minimum temperature increased by only 0.03 $^{0}C\ yr^{-1}$. The reduction in the yield per tree per day in this region will be 4.69% for the next decade.

In Agarthala, the reduction in yield per tree per year in the next ten years will be very small going by the present warming trend (1.10%) which is 0.02 $^{0}C\ yr^{-1}$ for Tmax and Tmin 0.06 $^{0}C\ yr^{-1}$ for Tmin (during the period 1984-2007). For the last 18 years (1992-2009) Tmax in Tura increased by 0.15 $^{0}C\ yr^{-1}$. But the minimum temperature increased by 0.05 $^{0}C\ yr^{-1}$ in this region. The cumulative effect of the expected changes in Tmax and Tmin in this region could lead to an increase in the yield per tree per year by 11.25% in the next ten years.

Thus it can be seen that in the cold NE, climate warming may have a stimulatory effect where as in the traditional regions and the Konkan, the effect can be just the opposite. It may be noted that in Kerala and the Konkan, temperatures remain much higher than in the NE and this may be one reason for the qualitative difference in the impact of climate warming on rubber yield observed between NE and the rest of the regions. However, interestingly, climate warming seems to have a more strong impact in reducing rubber yield in Kottayam than in Padiyoor or north Konkan. In general, the summer temperatures in Padiyoor and Dapchari are well above those of Kottayam, but winter is cooler in Dapchari than in Kottayam or Padioyyor (Jacob et.al., 1999). Obviously, the prevailing temperatures have a complex effect on how further rise in temperatures may impact rubber yield. While this conclusion is made, it is also pointed out that the robustness of the data and the statistical significance of the MLR models also should be borne in mind. However, the present suggest that warming may reduce yields in Kerala and the Konkan but may not do so and might even improve yield in NE.

4.6.3. Approach 2: (ii) Separate regression models for yield (per tree, per day) of individual clones grown in different regions

The approach followed for this analysis was exactly like the above one, but multiple linear regression analyses were done for individual clones grown at the different agro-climatic locations separately. The results showed that variations in yield per tree per day were explained by Tmax and Tmin and not any other climate variable (Table 4.7). Traditional regions like Kottayam in central Kerala and Padiyoor in northern Kerala and in the north Konkan (Dapchari), rising Tmax and Tmin had a negative impact on yield per tree per day for clone RRIM 600. For the two stations from NE, rising Tmax had a positive effect, but rising

Tmin had a negative effect on yield per tree per day of every clone studied. These effects were similar to the effects noticed in these regions when all clones grown at one region were pooled together and analyzed. Thus, qualitatively the effects on Tmax and Tmin were the same in the five regions studied here when data was analyzed with all clones pooled together or each clone was analyzed individually (Table 4.7 – 4.9).

Table 4.7. Percentage change in NR productivity (on a per tree per day basis) in Kottayam, Padiyoor and Dapchari for one degree Celsius rise in Tmax and Tmin and predicted yield for the next 10 years with the current warming trends.

Station	Clones	Data period	Parameter	MLR Coeff.	MLR Intercept	MLR R^2	% Change (for 1 °C rise)	% Change (for next 10 years)
Kottayam	RRII 105	2003-08	Tx Tn	-6.37 -4.26	363.17	0.27	**-15.70**	**-6.60**
	RRII 414	2003-08	Tx Tn	-6.45 -5.2	393.48	0.31	**-15.70**	**-6.45**
	RRII 417	2003-08	Tx Tn	-8.51 -6.54	500.98	0.25	**-17.30**	**-7.15**
	RRII 422	2003-08	Tx Tn	-7.84 -4.7	433.87	0.35	**-15.18**	**-6.45**
	RRII 429	2003-08	Tx Tn	-8.71 -4.14	443.14	0.42	**-16.60**	**-7.23**
	RRII 430	2003-08	Tx Tn	-10.84 -4.73	536.33	0.35	**-17.16**	**-7.53**
Padiyoor	RRII 105	2007-08	Tx Tn	-2.52 -1.47	163.1	0.22	**-11.28**	**-3.86**
	RRII 414	2007-08	Tx Tn	-2.14 -1.51	157.92	0.22	**-9.41**	**-3.42**
	RRII 417	2007-08	Tx Tn	-3.66 -1.94	218.23	0.28	**-13.49**	**-4.47**
	RRII 422	2007-08	Tx Tn	-1.62 -0.95	124.77	0.13	**-6.91**	**-2.37**
	RRII 429	2007-08	Tx Tn	-1.89 -0.72	122.03	0.22	**-7.51**	**-2.21**
	RRII 430	2007-08	Tx Tn	-3.11 -4.02	250.3	0.22	**-18.38**	**-7.80**
	RRII 600	2007-08	Tx Tn	-2.84 -1.38	160.74	0.38	**-14.93**	**-4.80**
Dapchari	RRIM 600	2006-09	Tx Tn	-1.01 -5.51	204.98	0.5	**-11.25**	**-4.69**

Table 4.8. Percentage change in NR productivity (on a per tree per day basis) in Tura for one degree Celsius rise in Tmax and Tmin and predicted yield for the next 10 years with the current warming trends.

Station	Clones	Data period	Parameter	MLR			% Change (for 1 °C rise)	% Change (for next 10 years)
				Coeff.	Intercept	R^2		
Tura	GL1	2000-08	Tx	3.56	-26.02	0.39	**2.51**	**12.57**
			Tn	-2.77				
	GT1	2000-08	Tx	3.95	-34.53	0.35	**3.44**	**13.15**
			Tn	-2.76				
	PB 235	2000-08	Tx	4.59	-37.33	0.33	**3.17**	**12.46**
			Tn	-3.25				
	PB 260	2000-08	Tx	3.39	-24.65	0.27	**2.83**	**11.6**
			Tn	-2.45				
	PB 310	2000-08	Tx	3.62	-25.42	0.32	**2.90**	**10.92**
			Tn	-2.51				
	PB 311	2000-08	Tx	5.16	-48.64	0.33	**3.98**	**12.98**
			Tn	-3.29				
	PB 5/51	2000-08	Tx	3.22	-26.49	0.25	**3.35**	**12.06**
			Tn	-2.18				
	PB 86	2000-08	Tx	3.06	-18.59	0.30	**2.45**	**10.49**
			Tn	-2.25				
	PR 225	2000-08	Tx	3.72	-36.16	0.30	**4.00**	**14.1**
			Tn	-2.49				
	RRIC 102	2000-08	Tx	3.37	-34.46	0.27	**4.43**	**13.78**
			Tn	-2.08				
	RRIC 105	2000-08	Tx	2.16	-8.23	0.18	**1.97**	**8.74**
			Tn	-1.61				
	RRII 105	2000-08	Tx	4.56	-27.3	0.40	**1.81**	**11.74**
			Tn	-3.8				
	RRII 118	2000-08	Tx	3.12	-20.65	0.25	**2.83**	**10.43**
			Tn	-2.14				
	RRII 203	2000-08	Tx	3.9	-25.77	0.30	**2.8**	**10.5**
			Tn	-2.7				
	RRII 208	2000-08	Tx	2.42	-0.97	0.22	**1.39**	**7.07**
			Tn	-1.89				
	RRII 5	2000-08	Tx	2.56	-9.53	0.23	**1.90**	**8.78**
			Tn	-1.94				
	RRIM 600	2000-08	Tx	4.06	-11.67	0.40	**1.18**	**8.99**
			Tn	-3.49				
	RRIM 605	2000-08	Tx	3.56	-32.59	0.32	**3.67**	**13.52**
			Tn	-2.44				

Table 4.9. Percentage change in NR productivity (on a per tree per day basis) in Agarthala for one degree Celsius rise in Tmax and Tmin and predicted yield for the next 10 years with the current warming trends.

Station	Clones	Data period	Parameter	MLR Coeff.	MLR Intercept	R^2	% Change (for 1 °C rise)	% Change (for next 10 years)
Agarthala	RRII 105	2003-08	Tmax	0.18	58.17	0.13	-3.18	-1.74
			Tmin	-1.35				
	RRII 414	2003-08	Tmax	0.77	23.9	0.03	0.18	-0.60
			Tmin	-0.71				
	RRII 417	2003-08	Tmax	0.64	54.27	0.19	-2.61	-1.78
			Tmin	-1.69				
	RRII 422	2003-08	Tmax	1.33	25.55	0.03	0.71	-0.50
			Tmin	-1.00				
	RRII 429	2003-08	Tmax	0.87	27.03	0.01	0.88	-0.15
			Tmin	-0.48				
	RRII 430	2003-08	Tmax	0.41	61.06	0.22	-3.59	-2.12
			Tmin	-1.78				
	RRIM 600	2003-08	Tmax	0.49	38.73	0.10	-1.25	-1.04
			Tmin	-0.93				

Results of the regression models developed for each clone indicate that for a unit (concomitant) increase in Tmax and Tmin, yield per tree per day was decreased by roughly 15 to 17% in Kottayam, 7 to 18% in Padiyoor and 11% in Dapchari. Using the estimated Tmax and Tmin for the next 10 years, I estimated what might be the yield per tree per day by the year 2020. In the next 10 years, i.e. by the year 2020, about 7% reduction in yield per tree per day could be expected in Kottayam, irrespective of the clones from the 2010 base year. In Padiyoor this loss will be in the range of 2 to 6% and in Dapchari this will be about 5% in the next 10 years. There were no appreciable differences in the extent of loss in yield per tree per day as climate warmed based on the present results. This may be because there are no clonal differences in their relative yield responses to climate warming or because the data used in the present analyses is not robust enough to catch this difference. In the two NE regions also, clonal variations were not large, but climate warming seems to have little impact on yield in Agarthala and considerable stimulatory effect in Tura in all clones. Similar results were obtained when all clones were pooled together and analyzed in these two stations.

Studies on physiological evaluation of young polybag plants indicated that clones like RRII 430, 429 and RRIM 600 had better intrinsic drought tolerance traits based on photosynthetic assimilation rates, stomatal conductance and quantum yield of photosystems (Sumesh et al. 2011; Thomas et al., 2012). But these clonal differences do not seem to translate into differences in their response to climate warming according to the results of the present study. Even as deficiencies in the present analyses could be a reason for not able to catch clonal variations in their response to climate warming in terms of yield performance, it is also likely that the intrinsic drought tolerance traits may not be associated with yield response at high temperature. Better tolerance to drought in some clones may help these clones to survive an extreme event like severe drought and also perhaps the high temperature prevailing at that time and thus help in early crop establishment. But this need not always lead to improved yield performance at a higher temperature on a later date. Availability of sugars and the capacity for rubber biosynthesis are the two factors that will have a direct and immediate bearing on yield. How far these physiological processes in different clones are sensitive to climate warming needs to be studied. Survival of the rubber plant (clone) and rubber yield may not show the same response to climate warming in every clone. However, an ideal climate-resilient clone should have better intrinsic traits for survival as well as an active rubber biosynthesis machinery that can tolerate adverse climate.

4.6.4. Approach 3: Regression analysis of commercial yield (per hectare, per month) with climate parameters

Monthly data for two years (2008 and 2009) on commercial yield (Kg/ha/month) estimated from yield data from a large number of growers from three different rubber growing regions of Kerala were used in this analysis. These regions were Kottayam and Kanjirapally (in Kottayam district) and Thaliparamba (in Kannur district) in northern Kerala. The corresponding monthly mean climate data from the same region were used to do MLR analysis and the models were as follows.

$Y = 999.53 - 6.14\ Tmax - 27.68\ Tmin$ for Kottayam Eqn. (7)

$Y = 789.36 - 11.33\ Tmax - 12.68\ Tmin$ for Kanjirapally Eqn. (8)

$Y = 281.91 + 4.13\ Tmax - 11.26\ Tmin$ for Thaliparamba Eqn. (9)

In these models also only Tmax and Tmin were present suggesting that these two climate variables have the maximum impact on yield per ha per month. In Kottayam and Kanjirapally regions, both Tmax and tmin had a negative impact on yield per ha per month. However, in Thaliparamba Tmax showed a positive impact and Tmin showed a negative impact on yield per ha per month. These MLR models were made using monthly mean values of the Y and

X variables for the whole year for several years. The reduction in yield per ha per month (for 1 °C rise in both maximum and minimum temperatures) was 18.83, 15.06 and 4.15% for Kottayam, Kanjirapally and Thaliparamba, respectively. These results were comparable with the results obtained from the respective regions when yield per tree per day was used as the dependent variable (Table 4.10).

Table 4.10. Percentage change in the future productivity of rubber (on a per ha per year basis) for one degree rise in temperature

Region	Data period	Parameter	MLR			% Change (for 1 °C rise)	Estimated productivity from MLR model (kg ha^{-1})
			Coeff.	Intercept	R^2		
Kottayam	2008-09	Tmax	-6.14	999.53	0.24	**-18.83**	**2155**
		Tmin	-27.68				
Thaliparamba	2008-09	Tmax	4.13	281.91	0.24	**-4.15**	**2062**
		Tmin	-11.26				
Kanjirapally	2008-09	Tmax	-11.33	798.36	0.25	**-15.06**	**1913**
		Tmin	-12.68				

Climate has warmed in the traditional and non- traditional rubber growing tracts of India and that this will have qualitatively and quantitatively different impacts on NR productivity. Regions other than NE India are going to be relatively more affected by the adverse effect of climate warming than NE India (Table 4.6) where warming conditions may increase productivity even as the prevailing cold conditions may be a limiting factor at present. Rise in temperature, especially in minimum temperature would have a positive impact on NR cultivation in NE India. Extrapolating the present warming trends, the MLR models clearly indicate that NR productivity will be relatively more affected in Kerala than any other NR growing regions in the next one decade, although absolute productivity may still remain high in this region. However, NR productivity may see an improvement in NE in the coming decade as the region continues to get warmer.

4.7. Conclusion

Results given in this chapter categorically prove that as climate warms, rubber yield will decline in the traditional rubber growing regions. Because, both Tmax and Tmin had a negative impact on rubber yield. However in the NE, climate warming can improve rubber yield, because Tmax had a positive impact on rubber yield there. Thus climate warming has different effects in different agro-climatic regions (Satheesh and Jacob, 2011) and this appears to follow the law of limiting factors. It is generally considered that the severe winter condition is a limiting factor for growth and productivity of rubber in the NE (Jacob et al., 1999) and therefore, a warming trend (at least to some small extent) may only improve rubber yield in this region. Additionally, more areas in NE may become congenial for rubber cultivation if the present warming trend continues. Using a modified ecological niche modelling approach (Debabrata Ray, Scientist at RRII, personal communication) it has been shown that if the present warming trend continues in the NE as indicated in the IPCC reports (IPCC, 2007b), more areas may indeed become cultivable for rubber by 2050 AD (Ziegler et al., 2009).

In Kerala and the Konkan regions, the prevailing temperatures are already at the higher side of the temperature threshold for rubber cultivation (Jacob et al., 1999) and therefore any further warming can become harmful in these regions. This is what the models developed in the present study also reveal. Both Tmax and Tmin have a negative impact on yield per tree in Kerala and the Konkan region. Thus it appears that NE India may hold better prospects for growing rubber in future than Kerala and the Konkan regions, if the current warming trends continue. Presently, government of India is giving special focus on expanding rubber cultivation in the NE as compared to other regions such as the Konkan and the results of this thesis indicate that this is a wise step.

The results of my analyses of how climate warming is happening in Kerala and what is in store for future paint a rather bleak picture for Kerala, especially the erstwhile Travancore region which is the bastion of rubber cultivation in the country. Kottayam has registered markedly higher rates of warming, both in Tmax and Tmin compared to the rest of the rubber growing regions. These warming trends had a greater inhibitory effect on rubber yield in Kottayam (representing the erstwhile Travancore region) than Malabar or the Konkan regions.

According to the models, rising temperatures should decrease yield in the traditional regions which produced almost the entire rubber in the past. Even today, NE contributes only a small per cent (less than 4.0%) of the total rubber produced in the country (Indian Rubber statistics, 2012). Historical climate data clearly show that temperature did in fact go up in the traditional rubber growing regions in the last decades. This means, over the years productivity should have gone down. On the contrary, productivity did go up and not down in the recent decades. This is because more areas came under high yielding clones, especially RRII 105 which contributed to higher yields for the periods covered under this study. During the 1980s, there has been large scale planting in Kerala with clone RRII 105 which was on an average close to 20 to 25, 000 ha per year. RRII 105 has been one of the highest yielding clones anywhere in the world. As a large share of yielding plantations came under RRII 105, NR productivity also increased over the years masking the actual impact of climate warming on productivity.

Also, improved agro-management practices followed by the growers should have given better yields, masking any adverse impact of climate warming. Some estates have resorted to tapping much early in the morning when the ambient temperature is low and this has also resulted in increasing the yield (personal communication from Harrison Malayalam Ltd.). In this context, it may be noted that in 2012 year, as many as close to 20% of the small growers from central Kerala resorted to giving lifesaving irrigation at least once to their newly planted rubber during the first year (RRII-unpublished) which was something that was unheard of a decade ago. Thus growers have been adapting to climate warming in recent years.

If large scale adoption of RRII 105 had not happened and the area under this high yielding clone had not increased, there was every possibility that NR productivity would have gone down over the years as a result of climate warming that has already happened in the traditional areas. According to the MLR models, NR productivity must have come down in the recent decades owing to climate warming. In fact this did actually happen. During the late 1970s and early 1980s, the mean productivity of RRII 105 under the best management practices of RRII research farms located in the traditional regions have been in the range of 60-65 g t^{-1} t^{-1} , but of late this is mostly in the range of 50-55 g t^{-1} t^{-1} or even less (RRII Annual Report, 1986-1987 and 2008-2009). Since the genetics (clone) was the same and the management practices were as constant (as can be expected as the trials were in RRII's own experimental farms where management practices did not undergo any substantial changes over the years), the most convincing reason for this reduction in productivity seems to be the appreciable temperature warming that has happened in the traditional regions farms during this period. There might have been other factors too, such as likely deterioration in soil productivity or other unknown factors, but the high rate of rise in both maximum and minimum temperature strongly indicates the significant role these parameters would have played in reducing productivity in the past.

My analyses (Figure 4.6) indicate that had there been no climate warming and if the current clone composition and agro-management practices were existing in the past, the potential productivity of rubber would have been much higher than what was actually achieved.

Because, temperatures were more congenial in the past than today for better rubber yields. Over the years, due to reasons explained above, rubber productivity did increase overcoming the inhibitory effects of climate warming (Figure 4.6). The extrapolated trend of current growth in rubber productivity as shown in figure 4.6 can be misleading, because, according to my estimate, which is based on temperature sensitivity of rubber yield and projected future temperature based on the current warming rates (based on data from Kottayam), rubber productivity will take a big beating in the years to come. My results also clearly indicate that warming-induced loss of yield will be the highest in the erstwhile Travancore region of Kerala which has perhaps close to half of the yielding rubber plantations in the country and hence this will make a major dent not only in productivity, but also in total amount of rubber produced in the country in the near future. This can make the estimated deficit of rubber produced in the country even bigger. However, my results also suggest that this can be averted to some extent by more rubber being produced from NE, because climate warming may not decrease rubber yield in this part of the country. Therefore, improving the present productivity and area under rubber in NE assumes importance. Exploring possibilities of cultivating other sources of NR such as Guayule that grows in hot arid regions become relevant here.

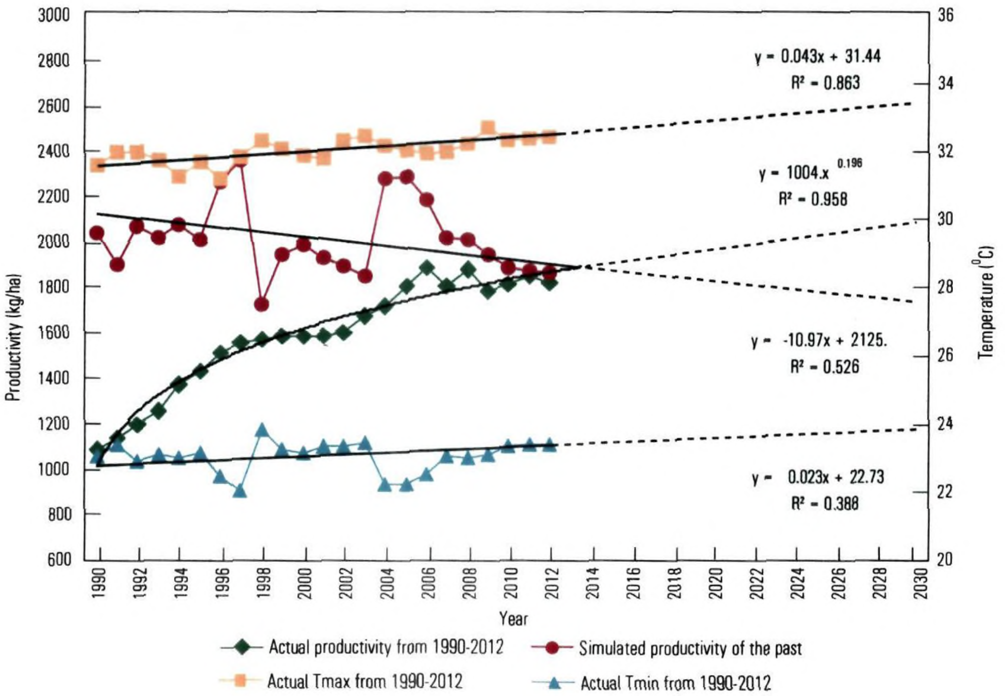


Figure 4.6. Future of natural rubber productivity in a warming climate. simulated temperature and productivity are given in dashed lines). Future will be less than expected growth due to climate warming.

Over the years, it might have been true for other crops also, that but for the adoption of high yielding varieties and improved agronomy, their productivity would have gone down due to climate warming. Climate change will restrict realizing the full potential of high yielding clones and varieties in farmer's fields in future. This points to the need to evolve cultivars and clones that are climate-resilient. From the present study, it cannot be categorically stated that any particular clone had better yield performance in a future warmer world.

The present results clearly indicate how maximum and minimum temperatures have been increasing in the past, how this has adversely affected productivity in the past and what rising temperatures might do to rubber productivity in future in different agro-climatic regions of India where this crop is cultivated today. Climate change is obviously much more complex than daily variations in weather parameters such as daily maximum or minimum temperature. Changes in cloud formation, wind, rainfall pattern, occurrence of extreme weather events like storms, floods, long dry spells, unexpected breaks in monsoon, spread of new and pests and diseases etc. are important factors that can seriously influence rubber yield.

Climate has warmed in the traditional and non- traditional rubber growing tracts of India and that this will have qualitatively and quantitatively different impacts on NR productivity in different parts of the country. Regions other than NE India are going to be relatively more affected by the adverse effect of climate warming (Table 4.6). But in NE, warming conditions may increase productivity even as the prevailing cold conditions may be a limiting factor at present. Rise in temperature, especially in maximum temperature would have a positive impact on NR cultivation in NE India. Extrapolating the present warming trends, the MLR models clearly indicate that NR productivity will be relatively more affected in Kerala than any other NR growing regions in the next one decade, although absolute productivity may still remain high in this region. However, NR productivity may see an improvement in NE in the coming decade as the region continues to get warmer.

4.8. References

Achanta, A. N. (1993). An assessment of the potential impact of global warming on Indian rice production. In: A. N. Achanta, ed., The Climate Change Agenda: An Indian Perspective. New Delhi: Tata Energy Research Institute.

Acock, B. and Allen, L.H. (1985). Crop responses to elevated carbon dioxide concentrations. In: B.R. Strain and J.D. Cure (eds). Direct Effects of Increasing Carbon Dioxide on Vegetation. DOE/ER-0238. U.S. Department of Energy. Washington DC. pp 53-97.

Aggarwal, P. K. (2003). Impact of climate change on Indian agriculture. Journal of Plant Biology. 30(2): 189–198.

Aggarwal, P. K. and Sinha, S. K. (1993). Effect of probable increase in carbon dioxide and temperature on productivity of wheat in India. Journal of Agricultural Meteorology 48 (5): 811–814.

Akossou, A.Y.J., Godui, A. and Fonton, N.H. (2012). Effect of climate factors on the radial growth of Teak (Tectona grandis L.F.) in Parakou and Tchaourou Districts in Northern Benin. Journal of Agricutural Science and Technology. B2: 721-730.

Allen, L.H. Jr., K.J. Boote, J.W. Jones, P.H. Jones, R.R. Valle, B. Acock, H.H. Rogers, and R.C. Dahlman. 1987. "Response of Vegetation to Rising Carbon Dioxide: Photosynthesis, Biomass, and Seed Yield of Soybean." Global Biogeochemical Cycles.1:1–14.

Aravindan. (2006). Short supply seen lasting in rubber till 2020. Business Line print edition dated December 20, 2006.

Baker, J.T., Allen, L.H., Boote, K.J., Jones, P. and Jones. J.W. (1989). Response of soybean to air temperature and carbon dioxide concentration. Crop Science. 29: 98-105.

Boomiraj, K., Chakrabarti, B., Aggarwal, P.K., Choudhary, R. and Chander, S. (2010). Assessing the vulnerability of Indian mustard to climate change. Agriculture, Ecosystems & Environment. 138(3-4): 265-273.

Chandrasekhar, T.R., Jana, M.K., Thomas, J., Vijayakumar, K.R. and Sethuraj, M.R. (1990). Seasonal changes in physiological characteristics and yield in newly opened trees of Hevea brasiliensis in North Konkan. Indian Journal of Natural Rubber Research. 3: 88-97.

Chatterjee, A. (1998). Simulating the impact of increase in temperature and CO_2 on growth and yield of maize and sorghum. M.Sc. Thesis, Indian Agricultural Research Institute, New Delhi.

Coakley, S. M., Scherm, H., and Chakraborty, S. (1999). Climate change and plant disease management. Annual Review of Phytopathology. 37:399-426.

Cure, J.D. and B. Acock. 1986. "Crop Responses to Carbon Dioxide Doubling: A Literature Survey." Agriculture and Forest Meteorology. 38: 127–145 .

Cynthia, R., Ana Iglesias, X.B. Yang, Paul R. Epstein, and Eric Chivian. (2001). Climate change and extreme weather events: Implications for food production, plant, and pests. Global Change & Human Health. 2 (2): 90-104.

Cynthia, R., Ana, I., Yang, X.B., Epstein, P.R. and Chivian, E. (2000). Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases, and Pests. Published by: Centre for health and the global Environment. Harvard Medical School, 260 Longwood Avenue, Room 262A, Boston, MA 02115.

Dai, A. (2013). Increasing drought under global warming in observations and models. Nature Climate Change. 3: 52–58. doi:10.1038/nclimate1633.

DES India. (2012). Agricultural Statistics at a Glance 2012. Directorate of Economics and Statistics, Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India.

DES Kerala. (2012). Gross Domestic Product of Kerala And India from 2004-05 to 2011-12. Directorate of Economics and Statistics, Thiruvananthapuram, Government of India.

Drake, B.G., Gonzalez-Meler, M.A. and Long, S.P. (1997). More efficient plants: a consequence of rising atmospheric CO2?. Annual Review of Plant Physiology and Plant Molecular Biology. 48: 609–639.

Gadgil, S., Abrol, Y. P. and Rao, Seshagiri, P. R. (1999). On growth and fluctuation of Indian food grain production. Current Science. 76(4): 548–556.

Gangadhar Rao, D. and Sinha, S. K. (1994). Impact of climate change on simulated wheat production in India, In: C. Rosenzweig and I. Iglesias (eds.). Implications of climate change for international agriculture: Crop modelling study. USEPA230-B-94-003. USEPA, Washigton, DC. pp. 1–17.

Gangadhar Rao, D., Katyal, J. C., Sinha, S. K. and Srinivas, K. (1995). Impacts of climate change on sorghum productivity in: India: Simulation study, American Society of Agronomy, 677 S. Segoe Rd., Madison, WI 53711, USA, Climate Change and Agriculture: Analysis of Potential International Impacts. ASA Spacial Publ. No. 59. pp. 325–337.

George, P.J. and Jacob, C.K. (2000). Natural Rubber. Published by Rubber Research Institute of India, Kottayam, Kerala, India. ISBN 81-87439-009.

Gleadow ,R.M., Evans, J.R., Mc Caffrey,S. and Cavagnaro,T.R. (2009). Growth and nutritive value of cassava (Manihot esculenta Cranz.) are reduced when grown at elevated CO_2. Plant Biology. 11(Suppl. 1): 76–82.

Gleadow, R.M. (2010). Food security in a warming world. Australasian Science. Jan/Feb 2010: 33-35.

Halpert, M.S., and Ropelewski, C.F. (1992). Surface temperature patterns associated with the Southern Oscillation. Journal of climate. 5: 577-593.

Indian Rubber Statistics, (2012). Compiled by: The Statistics & Planning Department. The Rubber Board, Kerala, Ministry of Commerce & Industry, Govt. of India. 34: 7-8.

International Food Policy Research Institute (2007). Climate change impact on food security in Sub-Saharan Africa: Insights from comprehensive climate change scenarios. Ringler. C., Zhu, T., Cai, X., Coo, J. and Wang, D. (Eds.). Cambridge and New York, Cambridge University Press.

IPCC Foutrh Assessment Report (AR4), (2007a). Climate Change 2007: Impacts Adaptation and

Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC Foutrh Assessment Report (AR4), (2007b). Climate Change 2007: The Physical Science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.).Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (1995). Climate Change 1995: The Science of Climate Change, Chapter 2. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York .

IRSG, (2012). Rubber Statistical Bulletin, April-June 2012. International Rubber Study Group, 111 North Bridge Road #23-06 Peninsula Plaza, Singapore 179098.

IRSG, (2013). Rubber Statistical Bulletin, April-June 2013. International Rubber Study Group, 111 North Bridge Road #23-06 Peninsula Plaza, Singapore 179098.

Jacob, J., Annamalainathan, K., Alam, B., Sathik, M.B.M., Thapliyal, A.P. and Devakumar, A.S. (1999). Physiological constraints for cultivation of Hevea brasiliensis in certain unfavorable agro-climatic regions of India.

Jacob, J., Greitner, C. and Drake, B.G. (1995). Acclimation of photosynthesis in relation to Rubisco and non-structural carbohydrate contents and in situ carboxylase activity in Scirpus olneyi grown at elevated CO_2 in the field. Plant Cell Environment. 18: 875–884.

Jane, S., Pfeifer, R.A., Habeck, M., Randolph1, J.C., Doering, O.C., Johnston. J.J. and Rao, G. (2002). Changes in soybean yields in the midwestern United States as a result of future changes in climate, climate variability, and CO_2 fertilization. Climatic Change. 53: 447–475.

Jerry, K., Tim, H., Andre, D. and Tim, W. (2012). Climate change impacts on crop productivity in Africa and South Asia. Environmental Research Letters. doi:10.1088/1748-9326/7/3/034032. 7 (2012) 034032 (8pp).

Kaiser, H.M., and T. Drennen. (1993). Agricultural Dimensions of Global Climate Change. St. Lucie: St. Lucie Press.

Kang, Y., Khan, S. and Ma, X. (2009). Climate change impacts on crop yield, crop water productivity and food security–A review. Progress in Natural Science, 19(12): 1665-1674.

Keeling, C. D., Whorf, T. P., Wahlen, M., M. and Van der Plicht, J. (1995). Interannual extreames in the rate of rise of atmosphric carbon dioxide since 1980. Nature. 375: 666–670.

Kimball, B. A. (1983). Carbon dioxide and agricultural yield: an assembledge and analysis of 430 prior observations. Agronomy Journal. 75: 779–786.

Kimball, B.A., Mauney, J.R., Nakayama, F.S. and Idos, S.B. (1993). Effects of increasing atmospheric CO_2 on vegetation. Vegetation. 104/105: 65-75.

Kimball, B.A., Pinter, P.J., Garcia, R.L., LaMorte, R.L., Wall, G.W., Hunsaker, D.J., Wechsung, G., Wechsung, F. and Kartschall, T. (1995). Productivity and water use of wheat under free-air CO_2 enrichment. Global Change Biology. 1:429-442.

Kumar, K. K., Kumar, K. R., Ashrit, R. G., Deshpande, N. R. and Hansen, J. W. (2004). Climate impacts on Indian agriculture. International Journal of Climatology. 24(11): 1375–1393. Kumar, S.N. and Aggarwal, P.K.(2013).Climate change and coconut plantations in India: Impacts and potential adaptation gains. Agricultural Systems. 117: issue C. 45-54.

Lal, M., Nozawa, T., Emori, S., Harasawa, H., Takahashi, K., Kimoto, M., Abe-Ouchi, A., Nakajima, T., Takemura, T. and Numaguti, A. (2001). Future climate change: Implications for Indian summer monsoon and its variability. Current Science. 81(9): 1196-1207.

Lal, M., Singh, K. K., Srinivasan, G., Rathore, L. S., Naidu, D. and Tripathi, C. N. (1999). Growth and yield response of soybean in Madhya Pradesh, India to climate variability and change. Agriculture and Forest Meteorology. 93: 53–70.

Lawlor DW. (2002). Limitation to photosynthesis in water stressed leaves: stomata vs. metabolism and the role of ATP. Annals of Botany. 89: 871-885.

Lobell, D.B., Burke, M.B., Tebald,i C., Mastrandrea, M.D., Falcon, W.P. and Naylor, R.L . (2008). Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science. 319: 607-610.

Lobell, D.B., Schlenker, W.S. and Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. Science. 333: 616-620.

Long, S.P. (1991). Modification of the response of photosynthetic productivity to rising temperature by atmospheric CO_2 concentrations: Has its importance been underestimated? Plant Cell and Environment. 14(8):729-739.

Long, S.P., Humphries, S. and Falkowski, P.G. (1994). Photoinhibition of photosynthesis in nature. Annual Review of Plant Physiology and Plant Molecular Biology. 45: 633-662.

Lutze, J.L., Roden, J.S., Holly, C.J., Wolfe, J., Egerton, J.J.G. and Ball, M.C. (1998). Elevated atmospheric [CO2] promotes frost damage in evergreen tree seedlings. Plant, Cell and Environment. 21: 631-635.

Mall, R. K. and Singh, K. K. (2000). Climate variability and wheat yield progress in Punjab using the CERES-wheat and WTGROWS models. Vayu Mandal. 30(3–4): 35–41.

Mall, R. K.,Singh, R., Gupta, A., Srinivasan, G. and Rathore, L. S. (2006). Impact of climate change on indian agriculture: a review. Climatic Change. 78: 445–478.

Maman, N., Lyon, D. J., Mason, S. C., Galusha, T. D. and Higgins, R. (2003). Pearl Millet and Grain Sorghum Yield Response to Water Supply in Nebraska. Agronomy Journal. 95: 1618-1624.

Manton, M.J., Della-marta, P.M., Haylock, M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I. and Yee. D. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961–1998.

International Journal of Climatology. 21: 269–284.

Mavi, H. S. and Tupper, G. J. (2004). Agrometeorology: Principles and Applications of Climate Studies in Agriculture. New York U.S.A., The Haworth Press Inc.

Mingkui, C. and Woodard, F.L. (1998). Dynamic response of terrestrial ecosystem carbon cycling to global climate change. Nature. 393: 249-252.

Mohamed, A., Ben, N., Van, D., and Abdoussallam. S. (2002). Impact of Climate Change on Agricultural Production in the Sahel - Part 1. MethodologicalApproach and Case Study for Millet in Niger. Climate Change. 54(3): 327-48.

Morison, J.I.L. and Gifford, R.M. (1984). Plant growth and water use with limited water supply in high CO_2 concentrations. I. Leaf area, water use and transpiration. Austral. J. Plant Physiology. 11: 361-374.

Murdiyarso, D. (2000). Adaptation to Climatic Variability and Change: Asian Perspectives on *Agriculture and Food Security. Environmental Monitoring and Assessment 61(1)*: 123-131.

NOAA. (2011). Human-caused climate change a major factor in more frequent Mediterranean droughts. Available at http://www.noaanews.noaa.gov/ stories2011/20111027_drought.html

Oerke, E.C., Dehne, H.W., Schohnbeck, F. and Weber. A. (1995). Crop Production and Crop Protection: Estimated Losses in Major Food and Cash Crops. Elsevier. Amsterdam and New York. 830 pp.

Parry, M. L., Rosenzweig, C. and Livermore, M. (2005). Climate change, global food supply and risk of hunger. Philosophical Transitions of the Royal Society B (2005). 360: 2125–2138.

Parry, M., Fischer, C., Livermore, M., Rosenzweig, C., and Iglesias, A. (1999). Climate change and world food security: A new assessment. Global Environmental Change. 9: 51–67.

Parthasarathy B. and Pant G. B. (1985). Seasonal relationship between Indian summer monsoon rainfall and southern oscillation. Journal of Climate. 5:369–378.

Pathak, H., Ladha, Aggarwal, P. K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S. K., Mishra, B., Sastri, A. S. R. A. S., Aggarwal, H. P., Das, D. K. and Gupta, R. K. (2003). Trends of climatic potential and on-farm yields of rice and wheat in the Indo-Gangetic Plains. Field Crops Research. 80: 223–234.

Patterson, D.T. (1993). Implications of global climate change for impact of weeds, insects, and plant diseases. In: International Crop Science I. Crop Science Society of America. Madison, WI.

Paulsen, G.M. (1994). High temperature responses of crop plants. In: K.J. Boote, J.M. Bennett, T.R. Sinclair, and G.M. Paulsen (Eds.). Physiology and Determination of Crop Yield. American Society of Agronomy. Madison, WI. pp. 365-389.

Poorter, H. and Navas, M.L. (2003). Plant growth and competition at elevated CO_2: on winners, losers and functional groups. New Phytology. 157: 175-198.

Ranade, P.S. (2009). Impact of climate change on agriculture. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 183-185.

Rao, G.S.L.H.V.P., Ram Mohan, H.S., Gopakumar, C.S and Krishnakumar, K.N. (2008). Climate Change and cropping systems over Kerala in the humid tropics. Journal of Agrometeorology. Special issue – Part 2: 286-291.

Rao, G.S.L.H.V.P., Rao, A.V.R.K., Krishnakumar, K.N. and Gopakumar C.S. (2009). Impact of climate change on food and plantation crops in the humid tropics of India. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 127-130.

Rao, G.S.L.H.V.P., Rao, A.V.R.K., Krishnakumar, K.N. and Gopakumar C.S. (2009). Impact of climate change on food and plantation crops in the humid tropics of India. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 127-130.

Ravindranath, N. H., Sandhya, R., Sharma, N., Nair, M., Gopalakrishnan, R., Rao, A.S., Malaviya, S., Tiwari, R., Sagadevan, A., Munsi, M., Krishna, N. and Bala. G. (2011). Current Science. 101(3): 384-394.

Reddy, D.R., Sreenvias, G. and Pranuthi, G. (2009). Climate change impacts on rice in Andhra Pradesh. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 124-126.

Richard, M. A., Brian, H. H., Stephanie, L. and Neil, L. (1998). Effects of global climate change on agriculture: an interpretative review. Climate Research. 11: 19–30.

Rosenzweig, C. (1985). Potential CO_2-induced climate effects on North American wheat-producing regions. Climatic Change. 4: 239-254.

Rosenzweig, C. and Hillel, D. (1995). Potential Impacts of Climate Change on Agriculture and World Food Supply. Consequences (Summer):24–32.

Rosenzweig, C. and Hillel, D. (1998). Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture. Oxford University Press. New York. 324 pp.

Rosenzweig, C., and Liverman, D. (1992). Predicted effects of climate change on agriculture: A comparison of temperate and tropical regions. In: Global climate change: Implications, challenges, and mitigation measures. S. K. Majumdar S.K. (Ed.). 342-61. PA: The Pennsylvania Academy of Sciences.

Rosenzweig, C., and M. L. Parry. (1994). Potential impact of climate change on world food supply. Nature. 367:133- 138.

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R. and Chivian, E. (2000). Implications of Climate Change for U.S. Agriculture: Extreme Weather Events, Plant Diseases, and Pests. Cambridge, Massachusetts: Center for Health and the Global Environment, Harvard Medical School. Cambridge, MA. 56 pp.

Roslyn, G., Tim, C., Cecilia, B., Alan, N. and John, H. (2010). Plant nutrition and nutritional value in a changing climate. Proceedings of the 1st Australian Summer Grains Conference, Gold Coast, Australia, 21st – 24th June 2010.

Rubber Asia. Nov-Dec 2013 Japan tops in per capita rubber consumption Nov-Dec 2013

Sage, R.F. (1995). Was low atmosphere CO_2 during the Pleistocene a limiting factor for the origin of agriculture? Global Change Biology. 1: 93-106.

Saseendran, A. S., K., Singh, K. K., Rathore, L. S., Singh, S. V. and Sinha, S. K. (2000). Effects of climate change on rice production in the tropical humid climate of Karala, India. Climatic Change. 44: 495–514.

Saseendran, S. A., Ma, L., Malone, R. W., Heilman, P., Ahuja, L.R., Kanwar, R.S., Karlen, D.L. and Hoogenboom, G. (2007). Simulating management effects on crop production, tile drainage, and water quality using RZWQM-DSSAT. Geoderma. 140: 297–309.

Satheesh, P.R. and Jacob, J. (2011). Impact of climate warming on natural rubber productivity in different agro-climatic regions of India. Natural Rubber Research. 24 (1): 1-9.

Schiermeier, Q. (2010). The real holes in climate science. Nature. 463: 284-287. Singh, J.P. and Lal, S.S. (2009). Climate change and potato production in India. Proceedings: Impact of Climate Change on Agriculture. ISPRS Archives XXXVIII-8/W3. 115-117.

Sinha, S. K. and Swaminathan, M. S. (1991). Deforestation, Climate Change and Sustainable Nutrition Security: A Case Study of India. Climate Change. 19: 201-209.

Srivani, O., Geethalakshmi, V., Jagannathan, R., Bhuvaneswari, K and Guruswamy, L. (2007). Impact of future climate change on growth and productivity of rice crop in Tamil Nadu. Asian Journal of Agricultural Research. 1(3): 119-124.

Sumesh, K.V., Satheesh, P.R., Annamalainathan, K., Krishnakumar, R and Jacob, J. (2011). Physiological evaluation of a few modern clones for intrinsic drought tolerance. Natural Rubber Research. 24(1): 61-67.

Sutherst, R.W. (1990). Impact of climate change on pests and diseases in Australasia. Search. 21:230-232.

Taub, D., Miller, B. and Allen, H. (2008). Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. Global Change Biology. 14: 565-575.

Thomas, M., Sathik, M.B.M., Luke, L.P., Sumesh, K.V., Satheesh, P.R., Annamalainathan, K. & James Jacob. (2012). Stress responsive transcripts and their association with drought tolerance in Hevea brasiliensis. Journal of Plantation Crops, 2012, 40(3): 180-187

Tonkaz, T., Dogan, E. and Kocyigit, R. (2010). Impact of temperature change and elevated carbon dioxide on winter wheat (Triticum aestivum L.) Grown under semi-arid conditions. Bulgarian Journal of Agricultural Science. 16 (5): 565-575.

Tuchman, N. C., Wetzel, R. G., Rier, S. T., Wahtera, K. A. and Teeri, J. A. (2002). Elevated atmospheric CO_2 lowers leaf litter nutritional quality for stream ecosystem food webs. Global Change Biology. 8: 163–170. doi: 10.1046/j.1365-2486.2002.00460.x

Uprety, D. C., Dwivedi, N., Jain, V., Mohan, R., Saxena, Jolly, M. and Paswan, G. (2003). Response of rice cultivars to the elevated CO_2. Biologia Plantarum. 46(1): 35–39.

Van, D.N., Abdoussalam, S. and Ben M.A. (2002). Impact of climate change on agricultural production in the Sahel - Part 2. Case study for groundnut and cowpea in Niger. Climatic Change. 54 (3):349-68. Wall, G.W., Brooks, T.J., Adam, N.R., Cousins, A.B., Kimball, B.A., Pinter ,P.J. Jr., LaMorte, R.L., Triggs, J., Ottman, M.J., Leavitt, S.W., Matthias, A.D., Williams, D.G. and Webber, A.N. (2001). Elevated atmospheric CO_2 improved sorghum plant water status by ameliorating the adverse effects of drought. New Phytologist. 152: 231-248. Schiermeier, Q. (2010). The real holes in climate science. Nature. 463: 284-287.

Went, W. (1953). The Effect of Temperature on Plant Growth. Annual Review of Plant Physiology. 4: 347-362.

Winch, T. (2006). Growing Food: A Guide to Food Production, Springer.

World Bank. (2010). World Bank Annual Report 2010. Available at http://web.worldbank.org

World development indicators data, World Bank. (2012). available at www.worldbank.org.

Ziegler, A.D., Fox J. and Xu. J. (2009). The Rubber Juggernaut. Science. 324: 1024-1025

Ziska L.H., Morris, C.F. and Goins, E.F. (2004). Quantitative and qualitative evaluation of selected wheat varieties released since 1903 to increasing atmospheric carbon dioxide: can yield sensitivity to carbon dioxide be a factor in wheat performance? Global Change Biol. 10: 1810-1819.

Ziska, L.H. and Dukes, J.S. (2011). Weed biology and climate change. Wiley-Blackwell publication. Printed at Malaysia by Vivar printing Sdn Bhd. ISBN: 9780813814179

CHAPTER 5

CO_2 SEQUESTRATION AND EVAPOTRANSPIRATION BY RUBBER PLANTATIONS

"Except during the nine months before he draws his first breath, no man manages his affairs as well as a tree does"

George bernad Shaw

5.1. Objective

Climate change that has happened in the rubber growing regions of India were analyzed and the impact of climate warming on rubber yield was assessed in the last two chapters. Global warming is the result of anthropogenic emission of greenhouse gases such as CO_2. Rubber plantations have remarkable ability to sequester CO_2 from the atmosphere which is an important ecosystem service provided by them. In this chapter the various ecosystem services like CO_2 sequestration and and evapotranspiration provided by rubber plantations are discussed with special reference to their CO_2 sequestration potential. There are different techniques to determine the CO_2 sequestration rate of ecosystems such as biometric method, eddy covariance flux analysis etc. which are attempted in this study. The first eddy covariance flux tower in India was installed in a rubber plantation belonging to the Rubber Research Institute of India in Kerala and the results obtained from this system are presented in this chapter.

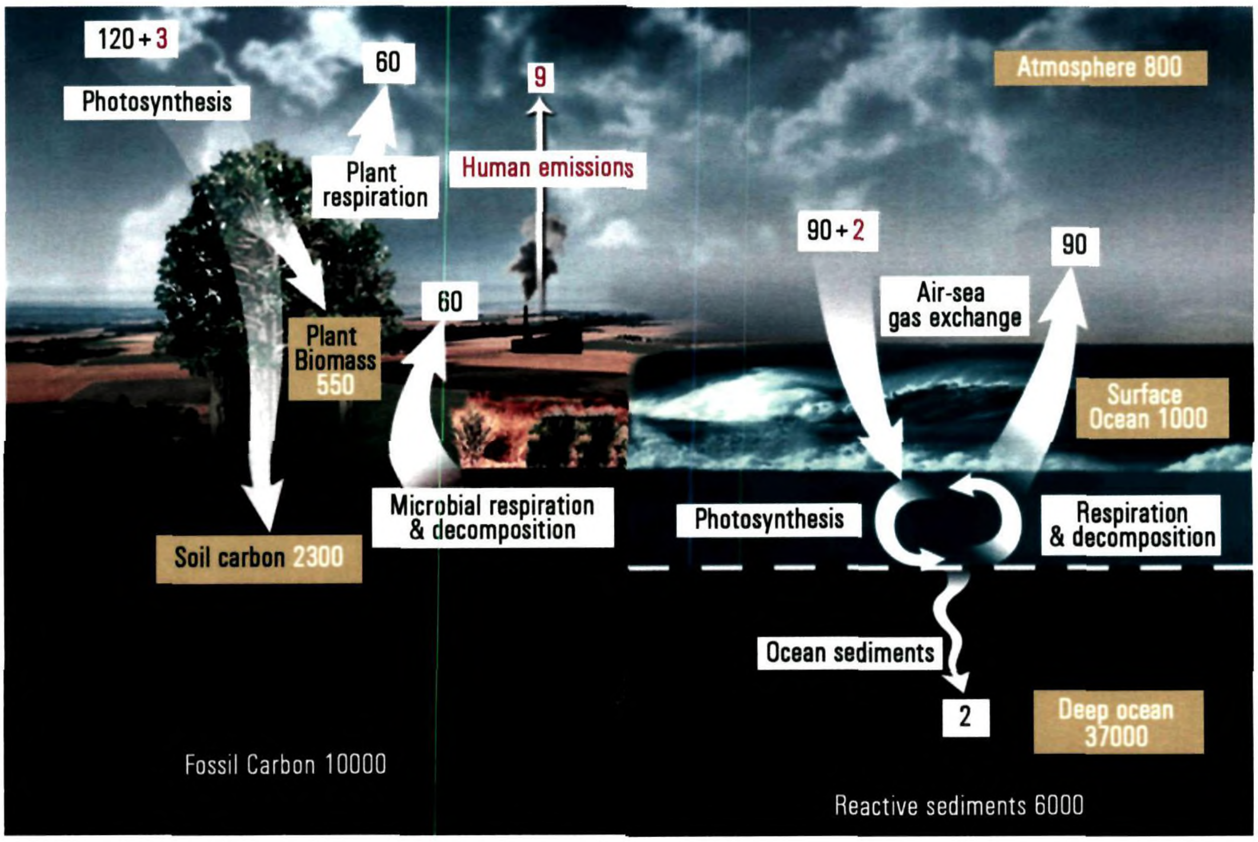
5.2. Review of literature

Managed and natural ecosystems provide numerous services to mankind (Gera and Suresh, 2010; Jacob and Mathew, 2004; Wall and Nielsen, 2012; Munang et al, 2010). They provide food, fuel and fiber. They aid in hydrological cycle, prevent degradation of soils, keep balance of atmospheric gases such as CO_2, O_2 etc. They help in keeping the climate, particularly temperature and rainfall of a region within certain minimal variations etc. In the context of global warming induced by rising concentration of CO_2 in the atmosphere, it is pertinent to examine the capacity of rubber plantations to sequester CO_2 from atmosphere.

5.2.1. Carbon sequestration

In climate change science, the term "carbon sequestration" is generically used to describe both natural and artificial processes by which CO_2 is either removed from the atmosphere or diverted from emission sources and stored in the terrestrial ecosystems, ocean or in geologic formations (Metz et al., 2005; Haszeldine, 2009). Before huge amounts of CO_2 emission started with the advent of industrial revolution, the uptake and release of CO_2 from and to the atmosphere maintained a near balance through natural processes and thus the CO_2 concentration in the atmosphere remained fairly constant at about 280 ppm for several millennia (IPCC, 2007a).

The natural process of CO_2 sequestration include uptake of this gas through photosynthesis by biosphere sinks namely, oceans and the two terrestrial sinks, forests and soils (IPCC, 2007a; Malhi et al., 2001; Grace et al., 1995; Dixon et al., 1994; Batjes, 1996). But today these natural processes are insufficient to offset the human induced emissions and make up the global carbon cycle neutral (Figure 5.1) That is why new technologies and strategies like carbon capture and storage have emerged as a solution to the uncontrolled emission of CO_2 into the atmosphere through human activities.



Source: http://earthobservatory.nasa.gov/Features/CarbonCycle

Figure 5.1. Global carbon cycle shows the movement of carbon between land, atmosphere, and oceans. Green letters are natural fluxes, and red are human contributions in gigatons (Gt) of carbon per year. White numbers indicate stored carbon.

Oceans are the primary long-term biosphere sink for the anthropogenic CO_2 emissions, currently accounting for a global net uptake of about 2 Gt of carbon annually (IPCC, 2007a). This process begins with natural chemical reactions between seawater and CO_2 in the atmosphere. The photosynthetic green plants absorb the dissolved CO_2 and convert it into biomass. In terrestrial carbon sequestration, natural forest ecosystems act as the sinks. Soils are the best carbon sinks in the biosphere because they contain approximately 1,500 Gt of organic carbon, more than the amount in vegetation and the atmosphere together (Batjes, 1996). While avoided deforestation will prevent loss of stored carbon into the atmosphere, afforestation and efficient agricultural practices will sequester much more CO_2 from the atmosphere.

The idea of geologic sequestration begins with capturing CO_2 from the exhausts of fossil fuel power plants and other major industries (IPCC, 2005; IPCC, 2007b; USDoE, 2009; NETL, 2008). The captured CO_2 is piped 1 to 4 kilometers below the land surface and injected into porous rock formations or in deep ocean beds. Compared to the rates of terrestrial carbon storage, geologic sequestration is currently used to store only small amounts of carbon per year. Much larger rates of sequestration are visualized to take advantage of the potential stability and capacity of geologic storage. This idea cropped up because man started emitting more CO_2 than what the planet can sequester from the atmosphere through natural processes. If the current dependence of GDP on CO_2 emission still continues, there is every likelihood that the world will emit much more CO_2 into the atmosphere as the world economy further grows. Natural CO_2 sequestration may not be adequate to keep the concentration of CO_2 in the atmosphere constant as we have been witnessing in recent decades.

5.2.2. Is it possible to stabilize atmospheric CO_2 through carbon sequestration?

U.S. Climate Change Science Programme (CCSP) developed computer models of future CO_2 emissions and stabilization of the present atmospheric CO_2 (see http://www.csrees.usda.gov). These models indicate that projected annual global emissions during the next century would need to be reduced by more than 75 percent in order to stabilize atmospheric CO_2 at about 550 ppm. This concentration would be about twice the level of CO_2 in the pre-industrial atmosphere and about 45 percent higher than the atmospheric CO_2 concentration as in 2007. The CCSP models illustrate that sequestration is necessary but insufficient to stabilize atmospheric CO_2. There is a general consensus that planting trees will help to sequester a significant amount of CO_2 from the atmosphere. But the reality is something different and is discussed in details in the end of this chapter. Stabilizing atmospheric CO_2 is likely to require significant changes in fossil fuel energy sources to renewable energy sources as well as carbon management for a sustainable low carbon growth trajectory.

5.2.3. Carbon sequestration by natural ecosystems

Forest ecosystems make an important contribution to global carbon budget (Aubinet et al., 2000; Dixon et al., 1993; Dixon et al., 1994; Gera et al., 2006; Jagadhish et al., 2009; Sanchez et al., 2009). This is because of their potential to capture and store atmospheric carbon in biomass and soil. Forest ecosystems, especially the Amazon rainforest have a greater role in influencing the global carbon and hydrological cycles. However, today these natural landscapes are being affected by climate change and rapid agricultural development. The tropical land-use changes and deforestation are responsible for 34% of today's anthropogenic greenhouse gas emissions (Denman et. al., 2007). The Brazilian Amazon represents a potentially large future source of greenhouse gases due to deforestation and subsequent agricultural activities. It was estimated that a net emission of 2.8 to 15.9 Pg (petagrams)

CO_2-eq has occurred from the Mato Grosso region of Brazilian Amazon from 2006-2009 (Gillian et al., 2010). Deforestation is the largest source of GHG emissions over this period, but land uses following deforestation account for a substantial proportion of 24-49% of the net GHG budget (Gillian et. al., 2010). Tropical forests, particularly the Amazon, have long been considered a large carbon sink based on their sequestration of atmospheric carbon dioxide. In the case of Mato Grosso region of Brazilian Amazon, some simulation models show that its natural tropical area will continue as a carbon sink, perhaps even enhanced by increased atmospheric CO_2 levels, but due to deforestation in this region, the net carbon budget of the region can become negative.

Generally natural vegetation is a carbon sink and 85% of the carbon sequestration is in natural forest and cerrado ecosystems. Amazon is a net sink for carbon dioxide. It was reported that 500 million hectare of Amazon sequestered 0.56 Pg C yr^{-1} (Grace et.al., 1995). The projections show that Mato Grosso would take up an additional 0.77 PgC (2.82 Pg CO_2-eq) from 2006-2050, if there were no new deforestation (Gillian et. al., 2010). Due to the changes in land cover and land use, the carbon sequestration potential of the natural ecosystem is reduced slightly to 0.65-0.72 Pg C (2.4-2.6 Pg CO_2-eq).

As on 2005 total land area of the earth surface was 13.4x109 hectare (World Resources Institute, http://www.wri.org). In this, forest ecosystems cover more than 4.1×10^9 hectares, equal to 30.5 percent of the total land area and the total cropped area constitutes only a very small fraction. Global carbon stock in the forest vegetation and soils was about 1146 Pg. Within this approximately 37 percent was in low latitudes, 14 percent in mid-latitudes and 49 percent in high latitudes. In 1990 around 1.6±0.4 Pg carbon was emitted into the atmosphere due to deforestation in the low latitudes, whereas the expansion of forest area in the mid and high latitudes sequestered 0.7±0.2 Pg of carbon per year resulting in a a net flux to the atmosphere of 0.9±0.4 Pg of carbon per year (Dixon et al., 1994).

In central Massachusetts, USA the deciduous forests the gross ecosystem production was 11.1 tons of C ha^{-1} yr^{-1}. Here the ecosystem respiration was 7.4 t C ha^{-1} yr^{-1}, so the net sequestration of the forests in central Massachusetts was 3.7±0.7 tons of C ha^{-1} yr^{-1} (Wofsy et. al., 1993).). Forests and woodlands in United Kingdom contain around 150 million tons of carbon. They have the capacity to sequester 4 million tons of carbon (14.68 million t CO_2) from the atmosphere every year. It is an undoubted fact that forests can mitigate atmospheric CO_2 emission. The potential of the forests to store or avoiding emissions may be as much as 60 to 90×10^{15} Gg of Carbon (Dixon et.al., 1993; Winjum et al., 1992; Trexler and Haugen, 1994).

5.2.4. Carbon sequestration by managed ecosystems

Several studies have reported that managed ecosystems including natural rubber can sequester significant amounts of carbon dioxide from the atmosphere (Phani, et al., 2009; Lalrammawia and Paliwal, 2010; Suruchi and Singh, 2002; Gera and Suresh, 2010; Jacob and Mathew, 2004; Wall and Nielsen, 2012; Munang et al, 2010). Published data shows that natural rubber plantation can sequester 139 to 318.7 tons CO_2 per hectare over a life cycle of 27 to 29 years (Yogaratnam, 2008; Yogaratnam, 2010). The presently existing rubber plantation in the world has the capacity to absorb about 90 million plus tons of carbon dioxide per year (Yogaratnam, 2010). A rubber plantation is nearly as effective as a natural forest in consuming carbon dioxide and giving out life sustaining oxygen (Sivakumaran and Tee, 2010). Ambily et al. (2012) have reported that different clones of rubber plants have different biomass and carbon sequestration potential. Among the clones RRII 429 (114 t C ha^{-1}), RRII 414 (106 t C ha^{-1}) and RRII 417 (102 t C ha^{-1}) showed the highest carbon sequestration potential which as reflected in their biomass production. Other clones like RRII 430, RRII 422 and RRII 105 showed a low carbon sequestration potentials of 60, 54 and 57 t C ha^{-1} respectively. In Hainan, China Niggli et al. (2009) estimated the global average sequestration potential of organic croplands to be 0.9 to 2.4 Gt CO_2 per year, which is equivalent to an average sequestration potential of about 200 to 300 kg C per hectare per year for all croplands. High carbon sequestration potential is also reported in grassland soils. The global carbon sequestration potential of pastures with improved management practices was calculated as 0.22 t C ha^{-1} yr^{-1} (Watson et al., 2000).

Chantuma et al. (2005) studied the wood production potential of rubber (clone RRIM 600) in the non-traditional rubber cultivation area of northeastern Thailand. In Nong Khai province of Thailand, the survival percentage in a 15-year old plantation was 90 and the wood volume was 138 m^3 ha^{-1}. In Chachoengsao province, in a 19 year old rubber plantation, the survival was 79 % and wood volume 188 m^3 ha^{-1}. The authors compared these results with figures from the traditional cultivation area in Phuket and Surat Thani in southern Thailand, where plantations were 25 years old. Survival was 78 and 83% and wood volume 256 and 300 m^3 ha^{-1}, respectively (Chantuma et al. 2005). Saengruksawong et al. (2012) estimated the carbon stock in rubber plantation of Phonpisai, Thailand and found that a 20 year old rubber plantation has an average biomass of 80. 57 Mg ha^{-1}. Soil carbon storage of the same aged plantation is about 20.7 Mg ha^{-1}.

Tree species like Amla (*Phyllanthus emblica*), Arjun (*Terminalia arjuna*), , Bahera (*Terminalia bellerica*) , Harar (*Terminalia chebula*), Jamun (*Sysigium cumini*), Neem (*Azadirachta indica*) and Reetha (*Sapindus mukorossi*) had significantly large sequestration potential in the range of 3.05 to 11.01 tons of CO_2 per hectare per year (Gera and Suresh, 2010). Recent study by Hooda et al. (2005) on sequestration potential of tree species planted on farm lands, viz., Poplar, Eucalyptus and Teak have shown the carbon sequestration potential was in the range of 1.42 to 2.85 tons of C ha^{-1} yr^{-1} (5.21 to 10.46 t C ha^{-1} yr^{-1}). The same study has also reported the sequestration potential of orchard species like Mango, Litchi and Citrus to be in the range of 0.20 to 1.70 tons of C ha^{-1} yr^{-1}. In another study carried out on the farm lands of Punjab with Poplar and Eucalyptus species, the capacity for CO_2 sequesteration was 1.42 to 2.54 tons of C ha^{-1} yr^{-1} (Gera et al., 2006). Kraenzel et al., (2003) measured above and below ground biomass and tissue carbon content of 20 year old teak (*Tectona grandis*) trees of four plantations in Panama and estimated the carbon storage potential. They constructed a regression model relating the diameter at the breast height (DBH) and the total stored carbon in teak. From this model they calculated the plantation level average carbon storage as 120 t C ha^{-1}.

5.2.5. Carbon credits and rubber plantations

There are several aspects of the natural rubber cultivation, processing and products manufacturing that qualify for earning carbon credits under clean development mechanism of the Kyoto Protocol (Jacob and Mathew, 2006). One ton of CO_2 that is prevented from being emitted into the atmosphere or removed from the atmosphere is one "carbon credit" or "certified emission reduction" (see http://unfccc.int/kyoto_protocol/items/2830.php). Once it is certified by the Executive Board of the CDM , this can be traded with Annex I countries (which are the developed countries that have legally binding emission reduction targets under the Kyoto Protocol, unlike the developing countries that can earn carbon credits and do not have any legal emission reduction requirements). The Annex I countries can use the credits to offset against their emission reduction targets. Theoretically, CO_2 sequesterdd by rubber planttaions can also earn carbon credits, however the stringet conditions for meeting the "additionality" criterion makes it highly difficult (http://unfccc.int/kyoto_protocol/items/2830.php; Jacob and Mathew, 2006; Jacob and Mathew, 2004; Jacob, 2005).

There are also several other aspects of natural rubber that can reduce CO_2 or other GHG concentration in the atmosphere. Rubber processing effluents are used for biomethenation and thus emission of methane is avoided (Mathew et al., 2006). The primary processing of natural rubber latex removes only the rubber (which is 30-40% in dry weight of the latex) and large quantities of effluents are generated during the processing. These effluents can be taken as an excellent feed material for biomethenation process as they are rich in carbohydrates and proteins which are good sources of methane production (Mathew et al., 2006).

Another significant ecosystem service of natural rubber is that while production of natural rubber results in sequestration of CO_2, use of synthetic rubbers will lead to huge emissions of GHGs into the atmosphere. Synthetic rubbers are produced from petroleum stocks. When natural rubber is used in place of synthetic rubber, there is indirect saving of GHG emission (Benny et al., 2006). For example a saving of emission of 11.98 tons of CO_2 can be achieved through the substitution of one ton of SBR with one ton of NR (Benny et al., 2006). Similarly, rubber seeds are a potential source of rubber seed oil (RSO) which can be converted in to biodiesel through its trans-esterification. Dry rubber seeds contain an average of 40 per cent rubber seed oil (Najku et al., 1996), which can be converted into biodiesel (Veeraputhran et al., 2006). Use of natural rubber modified bitumen will help maintain roads in good shape for longer time and this will indirectly save emissions because of reduced consumption of automobile fuels and this can be substantial (Sadeesh and Viswanathan, 2006).

5.3. Methodology

5.3.1. Experimental site

The experimental site (9^0 26′N and 76^0 48′E) was the Central Experimental Station (CES) of Rubber Research Institute of India (RRII), Chethackal, Pathanamthitta District, Kerala, South India (Figure 5.2). The observation site, an immature (four year old when the observations began that lasted for two years continuously) plantation, with different Hevea clones namely, RRII 105, PB 260, RRII 430 and ten selected ortet clones (Konny and Mundakayam selections) was spread over more than five hectare area with uniform growth. The average height of the trees was 12 m and girth was 40 cm at 150 cm above the bud union of the plant.

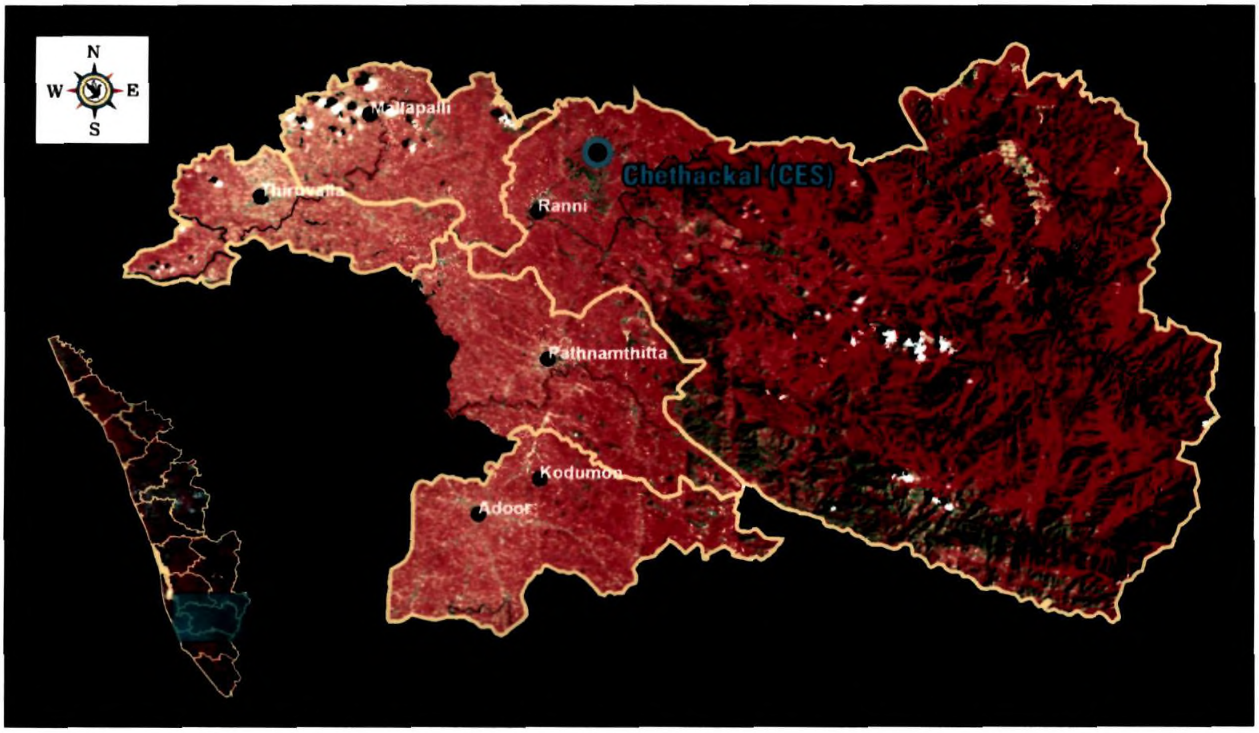


Figure 5.2. Map showing the location of the study area (Central Experiment Station, Chethackal, Pathanamthitta, Kerala located at 9^0 24′ 46.82" N ; 76^0 49′ 58.27" E with an elevation of 420 feet above MSL).

There are several methods to study the CO_2 sequestration potential of a perennial plantation crop like natural rubber. Biomass inventory method is the most easily available and commonly used method which gives an estimate of the total amount of carbon stored in the various components over a period of time (Jacob and Mathew, 2004; Jacob, 2005). Apart from this approach, in the present study another modern method was also employed that would measure (and not estimate) the total amount of CO_2 sequestered by the plantation in real time. This state-of-the-art method known as eddy covariance (EC) technique was used for the CO2 and water flux measurements in rubber plantation. This has been the first such system installed anywhere in India at that time.

5.3.2. Biomass inventory

From the experimental site, 450 rubber trees were selected (surrounding the eddy covariance tower) and the girth of the tree (in centimeters) were measured at a height of 1.5 meters from the bud union of the trees. Girth measurements were carried out every four months since May 2009 for three years. The dry weight of above ground rubber tree biomass was calculated using the Shorrock's regression model (Shorrocks et al., 1965):

Above ground biomass in Kg (W) = $0.002604\ G^{2.7826}$ Eqn. (1)

where, G is trunk girth (cm) at the height of 150 cm from bud union.

Generally the root biomass is 15-20% of shoot biomass in the case of natural rubber plants (Ambily et al., 2012). The amount of carbon stored in the trees was estimated from annual biomass increment of trees based on the carbon content of the biomass (Malhi et al., 2001).

5.3.3. Eddy covariance system (EC system)

The eddy covariance (EC) method is a more sophisticated micro-meteorological method in which the fluxes of CO_2 and water vapour and three-dimensional wind velocities are measured on real time basis (Goulden etal., 1996; Baldocchi, 2003; Aubinet et al., 2000). The flux describes how much of something moves through a unit area per unit time. Flux is dependent mainly on number of things crossing an area, size of an area being crossed and the time it takes to cross this area. In more scientific terms, flux can be defined as an amount of an entity that passes through a closed surface per unit of time. If the net flux is away from the surface, the surface may be called a source and if the opposite is happening, it is called a sink (Burba and Anderson, 2010).

The EC equipment was commissioned on top of a flux tower of 18 m height and the various sensors were fixed on the tower at 3 m above the canopy (Figure 5.3). The EC system comprises of a three dimensional sonic anemometer (CSAT3, Campbell, USA) for detecting wind velocity which is used together with an open path infra red gas analyzer (Li-7500, Li Cor, USA) which measures the concentration of CO_2 and water vapour. Additionally the system is equipped with a net radiometer (NR-Lite, USA) and temperature and relative humidity (RH) sensors (HMP 45, Vaisala) (Figure 5.3). Other weather parameters namely rainfall, maximum and minimum temperatures and sunshine hours. were collected from a nearby weather station at CES, Chethackal. The data was continuously logged in a logger (CR3000, Campbell, USA), which recorded the data from all sensors every 0.1 second and calculated every half hourly average which was used for further processing.

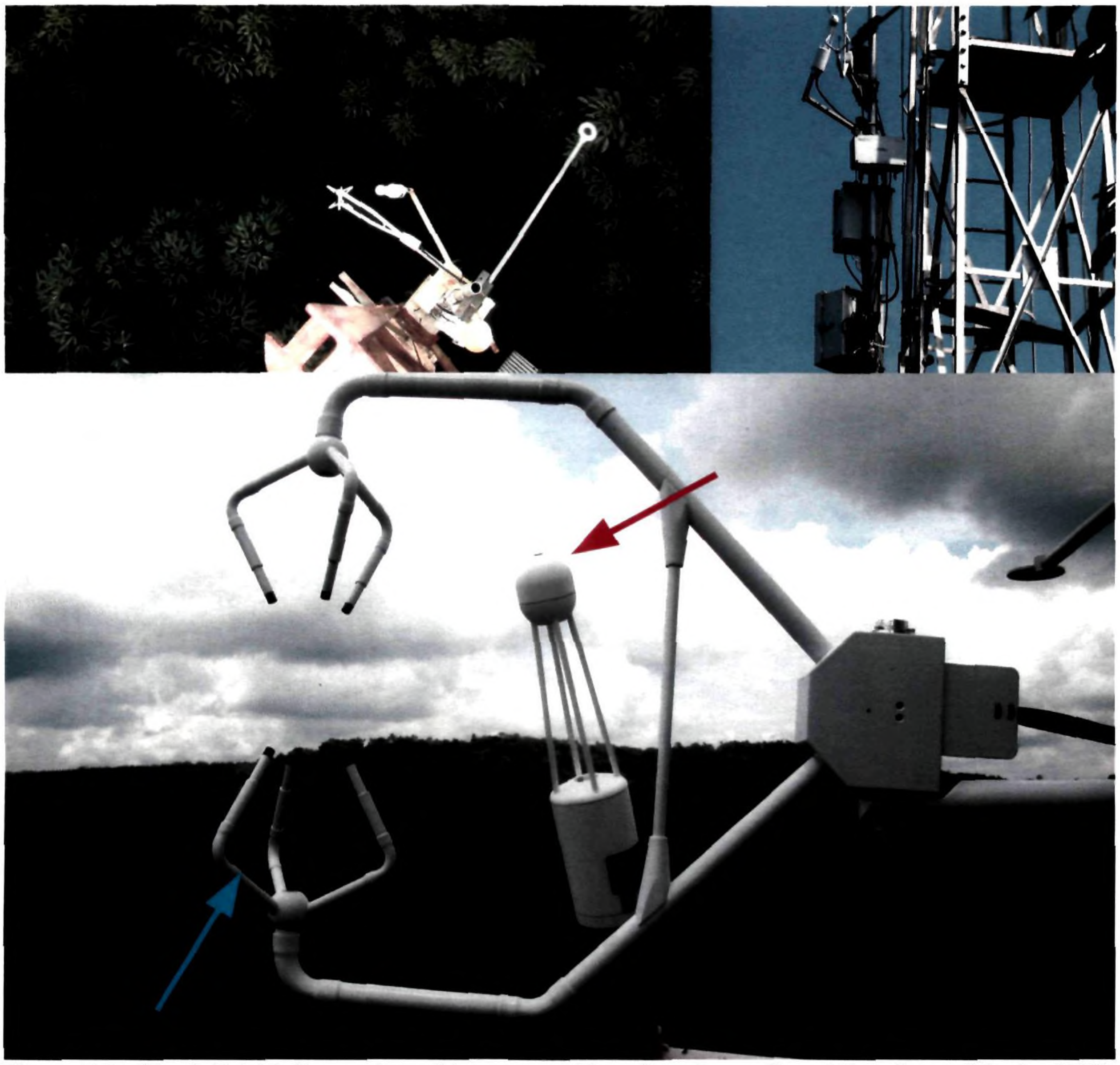


Figure 5.3. (Top left) A bird's eye view of the young rubber plantation at Central Experimental Station (CES), Rubber Research Institute of India, Kottayam, Kerala State, India. (top right) An eddy covariance system installed on a 18 meter tower inside the rubber plantation. (Bottom) Blue arrow: Campbell's three dimensional sonic anemometer (CSAT3) and red arrow: Li COR open path infra red gas analyzer (Li 7500).

5.3.3.1 Data processing and calculation of Eddy covariance fluxes

Carbon dioxide (*Fc*) and water vapour fluxes (*LE*) of the plantation were continuously measured by eddy covariance technique. There are several parameters necessitating correction of measured signals (Massman, 2002). Detrending was done by removing the linear trend of the raw data. Records outside the three standard deviation were replaced with the average of adjacent values. The planar fit method (Wilczak et al., 2001) was also used for the coordinate rotation, but no significant difference was found from the original data. The CO_2 flux (*Fc*) and the water vapour flux (*LE*) data were corrected for air-density effects through the Webb, Pearman, and Leuning (WPL) correction (Webb et al., 1980) and the planar fit corrections have been done for averaging the mean vertical wind by using Edi Re software. Daily diurnal *NEE* and day and night flux rates were also calculated. The latent heat of vapourization (*LE*) was converted in to evapo transpiration (*ET*) on per day basis.

The vertical turbulent fluxes Fc were calculated as the half-hourly covariance of the vertical wind speed and the CO_2 concentration (eqn. 2).

$$Fc = (\rho_a/M_a).\overline{w'.c'} \quad (\mu\text{mol m}^{-1}\text{ s}^{-1}) \qquad \text{Eqn. (2)}$$

were *Fc* is the CO_2 flux (mol m^{-2} s^{-1}), ρ_a is the air density (Kg m^{-3}), M_a is the molecular weight of air (Kg mol^{-1}), *w* is the wind speed (m s^{-1}) and *c* is the atmospheric CO_2 concentration (mol mol^{-1}). Overbars denote time averages, and primed quantities are the instantaneous deviations from their respective time average. The uptake of CO_2 by the vegetation causes a downward CO_2 flux, namely a flux from the atmosphere to the vegetation. Respiration causes an upward CO_2 flux during the day and during the night. The net CO_2 flux or net ecosystem exchange of CO_2 (*NEE*) is the sum of both processes. Within the canopy, a part of the respiration CO_2 is reassimilated. This recycling of the CO_2 is not measured by the eddy covariance tower, which only measures the fluxes above the canopy at a certain height.

Besides CO_2 fluxes, also water vapour fluxes are measured at CES, Chethackal using the same method. The latent heat flux calculated using the formula (eqn. 3):

$$LE = \lambda\overline{w'.\rho_q{}'} \quad (\text{W m}^{-1}\text{ s}^{-1}) \qquad \text{Eqn. (3)}$$

were *LE* is latent heat flux (Wm^{-2} s^{-1}), λ is the latent heat of vaporization (Wm^{-1}), *w* is the wind speed (m s^{-1}) and ρ_q is the fluctuation in specific humidity. Overbars denote time averages, and primed quantities are the instantaneous deviations from their respective time average. From this evapotranspiration (*ET*) was calculated for every 30 minutes. The measured water vapour fluxes are the result of plant transpiration and evaporation of soil water. Transpiration of water vapour is a plant physiological process coupled to photosynthesis. Evaporation of soil water is driven by available soil moisture and soil temperature, where the transpiration is determined by net radiation and by the leaf area index of the vegetation. The inevitable loss of water via evapotranspiration when stomata open to admit CO_2 uptake may lead to decreased water content in leaves if root water uptake does not compensate the loss from leaves. When the plant water status becomes low stomata close, conserving water but at the same time decreasing photosynthesis and thus reducing the net CO_2 uptake. The rates of ecosystem photosynthesis, respiration and decomposition may vary diurnally and seasonally in response to interactions between the physical environment like radiation, moisture and temperature and biotic factors like plant phenology, soil microbial metabolism and heterotrophic CO_2 release (Goulden et al., 2004). Attempts were also made to correlate the CO_2 flux values with prevailing environmental parameters.

Employing statistical tools, these primary data are used to calculate net ecosystem level fluxes of CO_2 and water vapour in real time. In the present study, ecosystem level net CO_2 sequestration rates (photosynthesis and respiration including litter decomposition) and evapotranspiration for a continuous one year period in a four-five year old rubber plantation is described. From the EC data the net ecosystem exchange (*NEE*) of CO_2 and water was calculated. The net CO_2 exchange obtained from the system is the difference between photosynthetic assimilation by the canopy and the total respiratory CO_2 efflux from the foliage, roots and soil (Lalrammawia and Paliwal, 2010).

5.4. Results and Discussion

5.4.1 Carbon sequestration by natural rubber plantations

5.4.1.1. Biomass inventory method

The amount of carbon sequestered by the rubber plantation was estimated by estimating the annual shoot biomass increment using Shorrock's method (Shorrocks et al., 1965). It was found that there was an increment of 8.84 Kg tree-1 every four months from May 2009 to May 2012 (Figure 5.4). From the shoot biomass estimation the amount of CO_2 sequestration was calculated as 13.26 ton CO_2 $ha^{-1}yr^{-1}$ which does not include root biomass, soil respiration and litter decomposition.

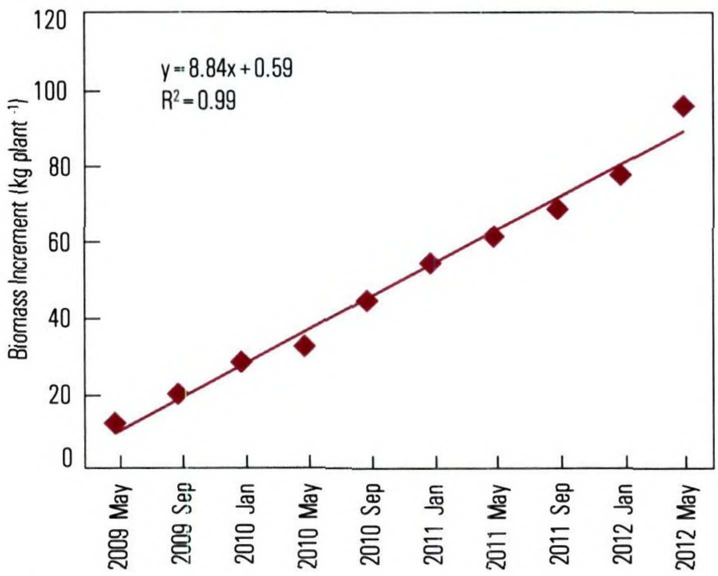


Figure 5.4. Change in tree biomass shown as growth increment from biomass inventory measurements form 2009 May to 2012 May.

5.4.1.2. CO_2 sequestration by rubber plantations measured from eddy covariance flux

The CO_2 flux rates were continuously measured from March 2009 to April 2011. Half hourly data of net radiation, air temperature, relative humidity (RH), fluxes of CO_2 (Fc), water (LE) and sensible heat (H) were obtained from the eddy system. The typical daily pattern of CO_2 exchange showed positive and negative values (Figure 5.5 and 5.6). Positive values measured during the night indicated net efflux of CO_2 from the ecosystem to the atmosphere (source), i.e, net ecosystem respiration (Reco). The flux values during daytime were almost always negative indicating net CO_2 assimilation by the ecosystem, i.e, net photosynthesis. The net ecosystem exchange of CO_2 (*NEE*) was calculated by subtracting the net ecosystem respiration from gross ecosystem exchange (*GEE*). By convention, net photosynthetic CO_2 flux in the day time is negative value and night time respiration is positive value (Figure 5.5).

NEE increases (i.e by default, the values become more negative) when the photo synthetically active radiation (PAR) increases in the morning (Figure 5.8). *NEE* decreases in late afternoon probably due to lesser light intensity and stomatal closure (Stephen and Theodore, 1979). The net rate of canopy CO_2 assimilation during day time was always higher than the respiratory CO_2 efflux during night time. This observation clearly indicated that the net assimilation rate of canopy is higher than the net respiratory CO_2 efflux in natural rubber ecosystem and thus rubber plantation is a net sink.

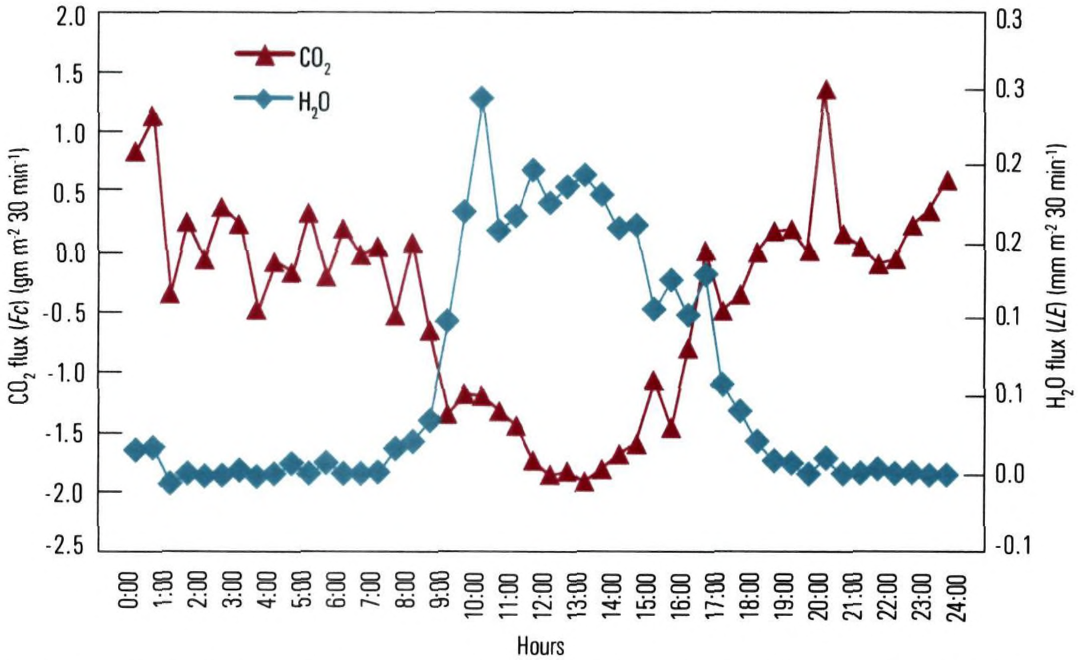


Figure 5.5. A typical diurnal CO_2 and water flux (25th July 2009) in an immature rubber plantation (5 years old). The symbols for CO_2 and ET indicated flux in carbon dioxide and water (evapotranspiration), respectively.

The daily CO_2 flux by the rubber ecosystem ranged from -33 to 9 g CO_2 m^{-2} day^{-1} (negative value in the raw flux data indicates the net CO_2 assimilation by the plantation-influx and the positive value for net ecosystem respiration-efflux) was recorded during the study period (Figure 5.6). Most of the days recorded CO_2 influx in to the plantation; however, a few days (around 32 days in two years) recorded net carbon efflux from the plantation to atmosphere, possibly due to poor sunlight during monsoon. On such days, around 1 - 9 g CO_2 m^{-2} day^{-1} was released to atmosphere. The net efflux values included the possible high rate of total soil respiration (*Rs*) both by autotrophic (*Ra*) and heterotrophic (*Rh*) components of the soil in addition to the net CO_2 release from leaf respiration. The soil respiration rate generally depends on the soil moisture, temperature, organic composition, density of microbial population and rate of decomposition of organic contents (Orchard and Cook, 1983).

Heavy rainy days witnessed a net efflux of CO_2 to atmosphere, most probably, due to a low rate of canopy photosynthesis and possible sudden spurt in release of locked up CO_2 from the soil. Sunny days (when soil moisture level was not deficient) were more favorable for carbon fixation by rubber plantation. On an annual average the *NEE* was 12.13 g CO_2 m^{-2} day^{-1} which is equivalent to 44.27 tons CO_2 ha^{-2} yr^{-1}.

The net CO_2 assimilation (*Aeco*) and net respiratory CO_2 efflux (*Reco*) are calculated for the entire study period (Table 5.1). While the mean Reco was 2.21 g CO_2 m_{-2} day_{-1}, the net assimilation rate (*Aeco*) recorded as -14.34 g CO_2 m-^{2} day^{-1} (Figure 5.7).

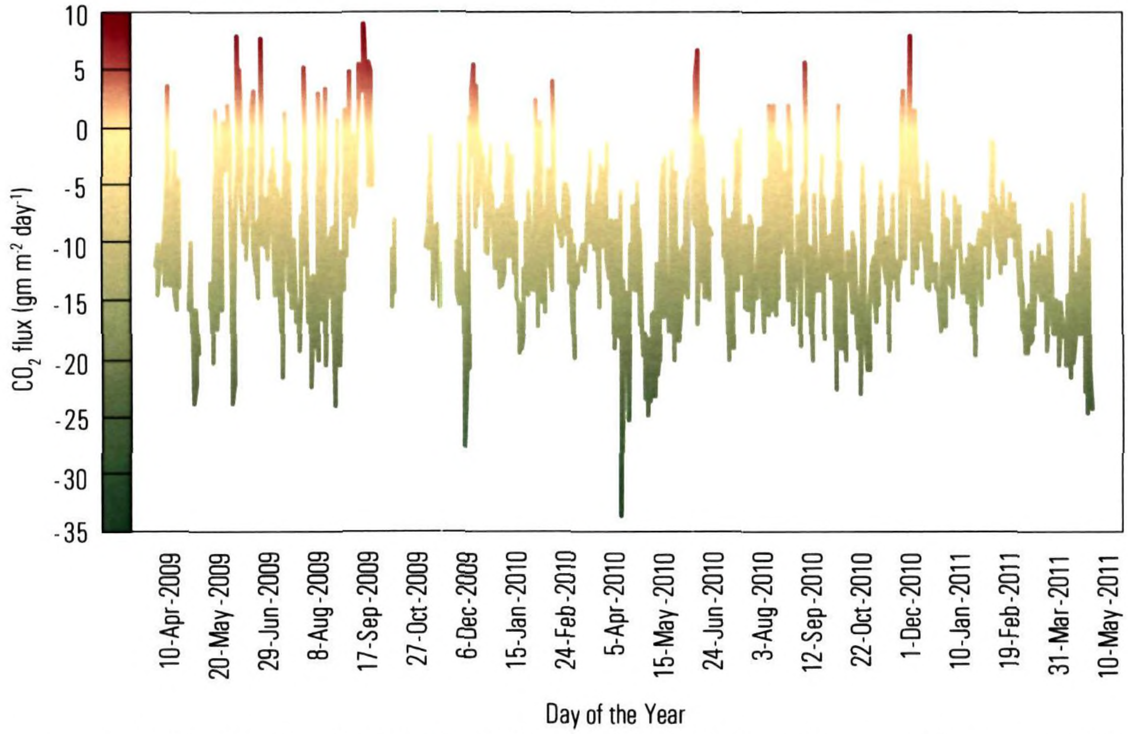


Figure 5.6. The CO_2 flux (*Fc*) (March 2009 to April 2011) in four- six years old immature rubber plantation in central Kerala region for the entire study period. Gap filling was not carried out. The gaps in the data series indicated failure of the sensors during heavy thunder showers etc.

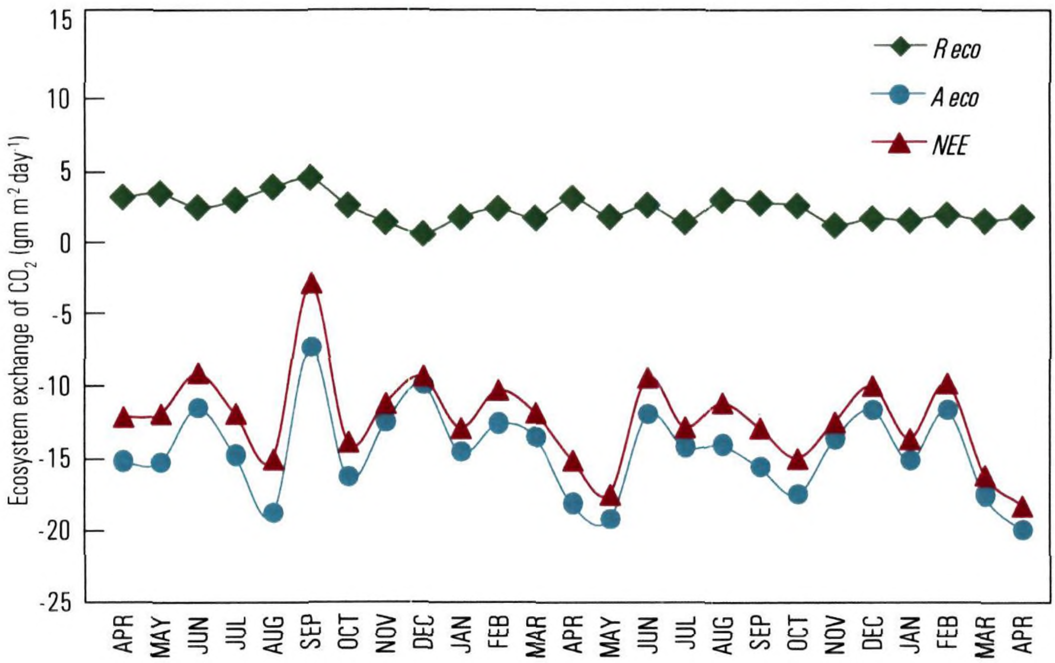


Figure 5.7. Mean monthly net ecosystem exchange in immature rubber plantation. The mean ecosystem respiration (*Reco*), ecosystem CO_2 assimilation (*Aeco*) and net ecosystem exchange (*NEE*) on per day basis are depicted.

Table 5.1. Monthly means of net CO_2 assimilation (*Aeco*), net respiratory CO_2 efflux (*Reco*), net ecosystem exchange (*NEE*) and water vapour flux during the study period.

Year	Month	H_2O (mm m^{-2} day^{-1})	*Reco* (gm CO_2 m^{-2}day^{-1})	*Aeco* (gm CO_2 m^{-2}day^{-1})	*NEE* (gm CO_2 m^{-2}day^{-1})
2009	MAR	3.07	1.80	-6.71	-4.91
2009	APR	3.09	3.08	-15.38	-12.30
2009	MAY	3.12	3.35	-15.42	-12.08
2009	JUN	3.21	2.38	-11.63	-9.25
2009	JUL	3.78	2.87	-14.93	-12.06
2009	AUG	3.36	3.78	-18.98	-15.20
2009	SEP	2.92	4.40	-7.42	-3.02
2009	OCT	3.15	2.48	-16.52	-14.04
2009	NOV	2.03	1.31	-12.69	-11.38
2009	DEC	2.72	0.48	-9.98	-9.50
2010	JAN	3.00	1.67	-14.75	-13.08
2010	FEB	2.42	2.28	-12.74	-10.46
2010	MAR	2.64	1.62	-13.64	-12.02
2010	APR	3.83	3.03	-18.30	-15.28
2010	MAY	3.45	1.72	-19.34	-17.62
2010	JUN	3.87	2.52	-12.11	-9.59
2010	JUL	3.27	1.35	-14.35	-13.01
2010	AUG	2.82	2.89	-14.21	-11.32
2010	SEP	2.92	2.68	-15.73	-13.05
2010	OCT	2.90	2.49	-17.63	-15.14
2010	NOV	2.20	1.13	-13.77	-12.64
2010	DEC	2.30	1.60	-11.74	-10.14
2011	JAN	2.58	1.46	-15.26	-13.79
2011	FEB	2.74	1.85	-11.82	-9.97
2011	MAR	3.45	1.43	-17.72	-16.29
2011	APR	3.56	1.73	-20.10	-18.37
AVG		**3.02**	**2.21**	**-14.34**	**-12.13**

The net CO_2 sequestration rates for every day was regressed with that day's Tmax, Tmin, rainfall and sunshine hours and none of these independent variables, except sunshine hours gave any meaningful correlation with CO_2 sequestration. Even in this case, a relationship could be seen between canopy photosynthesis and sunshine hours only for a few months of the study period (Figure 5.8). It is not that other factors had no effect on CO_2 sequestration, but the interactions were probably complex and not linear. Photosynthesis is a complex biochemical process which is carried out by the combined action of several biotic and abiotic factors. During summer months the sunlight was plenty but the soil moisture deficit and high atmospheric VPD restricted the canopy photosynthesis and *NEE*.

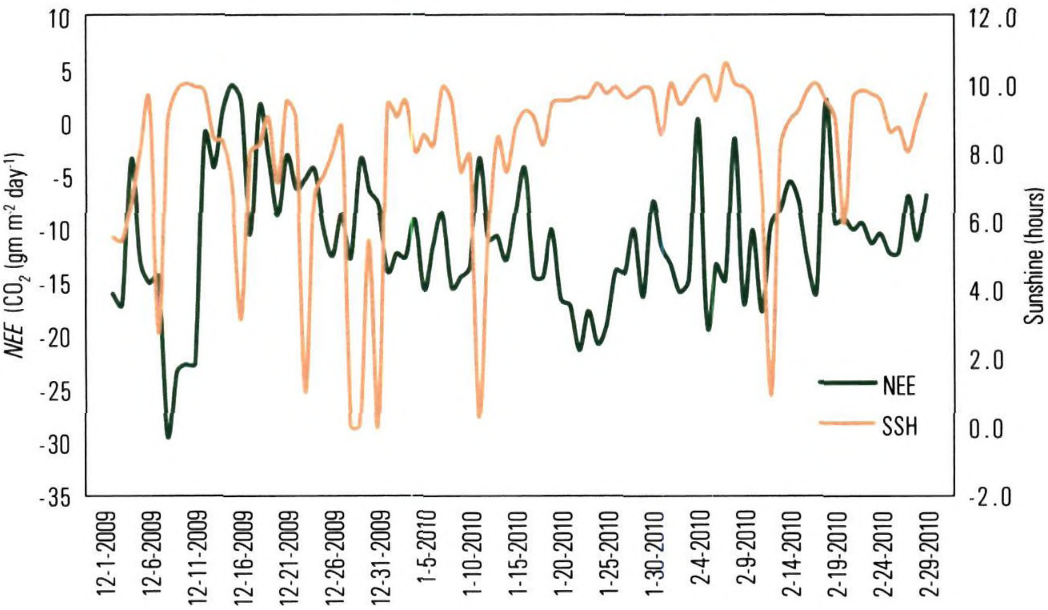


Figure 5.8. Sunshine hours have a good relationship with *NEE*. Days with lengthy sunshine hours recoded high rate of net ecosystem exchange (*NEE*).

5.4.1.3. Evapotranspiration by rubber plantations measured from eddy covariance flux

The evapo-transpiration (ET) values were calculated from latent heat of vapourization (LE). The mean ET rate of water loss was 3-4 from the rubber plantation per day during the study period (Figure. 5.9). In a three year old rubber plantation, evapotranspiration during summer months was about 4-5 mm per day (Jessy et al., 1992) and the annual average evapotranspiration was about 3.8 mm per day (Jessy et al., 1992).

Simultaneous and time integrated measurements of net CO_2 sequestration and water loss through evapotranspiration were used to work out the ecosystem level water use efficiency over the entire study period. Taking a net CO_2 sequestration rate of 44 ton CO_2 per ha per year and a net evapotranspiration loss of 3 mm per day, the water use efficiency comes to 1.65 micromol CO_2 per mol water. This is the time integrated (over the duration of the study) water use efficiency at the ecosystem (landscape) level.

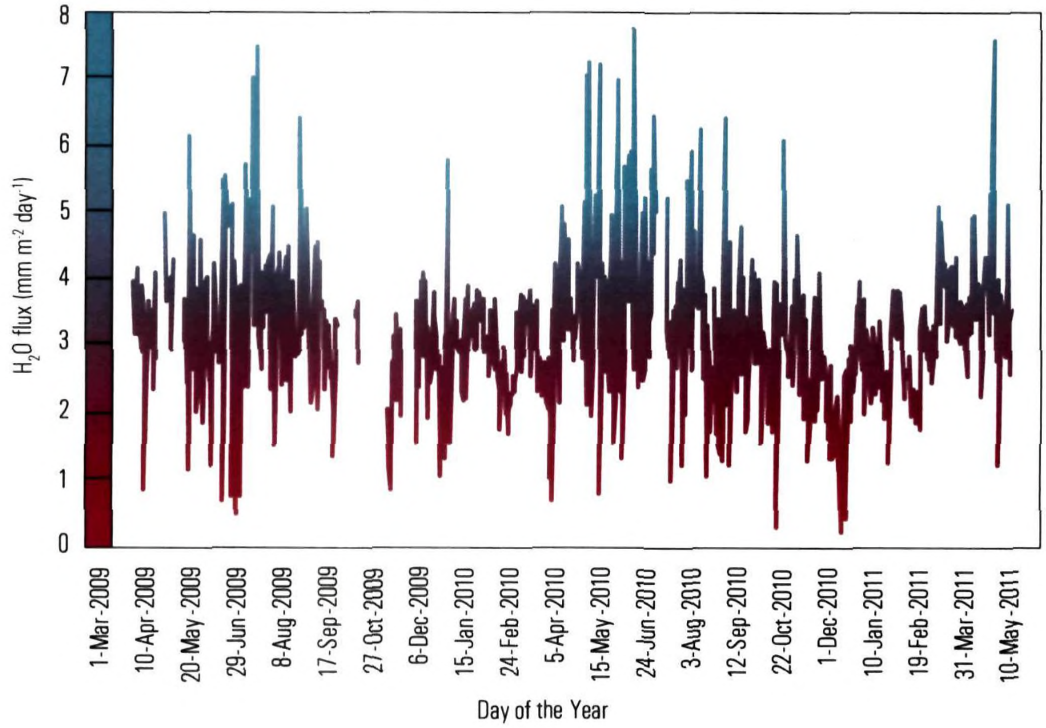


Figure 5.9. The water flux (*LE*) in four- six years old immature rubber plantation in central Kerala region for the entire study period.

From single leaf measurements of instantaneous photosynthesis made on fully mature leaves of young rubber plants at optimal conditions, the average net CO_2 assimilation rate comes to close to 10-12 micromol per m^2 leaf area per second and the mean transpiration rate comes to about 3-4 mmol per m^2 leaf area per second (Sumesh et al., 2011). This gives an instantaneous mean water use efficiency of 3.14 micro mol CO_2 per mol water vapour. Considering that the leaf area index of the study site was about 3-4, leaves were of different ages, both evaporation and transpiration were taken into account, CO_2 sequestration was expressed on a per land area basis (and not on leaf area basis as in the case of leaf photosynthesis) and the ambient conditions in the field were less than optimal and varied during the study period, the smaller time integrated water use efficiency observed at the landscape level (1.65 µmol CO_2 per mol water) is expected and within reasonable range when compared to the instantaneous water use efficiency calculated from single leaf measurements.

5.4.2. Role of rubber plantation in mitigating atmospheric carbon dioxide

The results discussed above show that natural rubber plants are a good sink for atmospheric CO_2. Studies from India and other natural rubber producing countries showed that the rate of CO_2 sequestration by natural rubber holdings varied from 28.8 to 40.1 $tCO_2\ ha^{-1}yr^{-1}$ (Table 5.2). The variation in sequestration potential was possibly due to the differences in the agro-climatic conditions prevailing in the respective countries. Even so, natural rubber plantations fixed much more carbon than the mature forests fixing (Dixon et al., 1994). For example, it has been reported that the mature Amazonian forests fix just 3 $tCO_2\ ha^{-1}yr^{-1}$ (Malhi et al., 2001).

Table 5.2. Rate of CO_2 sequestration by natural rubber plantation in some of the NR producing countries.

Country	C Stored in above ground biomass (A) ($t\ C\ ha^{-1}$)	C stored in below ground biomass (B) ($t\ C\ ha^{-1}$)	C stored in biomass ($t\ C\ ha^{-1}$)	C stored in soil (C) ($t\ C\ ha^{-1}$)	Total C stored (A+B+C)	Rate of CO_2 sequestration ($t\ C\ ha^{-1}yr^{-1}$)
Thailand[1]			217.6	49.0	266.6	33.3
Malaysia[2]	223.1	35.7	258.8	54.4	313.2	38.3
India[3]	128.0	14.0	142.0	23.0	165.0	28.8
Indonesia[4]	139.6			45 to 60	184.6 to 199.6	27.1 to 29.3
Ghana[5]			82.4	52.6	135.0	35.4
Brazil			47.4	105.6	153.0	40.1
Range	128.0 to 223.1	14.0 to 35.7	47.0 to 258.8	23.0 to 105.6	135.0 to 266.6	28.8 to 40.0

[1]Clone RRIM 600, Age 25 years, density 415 trees/ha, soil depth 0.30m
[2]Clone RRIM2025, Age 30 years, density 325 trees/ha, soil depth 0.45m
[3]Clone RRII 105, Age 21 years, density 325trees/ha , soil depth 0.15 m
[4]Clone GT1, Age 25 years, density 400 trees/ha, soil depth 0.3 m
[5]14 years old

The rate of net assimilation (*NEE*) rate calculated from the eddy covariance data was 12.13 gm $CO_2m^{-2}day^{-1}$. When extrapolate this value for one year per hectare, it will be 43.80 t $CO_2\ ha^{-2}day^{-1}$. If we take a modest rate of 30 t $CO_2\ ha^{-2}day^{-1}$, world's current total 12.2 million hectare of rubber plantation fix as much as 372 million t CO_2 every year which is equal to 0.10 Pg C per year (1 C equals 3.67 CO_2). While converting it in to ppm, it will be 0.05ppm (1Pg carbon equals 0.47 ppm, Malhi et al., 2001). This accounts for offsetting the current rate of buildup of CO_2 in the atmosphere (1.9 ppm CO_2yr^{-1}, IPCC, 2007) to the tune of 2.5% which is a significant ecosystem service provided by the world's natural rubber plantations in addition to these plantations providing livelihood means for millions of rubber growers and supporting the rubber industry that is indispensible for modern man.

5.5. Conclusions

Eddy covariance system is a micro-meteorological instrument used to measure the ecosystem level flux of CO_2 and water vapour. In India the first system of its type was installed in the Central Experiment Station of Rubber Research Institute of India in Kerala. Before the introduction of this methodology, the calculation of biomass in forest, agriculture and plantation ecosystems were carried out through biomass inventory method. The advantage of EC method over the biomass inventory is that it is more accurate and continuous measurements are possible in real time. Besides the CO_2 flux data, we will get all the weather parameters that we are getting from a conventional weather station. Another advantage over biomass inventory is that we need not to destroy the plants to estimate their biomass.

Natural rubber plantations are a good sink for atmospheric carbon dioxide. They can sequester remarkably large amounts of CO_2 every year, often much higher than natural forests. World's existing 12.2 M ha rubber plantations must be fixing almost 372 Mt CO_2 every year, which is equal to a reduction of 1.4 % of the total CO_2 emission from consumption and flaring of fossil fuel during 2010 (31780.4 million ton CO_2 in 2010) and 2.5% of the current rate of buildup of CO_2 in the atmosphere (1.9 ppm CO_2 yr^{-1}). This ecosystem services should be appreciated in the world climate conferences.

But this ecosystem service provided by world NR plantations went unappreciated in negotiations on market based mechanisms to address climate change in a post Kyoto regime, including the UNFCCC's Doha climate summit during December 2012. Kyoto Protocol rules are more difficult to consider the carbon sequestration credits from Afforestation/ Reforestation (A/R) sector than credits from energy sector. As on 31st September, 2013, out of 8143 registered CDM projects A/R projects were only 45. That itself means that A/R projects are not favored much possibly because there are no serious buyers for the credits from this sector.

One way forward on this issue is to set up a sectoral or domestic carbon trading mechanism independent of CDM and creating a market for these credits nationally. Payment for ecosystem/environmental services (PES) even on a voluntary basis is welcome. This is a transparent system for the additional provision of environmental services through conditional payments to voluntary service providers (Tacconi, 2012). To assess the state of the world's ecosystems UN in 2005 designed a Millennium Ecosystem Assessment (MEA) report in which it specified and identified twenty four ecosystem services (see http://www.wri.org/ publication/millennium-ecosystem-assessment-living-beyond-our-means) which include climate change mitigation, watershed services and biodiversity conservation. These three services are now getting more support, money and interest worldwide. Ecosystem services represent a part of the total economic value of the world by contributing to human welfare directly and indirectly. It was reported from a study that an average of US$ 33 trillion yr-1 (UD$ 16-54 trillion yr^{-1}) were estimated as the economic value of 17 ecosystem services for 16 biomes. This is equal to almost double of the global gross national product (GNP) of US$ 18 trillion yr^{-1} (Costanza et.al., 1997). The advantage of PES over CDM is that the former considers standing forests (no additonality needed) and allows the community to enter into an agreement with formal institution like Government.

5.6. References

Ambily, K.K., Meenkumari, T., Jessy, M.D., Ulaganathan, A. and Nair, N.U. (2012). Carbon sequestration potential of RRII 400 series clones of Hevea brasiliensis. Rubber Science, 25(2): 233-240.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalsk,i A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R. and Vesala, T. (2000) Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. Advanced Ecological Research. 30: 113-175.

Baldocchi, D.D. (2003). Assessing ecosystem carbon balance. Problems and prospects of the eddy covariance technique. Global Change Biology. 9: 476-492.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. European Journal of Soil Science. 47 (2): 151–163.

Benny, G., Jacob, K.V., Thomas, K.T., Jacob, J. and Mathew, N.M. (2006). Carbon Dioxide Emission Reduction through Substituting Synthetic Elastomers with Natural Rubber. In: James Jacob and N.M. Mathew (Eds.). Kyoto Protocol and the Rubber Industry. Rubber Research Institute of India, Kottayam, pp. 133-146.

Burba, G. and Anderson, D. (2010). A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications.LI-COR Biosciences. 4647 Superior Street. P.O. Box 4425, Lincoln, Nebraska 68504 USA.

Chantuma, A., Maenmeun, S., Chantuma, P. and Paechana, P. (2005). Potential of Rubber Wood Production and Quality- Case productivity in the North, and tapped woods properties. Paper presented in "Rubber: Wood, Cropping and Research" work shop. May 25.-27.2005, Kasetsart University, Bangkok. 7 p.

Costanza, R., Ralph, d'Arge., Rudolf, de G., Stephen, F., Monica, G., Bruce, H., Karin, L., Shahid, N., Robert, V. O' Neill, Jose, P., Robert, G.R., Paul, S. and Marjan, van den Belt. (1997). The value of world's ecosystem services and natural capital. Nature. 387: 253-260.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Da Silva Dias, P.L., Wofsy, S.C. and Zhang, X. (2007). Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp 499-588.

Dixon, R.K., Andrasko, K.J., Sussman, F.G., Lavinson, M.A., Trexler, M.C. and Vinson, T.S. (1993). Forest sector carbon offset projects: near-term opportunities to mitigate greenhouse gas emissions. Water Air and Soil Pollution. 70: 561-577.

Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexier, M.C. and Wisiniewski, J. (1994). Carbon Pools and Flux of Global Forest Ecosystems. Science. 263 (5144): 185-190.

Gera, M. and Suresh, C. (2010). Opportunities for carbon sequestration benefits from growing trees of medicinal importance on farm lands of Haryana. Indian Forester. 136 (3): 287-300.

Gera, M., Giresh, M., Bisht, N.S. and Gera, N. (2006). Carbon sequestration potential under agroforestry in Rupnagar district of Punjab. Indian Forester. 132 (5): 543-555.

Gillian, L.G., Jerry, M.M., David, W.K., Timothy, W.C., Carlos, E.P.C., John, F.M. and Carlos, C.C. (2010). Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon. Proceedings of National Academy of Science. January 2010: 34-42.

Goulden, M.L., Miller, S.D., Da Rocha, H.R, Menton, M.C., De Freitas, H.C., E Silva Figueira, A.M., and Dias De Sousa, C.A. (2004). Diel and Seasonal patterns of tropical forest CO_2 exchange. Ecological Applications. 14(4): 42-54.

Grace, J., Lloyd, J., McIntyre, J., Miranda, A.C., Meir, P., Miranda, H., Moncrieff, J., Massheder, J., Malhi, Y., Wright, I. and Gash, J. (1995). Carbon dioxide uptake by an undisturbed tropical rain forest in southwest Amazonia, 1992 to 1993. Science. 270: 778-780.

Haszeldine, R.S. (2009). Carbon capture and storage: How green can black be?. Science . 325:1647-652.

Hooda, N., Gera, M., Vasistha, H.B., Chandran, M. and Rassaily, S.S. (2005). Phase-I report on " Methodologies in Forestry Mitigation Project-case studies from Nainital and Udham Singh Nagar Districts of Uttaranchal", ICFRE, Dehradun.

IPCC. (2005). IPCC Special Report on Carbon Capture and Storage. Bert Metz, Ogunlade Davidson, Heleen de Coninck, Manuela Loos and Leo Meyer (Eds.). Cambridge University Press, UK. pp 431.

IPCC. Fourth Assessment Report (2007). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

IPCC. Fourth Assessment Report (2007b). Mitigation of climate change. Metz, B., Davidson, O.R. Bosch, P.R., Dave, R. and Meyer, L.A. (Eds). Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Jacob, J and Mathew, N.M. (2004). Eco-friendly NR plantations can tap vast global funding. Rubber Asia. March/April 2004.

Jacob, J and Mathew, N.M. (2006). Kyoto Protocol and Rubber Industry. Rubber Research Institute of India, Kottayam, Kerala, India.

Jacob, J. (2005). The science, politics and economics of global climate change: Implications for the carbon sink projects. Current science. 89(3): 464-474.

Jagadish, K., Rajiv, P. and Dadhwal, V.K. (2009). India's Forest and Tree Cover: Contribution as a Carbon Sink. Technical paper by Indian Council of Forestry Research and Education, available at www.envfor.nic.in.

Jessy, M.D., Mani, J., Mathew, M. and Punnoose, K.I. (1992). Evapotranspiration and crop coefficient of immature rubber : A lysimetric study. Indian journal of Natural Rubber Research. 5(1 & 2): 73-77.

Kraenzel, M., Castillo, A., Moore, T. and Potvin, C. (2003). Carbon storage of harvest-age teak (Tectona grandis) plantations, Panama. Forest Ecology and Management. 173: 213-225.

Lalrammawia, C. and Paliwal, K. (2010). Seasonal changes in net ecosystem exchange of CO_2 and respiration of Cenchrus ciliaris L. grassland ecosystem in semi-arid tropics: an eddy covariance measurement. Current Science. 98 (9): 1211-1218.

Malhi, Y., Phillips, O. and Grace, J. (2001). Are Amazonian rain forests absorbing carbon and increasing in biomass? A comparison of evidence and insights from measurements of carbon dioxide fluxes and forest biomass change. In: Tropical Ecosystems: Structure, diversity, and Human Welfare. Proceedings of the International Conference on Tropical Ecosystems. Oxford-IBH, New Delhi, pp. 27–28.

Massman, W. J and Lee, X. (2002). Eddy covariance flux corrections and uncertainties in long term studies of carbon and energy exchange. Agriculture and Forest meteorology. 113: 121-144.

Mathew, J., Jacob, J. and Jacob, C.K. (2006). Carbon Trading Potential of Methane Emission Reduction From Sheet Processing Effluents. In: James Jacob and N.M. Mathew (Eds.). Kyoto Protocol and the Rubber Industry. Rubber Research Institute of India, Kottayam, pp. 147-153.

Metz, B., Davidson, O., Coninck, H., Loos, M., Meyer, L. (Eds.) (2005). Special report on carbon capture and storage. Cambridge University press, Cambridge, 2005.

Munang, R., Ibrahim Thiaw, I., Rivington, M. and Goldman, R. (2010). The Role of Ecosystems in Developing a Sustainable 'Green Economy'. United Nations Environment Programme: Policy Brief 2 – 2010.

Najku, O.U., Ononogbu, I.C. and Ousu, J.Y. (1996). An investigation on oil of rubber seed (Hevea brasiliensis). Journal of Rubber Research Institute of Sri Lanka. 78: 52-57.

National Energy Technology Laboratory (NETL). (2008). Carbon Sequestration Atlas of the United

Niggli, U., Fliessbach, A., Hepperly, P. and Scialabba, N. (2009). Low greenhouse gas agriculture: mitigation and adaptation potential of sustainable farming systems. FAO, April 2009, Rev. 2-2009.

Orchard, V. A. and Cook, F. J. (1983). Relationship between soil respiration and soil moisture. Soil Biology and Biochemistry. 15: 447–453.

Phani, K. G., Ashutosh, A. M., Sunil, G. and Shashi, B. S. (2009). Carbon sequestration with special reference to agro forestry in cold deserts of Ladakh. Current Science. 97(7): 1063-1068.

Sadeesh, P.S. and Viswanathan, P.P. (2006). Natural rubber modified bitumen: Its potential as a CDM project. In: James Jacob and N.M. Mathew (Eds.). Kyoto Protocol and the Rubber Industry. Rubber Research Institute of India, Kottayam, pp. 159-163.

Saengruksawong, C., Khamyong, S., Anongrak, N. and Pinthong, J. (2012). Growths and Carbon Stocks of Para Rubber Plantations on Phonpisai Soil Series in Northeastern Thailand. Rubber Thai Journal. 1: 1-18.

Sanchez, J.M., Caselles, V., Niclos, R., Coll, C. and Kustas, W.P. (2009). Estimating energy balance fluxes above a boreal forest from radiometric temperature observations. Agricultural and Forest Meteorology. 149: 1037-1049.

seq/refshelf/atlas/ATLAS.pdf

Shorrocks, V.M (1965). Mineral nutrition, growth and nutrient cycle of *Hevea brasiliensis*. Growth and nutrient content. Journal of Rubber Research Institute of Malaysia. 19: 32-47.

Sivakumaran, S. and Tee, N.K. (2010). Sustainable cultivation of rubber: A possible framework. The Rubber International Magazine. January 2010: 34-42.

States and Canada, 2nd ed., U.S. Dept. of Energy. www.netl.doe.gov/technologies/carbon_

Stephen, G. P. and Theodore, T. K. (1979). Stomatal response of populus clones to light intensity and vapor pressure deficit. Plant Physiology. 64: 112-114

Sumesh, K.V., Satheesh, P.R., Annamalainathan, K., Krishnakumar, R and Jacob, J. (2011). Physiological evaluation of a few modern clones for intrinsic drought tolerance. Natural Rubber Research. 24(1): 61-67.

Suruchi, B. and Singh, R. (2002). Carbon sequestration estimates for forestry options under different land-use scenarios in India. Current Science. 83: 1380-1386.

Tacconi, L. (2012). Redefining payments for environmental services. Ecological Economics. 73 (1): 29-36.

Trexler, M.C. and Haugen, C. (1994). Keeping it green: evaluating tropical forestry strategies to mitigate global warming. World Resource Institute , Washington DC.

U.S. Department of Energy (DOE). (2009). Retrofitting the existing coal fleet with carbon capture technology. www.fossil.energy.gov (accessed June 25, 2009).

Veeraputhran, S., Benny, G. and Jacob, K.V. (2006). Carbon Trading Potential of Biodiesel from Rubber Seed Oil. In: James Jacob and N.M. Mathew (Eds.). Kyoto Protocol and the Rubber Industry. Rubber Research Institute of India, Kottayam, pp. 155-157.

Wall, D. H. and Nielsen, U. N. (2012). Biodiversity and Ecosystem Services: Is It the Same Below Ground? Nature Education Knowledge 3(12): 8.

Watson, R.T., Noble, I.R., Bolin, B., Ravindranath, N.H., Verardo, D.j., Dokken, D.J. (Eds.) (2000). IPCC Special Report on Land Use , Land Use Change and Forestry. Cambridge University Press, UK.

Webb, E. K., Pearman, G. I and Leuning, R. (1980). Corrections of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal of Royal Meteorological Society. 106: 86-100.

Wilczak J.M., Oncley ,S.P., and Stage, S.A. (2001) sonic anemometer tilt correction algorithms. Boundary-Layer Meteorology. 99:127–150.

Winjum, J.K., Dixon, R.K. and Schroeder, P.E. (1992). Estimating the global potential of forest and agroforest management practices to sequester carbon. Water Air and Soil Pollution. 64: 213-222.

Wofsy, S.C., Goulden, M.L., Munger, W.J., Fan, S.M., Bakwin, P.S., Daube, B.C., Bassow, S.L. and Bazzaz, F.A. (1993). Net exchange of CO_2 in a mid latitude forest. Science. 260: 1314-1317.

Yogaratnam, N. (2008). Carbon trading: options and opportunities for natural rubber. Daily Mirror. Sri Lanka. 30 Jul 08.

Yogaratnam, N. (2010). Sustainable development of rubber industry. Daily News. Monday, 15 February 2010. www.dailynews.lk

CHAPTER 6

INTERNATIONAL CLIMATE CHANGE NEGOTIATIONS AND ANALYSES OF GLOBAL EMISSIONS DATA

"How many planets might be needed to sequester the total emission if India were to follow Britain's pattern of industrialization"

Mahatma Gandhi

6.1. Introduction

The main theme of this thesis has been how climate has (particularly temperature) changed in the rubber growing regions of India and what that has already done to rubber yield and what that will do to rubber yield in future if the present warming trend continues. In the last chapter I have explained the excellent CO_2 sequestration potential of natural rubber plantations. In this chapter, I give a brief summary of international climate change negotiations and attempt to analyse the aggregate national and sectoral emissions of GHGs and CO_2 emission from consumption and flaring of fossil fuels. At the end I also show that unless proactive steps are not taken to reduce CO_2 emission per se, just by increasing CO_2 sequestration by terrestrial and aquatic biomes organisms alone, it is impossible to stabilize or reduce concentration of CO_2 in the atmosphere

6.2. International climate bodies

6.2.1. Intergovernmental Panel on Climate Change (IPCC)

During 1980s scientists and policymakers all over the world started to take anthrpogenically induced global warming seriously, although a lot of denial was there at that point. The Intergovernmental Panel on Climate Change (IPCC), the leading international body for the assessment of climate change was formed in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide the world with a clear scientific view on the state of knowledge in climate change and its potential environmental and socio-economic impacts. The IPCC is a scientific body which reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research or monitor climate related data or parameters. Thousands of scientists from all over the world contribute to the work of the IPCC on a voluntary basis. Review is an essential part of the IPCC process, with an objective of complete assessment of current information. The IPCC is an intergovernmental body and it is open to all member countries of the United Nations (UN) and WMO. Currently 194 countries are members of the IPCC.

The IPCC is currently organized in three Working Groups and a Task Force. They are assisted by Technical Support Units (TSU), which are hosted and financially supported by the Government of the developed country in which that Working Group/Task Force works. Working Group I deals with science of climate change, Working Group II with impacts, adaptation and vulnerability and Working Group III deals with the mitigation of climate change. The main objective of the Task Force on National Greenhouse Gas Inventories (NGGI) is to develop and refine a methodology for the calculation and reporting of national

GHG emissions and removals. In addition to the Working Groups and Task Force, further Task Groups and Steering Groups may be established for a limited or longer duration to consider a specific topic or question.

Every five year IPCC is releasing a comprehensive report on climate change and is known as Assessment Report. Thousands of scientists work together worldwide updating the scientific background. The participation of the scientific community in the work of the IPCC has been growing greatly, both in terms of authors and contributors involved in the writing and the reviewing of the reports and of geographic distribution and topics covered by the reports. Al Gore, former US Vice president along with the IPCC shared the Nobel Peace prize during 2007.

Besides IPCCs most comprehensive scientific reports about climate change, the Assessment Reports, it also handling the scientific and technical matters through Special Reports, Technical Papers and Methodology Reports. Many of these reports are prepared in response to requests from the UNFCCC or from other international organizations and conventions. Since 1991 the IPCC has supported the UNFCCC by preparing Methodology Reports for National Greenhouse Gas Inventories.

6.2.1.1. Assessment reports:

1990: First Assessment Report (FAR)
1995: Second Assessment Report (SAR)
2001: Third Assessment Report (TAR)
2007: Fourth Assessment Report (AR4)
2014: Fifth Assessment Report (AR5)

6.2.1.2. Special Reports:

1997 - Regional Impacts of Climate Change: An Assessment of Vulnerability
1999 - Aviation and the Global Atmosphere
2000 - Methodological and Technological Issues in Technology Transfer
2000 - Special Report on Emissions Scenarios (SRES)
2000 - Land Use, Land-Use Change and Forestry
2005 - Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons
2005 - Carbon Dioxide Capture and Storage
2011 - Renewable Energy Sources and Climate Change Mitigation
2012 - Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

6.2.1.3. Technical Papers:

1996 - Technologies, Policies and Measures for Mitigating Climate Change
1997 - An Introduction to Simple Climate Models used in the IPCC Second Assessment Report
1997 - Stabilization of Atmospheric Greenhouse Gases: Physical, Biological and Socio-Economic Implications
1997 - Implications of Proposed CO_2 Emissions Limitations
2002 - Climate Change and Biodiversity
2008 - Climate Change and Water

6.2.1.4. Methodology Reports:

1994 - IPCC Guidelines for National Greenhouse Gas Inventories
1996 - Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories
2000 - Good Practice Guidance and Uncertainty Management in Greenhouse Gas Inventories (GPG)
2003 - Good Practice Guidance for Land Use, Land-Use Change and Forestry
2003 - Definitions and Methodological Options to Inventory Emissions from Direct Human-Induced Degradation of Forests and Devegetation of Other Vegetation Types
2006 - IPCC Guidelines on National Greenhouse Gas Inventories

6.2.2. United Nations Framework Convention on Climate Change (UNFCCC)

United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty which is negotiated at the Earth Summit (United Nations Conference on Environment and Development-UNCED) held in Rio de Janeiro in June 1992. The convention entered into force on 21 March 1994. 195 countries have joined the convention including the European Community. The countries that signed this international treaty cooperatively considered the importance of limiting the global temperature rise and to cope with the impact of climate change. The ultimate objective of UNFCCC is to "stabilize the atmospheric greenhouse gas concentrations at a level that would avoid dangerous anthropogenic interference with the earth's climate system". The ultimate decision making body of the convention is known as the Conference of the Parties (CoP) to UNFCCC. Two subsidiary bodies meet at least twice a year to carry out preparatory work for the CoP. The two subsidiary bodies are (i) Subsidiary Body for Scientific and Technological Advice (SBSTA) which provides advice to the CoP on matters of science, technology and methodology, including guidelines for improving standards of national communications and emission inventories and (ii) Subsidiary Body for Implementation (SBI) which helps to assess and review the Convention's implementation, for instance by analyzing national communications submitted by Parties and also deals with financial and administrative matters.

During 1997, in the third Conference of the Parties (CoP3) held in Kyoto, Japan the convention agreed to develop a legally binding agreement known as Kyoto Protocol to the UNFCCC. This agreement gives legally binding greenhouse gas reduction commitments to the developed countries (listed in Annex I of UNFCCC). The Kyoto Protocol finally came into effect on February 16, 2005, 7 years after it was first negotiated, when the goal of getting countries responsible for a total of 55% of the global emissions was achieved with the ratification of Russia.

The Protocol fixed Annex I countries (developed countries and countries in economic transition listed in Annexure I of UNFCCC) a legally binding emission reduction target known as QELRCs (Quantifies Emission Limitation or Reduction Commitments). Annex I countries should reduce their greenhouse gas emissions by about 5.2 % below their 1990 levels national emission between 2008 and 2012 (first commitment period). The Protocol's provisions will apply only to those countries that have ratified it all major countries, except USA ratified the Protocol. Except Russia and the EITs, no other major developed country could meet their emission reduction target so far; thanks to the poor economic performance of these former communist countries.

The Kyoto Protocol provides four flexibility methods to the developed countries to meet their gas reduction commitments. They are (1) Emissions trading – trading of emission allowances between developed countries. The emissions trading method gives countries the opportunity to reduce emissions where it is most economically efficient to do so. (2) Joint implementation – allows developed countries to sponsor foreign projects to decrease emission levels in countries in economic transition. In exchange for the developed country's investment, the host country provides the investor with emission reduction units, also known as carbon credits. The developed economies can afterwards use their carbon credits towards meeting their emission-reduction requirements under the Kyoto Protocol. (3) Clean Development Mechanism – which promotes environment friendly foreign investments from industrialized countries in developing countries. The developing countries are thus assisted for sustainable development.

Major milestones in international climate change negotiations are listed in Table 6.1.

Table 6.1. Milestones in the Conference of the Parties (CoP) to United Nations Framework Convention on Climate Change (UNFCCC) and important decisions taken by the parties in each meeting.

CoP	Host Country	Official Document	Decision
CoP 1 -1995	Berlin, Germany	Berlin Mandate	Launched a process to decide on stronger commitments for Annex I Parties
CoP 2 -1996	Geneva, Switzerland	Geneva Declaration	Renewed the momentum of the Kyoto Protocol negotiations (taken note of, but not adopted)
CoP 3 - 1997	Kyoto, Japan	Kyoto Protocol	Set legally binding targets and timetables for cutting the greenhouse gas emissions of Annex I Parties
CoP 4 -1998	Buenos Aires, Argentina	Buenos Aires Plan of Action	Set out program of work on issues under the Protocol; Established deadline for completion as CoP 6 in 2000
CoP 5 - 1999	Bonn, Germany	No declaration	It was primarily a technical meeting, and did not reach major conclusions.
CoP 6 I-II – 2000 -2001	The Hague, Netherlands Bonn, Germany	Bonn Agreement	Part I could not reach agreement, so resumed in Bonn Part II reached the Bonn Agreement (political package) Between Part I & II, the US announced it would not ratify the Kyoto Protocol
CoP 7 - 2001	Marrakech, Morocco	Marrakesh Accords (rule book of KP)	Translated Bonn Agreement into decisions setting out detailed rules for the implementation of the Protocol and took important steps toward implementation of the Convention. Operational rules for international emissions trading among parties to the Protocol and for the CDM and Joint implementation.
CoP 8 -2002	New Delhi, India	Delhi Declaration on Climate Change and Sustainable Development	Reaffirmed development and poverty eradication as overriding priorities in developing countries and highlighted the importance of adaptation
CoP 9 - 2003	Milan, Italy	No declaration	President's summary of round table discussions included in report of the session. Included A/R programs under LULUCF sector under CDM.
CoP 10 – 2004	Buenos Aires, Argentina	Buenos Aires Programme of Work on Adaptation and Response Measures; seminar of government experts	The Program on the Ethical Dimensions of Climate Change
CoP 11 -2005	Montreal, Canada	Decisions establishing the AWG-KP and Dialogue	Under the Protocol, a new working group was established (CMP) to discuss future commitments for developed countries for the period after 2012. Under the Convention, a dialogue on long-term global cooperative action to address climate change was also launched

CoP 12 -2006	Nairobi, Kenya	Nairobi Work Programme on Impacts, Vulnerability and Adaptation	Decisions related to financial flows were adopted and the two Montreal processes made progress
CoP 13 - 2007	Bali, Indonesia	Bali Road Map	Includes a number of forward-looking decisions that represent the various tracks. It includes the Bali Action Plan, which charts the course for a new negotiating process designed to tackle climate change, with the aim of completing this by 2009. Delegates agreed on REDD actions
CoP 14 - 2008	Poznań, Poland	Poznan programme	Delegates agreed on principles of financing for a fund to help the poorest nations cope with the effects of climate change. And also they approved a mechanism to incorporate forest protection into efforts.
CoP 15 - 2009	Copenhagen, Denmark	Copenhagen Accord	Agreed on non-binding economy wide emission targets. Discussion on abandon the Kyoto protocol. The parties recognizes that the increase in global temperature should be below 2 ^{0}C on the basis of equity and in the context of sustainable development
CoP 16 - 2010	Cancun, Mexico	Cancun Agreements	Parties shared a vision for long-term cooperative action in order to achieve the objective of the Convention. Nationally appropriate mitigation commitments or actions by developed country Parties and Nationally appropriate mitigation actions by developing country Parties.
CoP 17 - 2011	Durban, South Africa	Durban Platform	Parties to adopt a universal legal agreement on climate change as soon as possible, and no later than 2015. Agreed to create a second Kyoto commitment period.
CoP 18 - 2012	Doha, Qatar	Doha climate gateway	Adoption of a second commitment period of the Kyoto Protocol from 2013 to 2020. Making progress on further clarifying the process under the Durban Platform negotiations. Agreement to continue the work programme on long-term finance for another year
CoP 19 - 2013	Warsaw, Poland	Warsaw Outcomes	Decisions on further advancing the Durban Platform, the Green Climate Fund and Long-Term Finance, the Warsaw Framework for REDD Plus, the Warsaw International Mechanism for Loss and Damage and other decisions.
CoP 20- 2014	Will be held in Lima, Peru on 1-12 December 2014		
CoP 21-2015	Will be held in Paris, France on 30 Nov.- 11 December 2015		

6.3. Indian stand at world climate change negotiations

India is a major emitter of CO_2 today, although its historical contribution to the present CO_2 level in the atmosphere is not large. Today, India is the 4th largest emitter of GHGs in the world, next only to China, United States and Russia(see http://data.worldbank.org/indicator). India has always taken an aggressive stand that the developed countries should make deeper cuts in their GHG emissions and that developing countries should not be bound by legally binding GHG emission reduction targets. Because these countries need to use cheaper forms of energy such as coal and petroleum for energy, the primary driver of GDP. Even as Indian aggregate emissions are high, its per capita emission is very low (see http://data.worldbank.org/indicator).

India is a member of many international climate change treaties like UNFCCC, Kyoto Protocol, bilateral partnership with UK, US and EU on climate research and technology, and also a member of the Asia Pacific Partnership on Clean Development and Climate etc. India highlights the historical responsibility of industrialized countries in the present concentration of atmospheric CO_2. India emphasizes that its per capita emissions are lower than any other developed country. With this statement India argues in the international meetings that it should be outside from the emission reduction commitments given by the international binding agreements.

The non-binding Copenhagen Accord, agreed by India during CoP 15 at Copenhagen, Denmark, had outlined several actions for reducing greenhouse gases for both developed and developing countries. India rejected the developed nation's suggestions to take peaking year for emissions. However, India agreed the goal of limiting the global temperature rise to 2 ^{0}C above pre-industrial levels. During the meeting, the Government of India agreed to reduce the emissions intensity of its GDP by 20-25% by 2020 in comparison to the 2005 level through nationally appropriate mitigation actions (NAMAs). At Cancun, developed nations tried to abolish the Kyoto Protocol which India objected. India knew that without Kyoto Protocol, countries like India and China would end up having similar commitments as developed nations. Doha climate meet (CoP 18) agreed for a second commitment period for Kyoto Protocol from 2013 to 2020 as described in the 'Durban Platform' which was set out in the Durban climate meet (CoP 17).

When compared to the developed nations or even with developing nations, the responsibility of India in the accumulation of atmospheric CO_2 and associated global climate change was negligible. An in-depth study on the global and regional carbon emission and economic growth of present and past is attempted in this chapter.

6.4. Review of literature

There is unequivocal evidence that climate change is accumulation of greenhouse gases in the atmosphere through anthropogenic activities is the main reason for it (IPCC, 2007). The global average temperature may rise by 1.6 to 4.5 ^{0}C at the end of this century (IPCC, 2007). Recent monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii showed that present atmospheric CO_2 concentration during the month of May, 2013 was at a record high level of 399.77 ppm, much higher than the pre-industrial concentration of 280 ppm (NOAA, 2013; Pieter and Keeling, 2013; Keeling et al., 1976; Thoning et al., 1989). Every greenhouse gas showed a huge build up in the atmospheric concentration when compared to pre-industrial periods (IPCC, 2007; Blasing, 2013) (Table. 6.2).

For limiting the surface temperature increase to 2 ^{0}C above pre-industrial levels, atmospheric CO_2 concentration has to be limited at around 450 ppm. If this exceeds 750 ppm, the possible temperature changes would be more than 5 ^{0}C (HDR, 2007) leading to "runaway" climate change that can be irreversible. This report says that, to avoid dangerous climate change, the developed nations should reduce their emission by at least 80 percent. If the CO_2 emission continues with its current trend, dangerous climate change will be unavoidable. It projected that energy related carbon dioxide emissions will increase more than 50 percent of 2005 levels by 2050. The only way to mitigate climate change is rapid development and deployment of low-carbon technologies, they say. Rogelj et al. (2010) estimated that the current emission targets of the countries could not be able to limit the global threshold temperature rise of 2 ^{0}C at the end of the century. The pledges taken by the parties to UNFCCC in the Copenhagen Accord were not enough and the authors estimated increase of 47.9 to 53.6 Gt CO_2-eq yr^{-1} by 2020. This is almost 10-20% higher than today's level. In their opinion, the only way to achieve the target of 2 ^{0}C without such useless extreme pledges is to increase the emission cuts nationally.

Deforestation is one of the major sectors of GHG emission and Brazil leads the list of nations (Houghton, 2005). It is clearing a forest cover of an average of 19500 km2 per year from 1996 to 2005 and released around 0.7 to 1.4 Gt CO_2-eq per year to the atmosphere (Houghton, 2005).

Table. 6.2. Pre-1750 and recent tropospheric concentration of different greenhouse gases and their global warming potential, atmospheric lifetime and radiative forcing.

GAS	Pre-1750 tropospheric concentration	Recent tropospheric concentration	GWP (100-yr time horizon)	Atmospheric lifetime (years)	Increased radiative forcing (W/m^2)
Concentrations in parts per million (ppm)					
Carbon dioxide (CO_2)	280	392.6	1	~ 100	1.85
Concentrations in parts per billion (ppb)					
Methane (CH_4)	700	1874	25	12	0.51
Nitrous oxide (N_2O)	270	324	298	114	0.18
Tropospheric ozone (O_3)	25	34	n.a.	hours-days	0.35
Concentrations in parts per trillion (ppt)					
CFC-11 (CCl_3F)	zero	238	4,750	45	0.060
CFC-12 (CCl_2F_2)	zero	531	10,900	100	0.17
CF-113(CCl_2CClF_2)	zero	75	6,130	85	0.024
HCFC-22($CHClF_2$)	zero	226	1,810	12	0.041
HCFC-141b(CH_3CCl_2F)	zero	23	725	9.3	0.0025
HCFC-142b(CH_3CClF_2)	zero	23	2,310	17.9	0.0031
Halon 1211 ($CBrClF_2$)	zero	4.2	1,890	16	0.001
Halon 1301 ($CBrClF_3$)	zero	3.3	7,140	65	0.001
HFC-134a(CH_2FCF_3)	zero	68	1,430	14	0.0055
Carbon tetrachloride (CCl_4)	zero	86	1,400	26	0.012
Sulfur hexafluoride (SF_6)	zero	7.47	22,800	3200	0.0029
Other Halocarbons	zero	Varies by substance			collectively 0.021

Fossil fuel combustion, cement production and land use change are the main sources of CO_2 emission in to the atmosphere (Rosa and Dietz, 2012; Ehrlich and Holdren, 1971; Jacob, 2005). These three sources together emitted approximately 405 Gt carbon to the atmosphere from the period 1850 to 1998 (Lal and Bruce, 1999). In 1988, 6 Gt of CO_2 was released in to the atmosphere through anthropogenic activities and it became 8 Gt after a decade (Andrasko, 1990; Houghton, 1997). If we stabilize the fossil fuel emission to the present rate of <0.03 Gt C yr^{-1}, warming of the atmosphere can be restricted to <0.2 ^0C. However, if the entire known fossil fuel reserve of ~4000 Gt C is used up, the atmospheric

CO_2 concentration will reach a level of ~1000 ppm and will result in a warming of >5 ^{0}C at the end of this century (Pandey, 2002).

Carbon dioxide is the main GHG causing global warming. Keeling et al. (1995) proposed that the recent disproportionate rise and fall in CO_2 growth rate caused inter-annual variations in global air temperature and precipitation. They suggested that the anomalous CO_2-induced rise in temperature was partially masked by a slowing down in the growth rate of fossil-fuel combustion. But recently the growth in fossil fuel emission has increased. Emission growth rate since 2000 was greater than the climate change emissions scenarios developed in the late 1990s by IPCC (Raupach et al., 2007). If the global temperature increases by in the current rate of 0.03 ^{0}C per year (IPCC',2007) for a long time, an estimated amount of 61 Pg soil organic carbon (double the amount of what is present in the atmosphere) will be released in to the atmosphere in the next 60 years. This amount is approximately equal to 19% of total fossil fuel emission during the same period of time (Jenkinson et al., 1991). Davis et al. (2010) estimated the future emission of CO_2 from different sectors. In their opinion the mitigation of climate change is possible only through overcoming inaction in political, technological and geophysical systems. They calculated the cumulative future fossil fuel emission of 496 Gt CO_2 between 2010 and 2060. This will result in the atmospheric concentration of 430 ppm and warming of 1.3 ^{0}C above pre-industrial period which is a modest estimate.

In an article Stern (2009) outlined a plan to overcome the obstacles in the international agreements on climate change. In this, he presents a new approach of setting strong achievable targets for the reduction of GHGs by considering future economic growth in developing countries. In order to limit the global average temperature below 2 ^{0}C, we need to peak the global emission within the next ten years by reducing the global emission to half of 1990 levels (of about 20 Gt CO_2-eq) by 2050. Today the global emission is around 50 Gt CO_2-eq yr^{-1}. Developed nations like European Union, Japan and United States should reduce at least 80% of their 1990 emissions by 2050 which is a highly ambitious target given that most of these countries were not able to meet the much more modest Kyoto targets. Developing nations like China and India also need to reduce their emission without compromising the economic development. In his review 'The Economics of Climate Change' (Stern, 2006), he reported that the stabilization of atmospheric GHGs at around 500-550 ppm CO_2-eq would require around 1% of global GDP.

More than 80% of world total energy is derived from fossil fuels. Of this coal is supplying 25% of the total energy which emits 40% of world's fossil carbon emission. Almost 6 billion tons of coal is used worldwide, releasing 18 billion tons of CO_2 every year (Chu, 2009). During the period of 1990-2004, developed countries decreased their carbon intensity of economy (tons of CO_2 per 2005 US $) by 25%. In 1990, total GHG emission from United States was 6242 Tg CO2-eq and it went up to 7262 Tg CO_2-eq in 2005, almost 16% increase during this period (Dutt, 2009). Raghunandan et al. (2009) reported that developed countries were responsible for 75% of the historic emission, while today developing countries, particularly China and India are responsible for more than 50% of world's total emission.

In an article Fiala (2008) estimated the environmental coast of meat production. During 2009, world total beef consumption was 72 million tons. This was equivalent to 1100 million tons of CO_2-eq. He calculated the CO_2-eq emission from beef production by converting it into the equivalent emission from car driving. He found that the production of half pound of beef is equal to an emission of 7.4 pounds of CO_2-eq form a car drive of 9.81 miles. When compared to developed countries, developing countries consume much less amount of meat annually. Jacob (2005) reported that per capita meat consumption in India was only 3.4 Kg $person^{-1}$ yr^{-1} when compared to 123 Kg $person^{-1}$ yr^{-1} in US. The cost of producing 1 kg meat in terms of water requirement is 9680 L, while in the case wheat is only 1790 L Kg^{-1}. Developed countries consume more resources and energy than developing and least developed nations.

Results from various studies revealed that, at the end of the year 2050, cumulative CO_2 emissions should be stabilized to 1,000 Gt CO_2 in order to limit global warming below 2 ^{0}C with a 75% probability (Meinshausen et al., 2009). Pathways of global emissions that are in accordance with the target of keeping global warming below 2 ^{0}C compared to pre-industrial levels as visualized by the Copenhagen Accord will very likely require reductions of CO_2 emissions in industrialized countries by 25-40% below 1990 levels by 2020 (IPCC, 2007). However, such reductions would be insufficient to achieve a peak of global emissions in 2020 and reductions of 50% below 1990 levels by 2050. A broad range of energy technology options, including renewables, increased use of biomass, carbon capture and sequestration, nuclear power, and improved energy efficiency is available to reduce CO_2 emissions (IEA, 2008), with low or even negative costs (McKinsey, 2009). Several models suggest that the cost of transformation of the global energy system needed to meet atmospheric CO_2 stabilization targets should not exceed 2.5% of world GDP (Knopf et al., 2009). Additional promising low-cost measures to curb global warming include the reduction of emissions from deforestation and forest degradation (Kindermann et al., 2008) and reduction of emissions of non-CO_2 greenhouse gases, such as CH_4, N_2O and HFCs (Weyant et al., 2006).

6.5. Data Sources and Methodology

Historic data of global carbon dioxide concentration in the atmosphere and country-wise data on CO_2 emission, energy use, economic development and carbon and energy intensity of the economy available in public domains from various authentic sources were used in the present analyses of their interrelationships. These sources were given in the table 6.3 with the type of data downloaded for the analysis.

All the data were analyzed to understand the historic changes through regression analysis. Atmospheric carbon dioxide data for the period of 1958-2012 from National Oceanic and Atmospheric Administration (NOAA), Earth System Research Laboratory, Global monitoring division was used (see www.esrl.noaa.gov/gmd/ccgg/trends). The NOAA ESRL Carbon Cycle Group computes global mean surface values using measurements of weekly air samples from the Cooperative Global Air Sampling Network (Conway et al., 1994; Dlugokencky et al., 1994; Novelli et al., 1992; Trolier et al., 1996). The carbon dioxide data measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. This data recording were started by C. David Keeling of the Scripps Institution of Oceanography (SIO) in March of 1958 at a facility of the NOAA (Keeling, 1976). NOAA started its own CO_2 measurements in May of 1974. The data on atmospheric CO_2 concentration expressed as a mole fraction in dry air which is calculated as micromol/mol and expressed as ppm (parts per million). Country-wise emission and fossil fuel consumption data were collected from different sources (Table 6.3).

The analysis were mainly focused on the BASIC countries (Brazil, South Africa, India and China) set up during fifteenth Conference of the Parties (CoP 15) to UNFCCC at Copenhagen in 2009, world's big economy the United States, other Annex I countries and Non-Annex I countries of UNFCCC. The data period taken for analyses was 1980-2011. Trend analyses were carried out for CO_2 emission, energy consumption, and economic development in terms of GDP and carbon and energy intensity of the economy for all the groups. Rates of change were calculated for the period of 2000-2011. Being more than 80% of the CO_2 emission is from fossil fuels, in most cases the analysis of emissions were limited to the CO_2 emission from consumption and flaring of fossil fuels for which reliable data was available from the sources mentioned above. CO_2 equivalent of GHG emissions from land use change and forestry (LUCF) and non-energy CO_2 emissions from industrial processes like cement production were not taken into account in this analysis due to relatively large uncertainties in the data. World ranking were done using the data of 2011 for CO_2 emission, per capita CO_2 emission and cumulative emission form 1980 to 2011. All the data on CO_2 emission are represented in million tons (Mt), population in millions, energy consumption in quadrillion

British thermal units (qBtu) and gross domestic product in billion US dollars (bUS$) at market exchange rate or current rates.

The noncompliance of the agreements signed by the countries during Copenhagen meet was calculated for the year 2020. Using the current growth rate in emissions and GDP, projected emissions and carbon intensity of GDP were calculated for 2020 and compared with the voluntary agreements made by the world nations in the UNFCCC meets. Extent of Kyoto compliance of Annex I countries was also estimated. The source and period for which various data were taken are given table 6.3.

Table 6.3. Type of data taken for analysis in this chapter and its sources of download from different web portals of different organizations.

Type of data	Period taken for analysis	Website from which data downloaded
Atmospheric CO_2 concentration	1958-2012	Available at the website of National Oceanic and Atmospheric Administration (NOAA) and Scripps Institution of Oceanography (SIO). *www.esrl.noaa.gov/gmd/ccgg/trends* *http://scrippsco2.ucsd.edu/*
Carbon dioxide emission, GDP, Population and carbon intensity and energy intensity	1980-2011	Available at the website of The World bank's World Development Indicators (WDI), World Resource Institute's (WRI) Climate Analysis Indicators Tool (CAIT) and United States' Energy Information Administration (EIA) and International Monetary Fund (IMF) *http://data.worldbank.org/indicator* *http://earthtrends.wri.org/publications/data-sets* *http://www.eia.gov/countries/data.cfm* *http://www.imf.org/external/data.htm#data*
Science and Technology	2009 and 2011	The World bank's World Development Indicators (WDI) *http://data.worldbank.org/indicator*

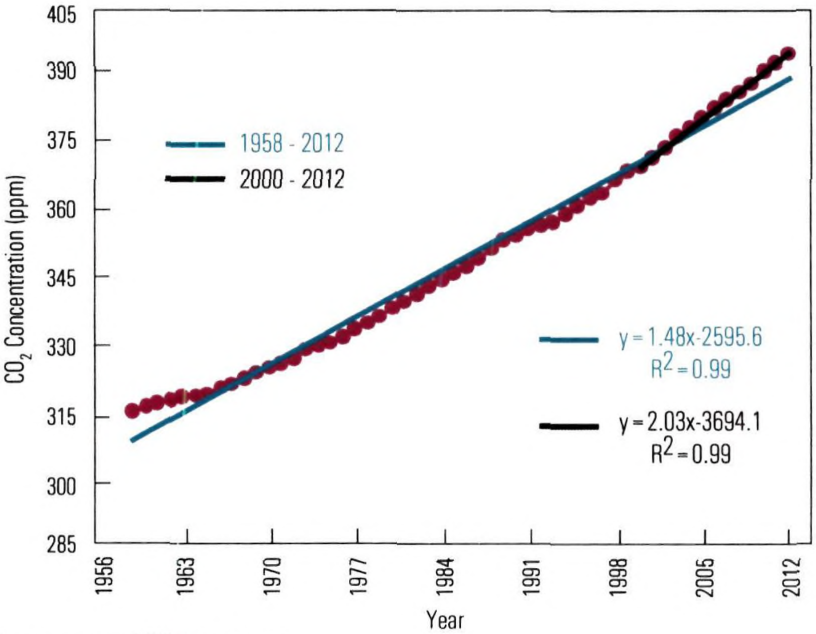
6.6. Results and Discussion

TI have analyzed the trends in world emissions in relation to fossil fuel use and economic growth. These analyses were done at the aggragate national level and for different sectors and the results are presented below. Finally, I also show that increased sequestration of atmosphereic CO_2 by terrestrial and oceanic biomes will be extremely inadequate to reduce or even stabilise atmpsphereic CO_2 conentraion. World must reduce its GHG emissions immediately if global warming and climate change have to be contained within the planned 2 ^{0}C rise.

6.6.1. Trends in rise in atmospheric carbon dioxide concentration

Terrestrial and oceanic biomes are net sinks of CO_2. Until industrial revolution, a balance between the sources and sink was maintained. But now this balance broken because the world is emitting more CO_2 that what the planet can sequester. The result is an increase in CO_2 concentration in the atmosphere. Global CO_2 emission through human activities accounts for more than 70% of the total GHG emission in the world.

Atmospheric CO_2 concentration was more or less steady at 280 ppm for the several thousand years before industrial revolution (IPCC, 2007). With industrial revolution, the atmospheric concentration of CO_2 started increasing and reached a concentration of more than 390 ppm today (Figure 6.1, NOAA, 2013). This increase of 110 ppm has happened in just 150 years which is an unprecedented increase in the recent geological history of the planet. A closer look at figure 6.1 shows that CO_2 concentration is increasing at an increasing rate. When atmospheric carbon dioxide variations were first started at Mauna Loa Observatory, Hawaii in 1958, the concentration was only 315.3 ppm, but now in 2013 the recorded average concentration at Mauna Loa Observatory is about 397.7 ppm (NOAA, 2013). IPCC's fourth assessment report showed a rate of increase of 1.9 ppm yr^{-1} during the period 1995-2005. But the rate has increased to 2.03 ppm yr^{-1} during the period 2000-2012 (Figure 6.1).



Data source: NOAA, 2013

Figure 6.1. Annual mean atmospheric carbon dioxide at Mauna Loa Observatory, Hawaii. Blue straight line indicate the long term trend line for the period 1958-2012 and the black line is the trend line for the period 2000-2013.

6.6.2. World GHG sources and trends in rise in world CO_2 emission

The sources of anthropogenic emission can be broadly classified into three sectors such as fossil fuels, land use change and waste. The main sources of CO_2 emissions which are coming under these sectors are power, deforestation, industry, agriculture, transport, buildings and others. Power sector is the main source of CO_2 emission which accounts for 24% of the total emission (Figure 6.2). Deforestation comes in second with 18% and the transport, agriculture and industry sectors together contribute 42% of the total with equal shares of 14% each. Buildings including residential and commercial buildings contribute 8% and other sources altogether accounts for 8% of the total CO_2 emission.

World GHG emission (including land use change) in 1990 was 35663.7 Mt CO_2-eq, but it was increased by 11518.9 Mt CO_2-eq and reached 47182.6 Mt CO_2-eq (32.3 % increase in 21 years) in 2010. World total GHG emission from land use change and forestry was 3620.9 Mt CO_2-eq in 1990 and decreased to 2639.9 Mt CO_2-eq in 2010 (a reduction of 27.1% in 21 years). Within the total GHG emission, the contribution of carbon dioxide was about 74% and rest of the greenhouse gases like methane, nitrous oxide and other fluorinated GHGs (HFC, PFC and SF6) contributed 16%, 8% and 2%, respectively. The main source of CO_2 emission is the consumption and flaring of fossil fuels which alone contributed more than 70% of the total CO_2 emission in the world (indicate which are the sectors that add up to 70% in figure 6.2). This chapter mainly focuses on the CO_2 emission from consumption and flaring of fossil fuels.

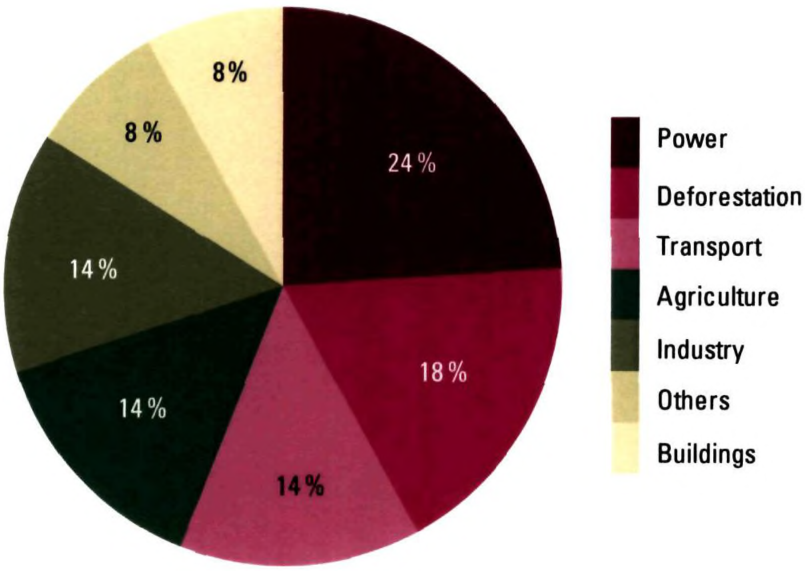


Figure 6.2. Percentage contribution of CO_2 emission from different sources.

In the middle of the 19th century, industrialization started with the uncontrolled use of fossil fuels resulted in the emission of huge amounts of CO_2 in to the atmosphere. Even though the global warming potential of CO_2 is 1 when compared to other GHGs that are having much higher values of GWP, the amount of CO_2 released in to the atmosphere was huge which led to increase in its atmospheric concentrations in parts per million compared to other GHGs which increased marginally in parts per billion only. Thus CO_2 contributed the highest to global warming. Today the world total CO_2 emission to the atmosphere from consumption and flaring of fossil fuels is about 32578.7Mt yr^{-1}. This was only 21523.2Mt yr^{-1} in 1990 and increased by more than 50% and has reached today's emission. Major contributors are the developed countries and the big economies in developing countries. China, United States, Russia, India, Japan and Germany are the major CO_2 emitting countries in the world. The emission of these six major emitters together represents more than 60% of the world's total CO_2 emission. China's contribution of CO_2 to the world total was about 27% which is more than the total CO_2 emission from power sector and U.S. alone representing an equal amount of CO_2 emission from deforestation (Figure 6.3). Again these countries are the major emitters of other GHGs too.

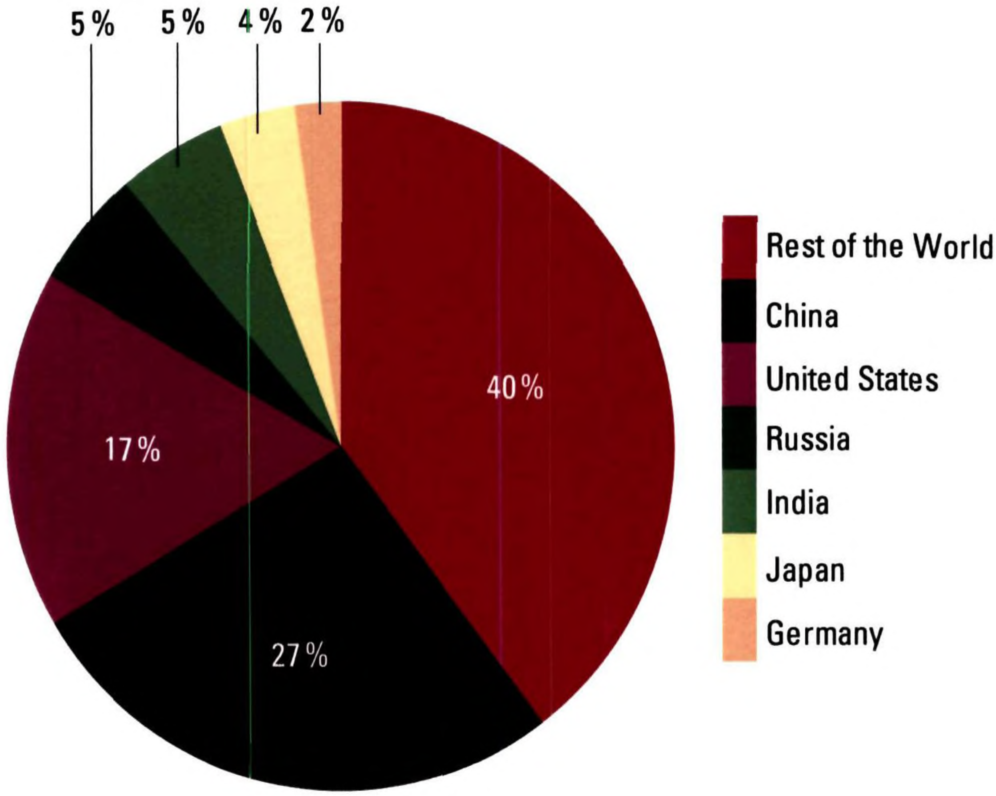


Figure 6.3. Percentage contribution of CO_2 emission by major emitters in the world.

Developing and least developed economies represent more than 80% of world's total population which together contributed more than 75% of global emission in 2011 (Table 6.4). The main contributor is China. Since 2006, China ranks first in the world CO_2 emission. Out of 32578.6 Mt yr^{-1} of world total CO_2 emission, China alone accounted for 8715.3Mt yr^{-1} in 2011. US contributed 17% (5490.6 Mt yr^{-1}) of the world total emission in 2011 (Table 6.4, Figure 6.4). World's top twenty emitters including the developed and developing nations represents more than 80% of global emission with 79% of the global gross domestic product. Global GDP in 2011 was 70371.4 bUS$ and more than 30% of this was from U.S. and China only.

Global CO_2 emission grew at a rate of 787.1Mt yr_{-1} during 2000-2011 of which more than 65% was contributed by China alone. Global cumulative CO_2 emission from 1980 to 2011 was 753896.1Mt and around 38% it was from US and China alone (Figure 6.5). In this United State's contribution was 169770.5 Mt (23% of world total) and China's was 112815.8Mt (15% of world total). If we consider the cumulative emission from the start of industrialization, US contribution to would be very huge and China's contribution may be less than 5%.

The only paradox between US and China or even with the developed and developing economies is that the per capita emission, per capita GDP and their human development index (HDI) are smaller in the latter (HDR, 2007). Almost all developed nations have a large per capita emission and per capita GDP due to less population compared to developing economies. In developing nations these two factors are almost similar or below the world average. Also the HDI of developing nations are generally below 0.7 (HDR, 2007; Table 6.4). HDI is a measure of human development in a country which is calculated based on the income, life expectancy and education. Within this the income of a country has the main contribution and good correlation with the HDI value. Because of the low income in developing countries, the living standard is also low and coming under the low human development.

Table 6.4. Different variable related to emission and economy of top twenty CO2 emitters in the world. All the data for the year 2011 and the emission rate calculated for the period of 2000-2011. Human development index values are for the year 2012.

Country	2011 CO_2 emission ($Mt\ yr^{-1}$)	Rate of emission (2000-2011) $Mt\ yr^{-1}$)	2011 Per capita CO_2 emission ($Mt\ yr^{-1}$)	Cumulative CO_2 emission from 1980-2011 ($Mt\ yr^{-1}$)	2011 CH_4 emission ($Mt\ CO_2$-eq yr^{-1})	2011 N_2O emission ($Mt\ CO_2$-eq yr^{-1})	2011 HFC, PFC and SF_6 ($Mt\ CO_2$-eq yr^{-1})	2011 GDP (current bUS$)	2011 Per capita GDP (current US$)	2012 Human Development Index (HDI)	2011 Population (Millions)
Poland	307.9	2.0	8.0	10917.9	65.5	26.8	2.6	515.7	13382.1	0.8	38.4
Spain	318.6	0.1	6.8	8722.4	36.8	22.6	12.1	1476.9	31984.7	0.9	46.8
France	374.3	-1.5	5.7	12671.4	83.8	38.7	21.7	2779.7	42521.8	0.9	65.3
Australia	392.3	5.5	18.0	10073.3	122.5	51.5	9.1	1384.1	62002.8	0.9	21.8
Italy	400.9	-4.3	6.6	13311.2	37.5	19.6	15.5	2192.4	36103.9	0.9	61.0
Indonesia	426.8	15.6	1.7	7284.4	218.9	91.3	1.2	846.3	3471.4	0.6	246.1
South Africa	461.6	9.4	9.4	11549.2	65.3	21.9	3.2	401.8	7942.8	0.6	49.0
Mexico	462.3	7.7	4.1	10994.0	115.9	43.1	12.0	1158.1	9702.9	0.8	113.7
Brazil	475.4	11.7	2.4	9437.1	443.3	207.6	10.6	2476.7	12576.0	0.7	197.6
United Kingdom	496.8	-5.2	7.9	18402.5	61.2	26.5	14.3	2444.9	38960.8	0.9	62.7
Saudi Arabia	513.5	18.3	19.7	8911.3	60.3	6.2	2.9	576.8	20777.7	0.8	26.1
Canada	552.6	-2.3	16.2	16499.4	104.5	33.0	29.8	1777.8	51554.1	0.9	34.0
Korea, South	611.0	13.0	12.5	11222.8	32.0	14.7	9.0	1114.5	22388.4	0.9	48.8
Iran	624.9	26.9	8.0	9620.5	115.3	23.9	3.1	514.1	6815.6	0.7	77.9
Germany	748.5	-10.0	9.2	17959.5	57.2	42.4	26.8	3600.8	44021.2	0.9	81.5
Japan	1180.6	-4.2	9.3	34804.3	40.3	25.7	70.8	5896.8	46134.6	0.9	127.5
India	1725.8	71.9	1.5	27303.0	621.5	234.1	23.5	1872.8	1533.7	0.6	1189.2
Russia	1788.1	20.3	12.5	31948.6	533.5	63.7	63.4	1899.1	13284.0	0.8	142.5
United States	5490.6	-26.8	17.6	169770.5	524.7	304.1	350.4	14991.3	48112.6	0.9	311.6
China	8715.3	509.5	6.5	112815.8	1642.3	550.3	222.7	7321.9	5447.3	0.7	1336.7
World	32578.6	787.1	4.7	753896.1	7515.2	2859.8	1003.3	70371.4	10102.2	0.7	6940.1

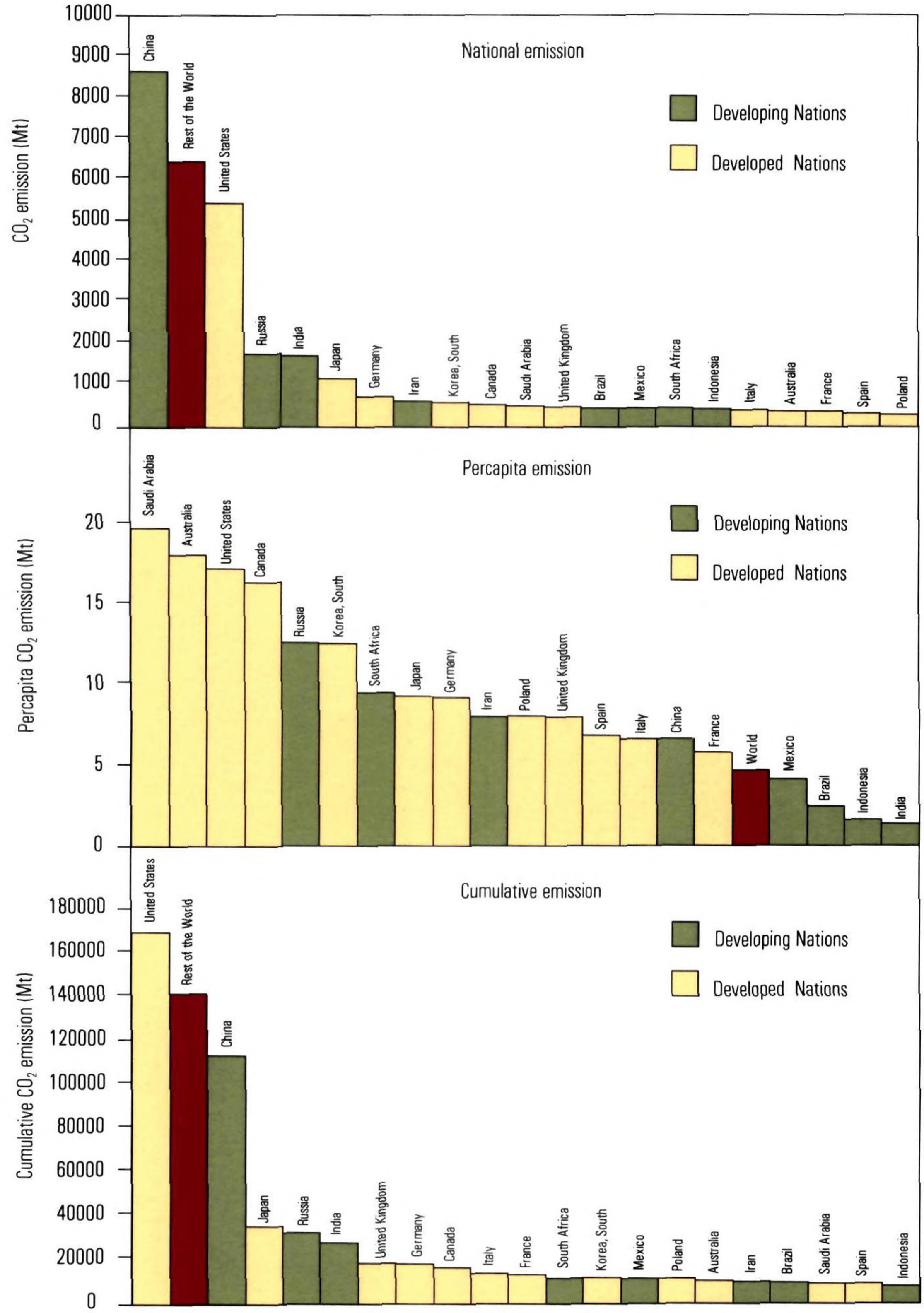


Figure 6.4. Top twenty CO_2 emitters in the world and their per capita emission rank for the year 2011 and rank in cumulative emission from 1980 to 2011

6.6.3. Emission, energy and economy: a comparison between BASIC countries (Brazil, South Africa, India and China) and Annex I countries to UNFCCC

During the ending days of the CoP15 held in Copenhagen in 2009, major emitters in the developing countries namely, Brazil, South Africa, India and China and the big emitter of developed nations the US conducted bilateral negotiations outside the meeting. The four developing countries then named as 'BASIC' countries based on the increasing order of CO_2 emission and the first letters of their names read from back. During the meeting the BASIC countries agreed for voluntary emission cuts. Annex I parties mentioned in the Appendix I of Copenhagen Accord provided their mitigation action as quantified economy-wide emissions targets for 2020 and the non-Annex I countries mentioned in the appendix II of Copenhagen Accord provided their mitigation actions as nationally appropriate mitigation actions (NAMAs). Brazil's voluntary commitment was the reduction of Amazon deforestation and Cerrado deforestation which together accounts for about 668 Mt CO_2-eq by 2020. South Africa reiterated that it will take NAMA to enable a 34% reduction of 'Business As Usual' (BAU) emissions growth trajectory by 2020 and a 42% reduction by 2025. India will attempt to voluntarily reduce carbon intensity of its economy by 20-25% of 2005 level by 2020 (which is even otherwise an achievable target going by the present rate of decarbonisation of Indian economy, Figure 6.9). Here the emissions from agriculture sector will not be taken into account for the calculation of the emissions intensity. China's voluntary emission reduction commitment through nationally appropriate mitigation actions was to reduce its carbon intensity of the economy by 40-45% of 2005 level by 2020 (which appears highly unlikely, Table 6.7). The other actions they proposed were that they will increase the share of non-fossil fuels in national primary energy consumption to around 15% by 2020 and increase forest coverage by 40 million hectares and forest stock volume by 1.3 billion cubic meters by 2020 from the 2005 levels. United States' economy wide emission reduction target was an offer to reduce of 17% of its 2005 level CO_2 emission by 2020.

Trends in emission, economy and carbon intensities of BASIC countries and Annex I countries are discussed below. India and China are discussed in greater details as there is a usual practice of treating China and India together in the international climate negotiations due to their similarities in faster economic growth or population, although there are more differences than similarities in economy, emission and energy consumption between these two countries.

6.6.3.1. Why big economies' emission is always big?

It is a well-established fact that economic growth is driven by the energy consumption. If we consume more energy, the economy will grow faster. More than 85 % of the world's commercial energy is supplied by the fossil fuels (IPPC, 2007) which are the major source of CO_2 emission. For the growth of the economy, a country needs to consume more energy and for more energy we need to burn more and more fossil fuels. It will emit huge amount of CO_2 in to the atmosphere and ultimately result in the global warming. There is a near perfect correlation between energy consumption, fossil fuel usage, carbon dioxide emission, and economic growth (Figure 6.5). Since 2000 to 2011, world GDP has grown by 3620.8 bUS\$ yr^{-1}. At the same period the energy consumption and the CO_2 emission from fossil fuel also increased at the rate of 11.53 quadrillion Btu yr-1 and 787.1 Mt yr^{-1}, respectively. United States is the biggest economy in the world with a GDP of 14,991.3 bUS\$ in 2011(Figure 6.6). The percentage contribution of US GDP to the world total was 21.3% with 16.9% of CO_2 emission by consuming world's 19.2% of energy (Table 6.5, Figure 6.6). China's economy is the second with a contribution of 10.4% of the world GDP by consuming 19.8% of global energy consumption with 26.8% of global emission. This makes the carbon intensity of Chinese GDP much bigger than that of the US. The Annex I countries to UNFCCC (42 developed nations) together represent 65.3% GDP, 50.5% energy consumption and 43.2% CO_2 emission of the world total. The economy of the developing nations usually consume less energy when compared to developed nations, but carbon intensity of their GDPs is higher, despite their economic development is very small. This is because of the large dependence of poor economies on carbon intensive technology. Countries like Tuvalu and Kiribati are the least developed nations in the world and their energy consumption and emission are the least negligible.

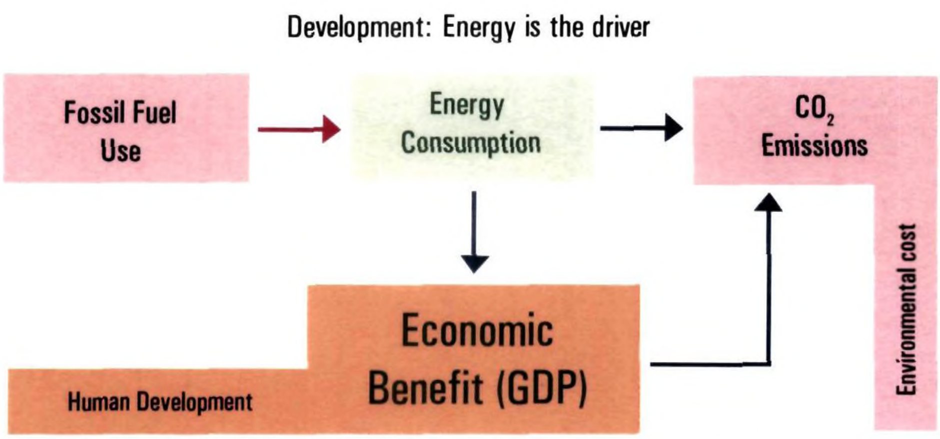


Figure 6.5. E[3] Vicious cycle. The relationship between fossil fuel use, energy consumption, emission and economic development.

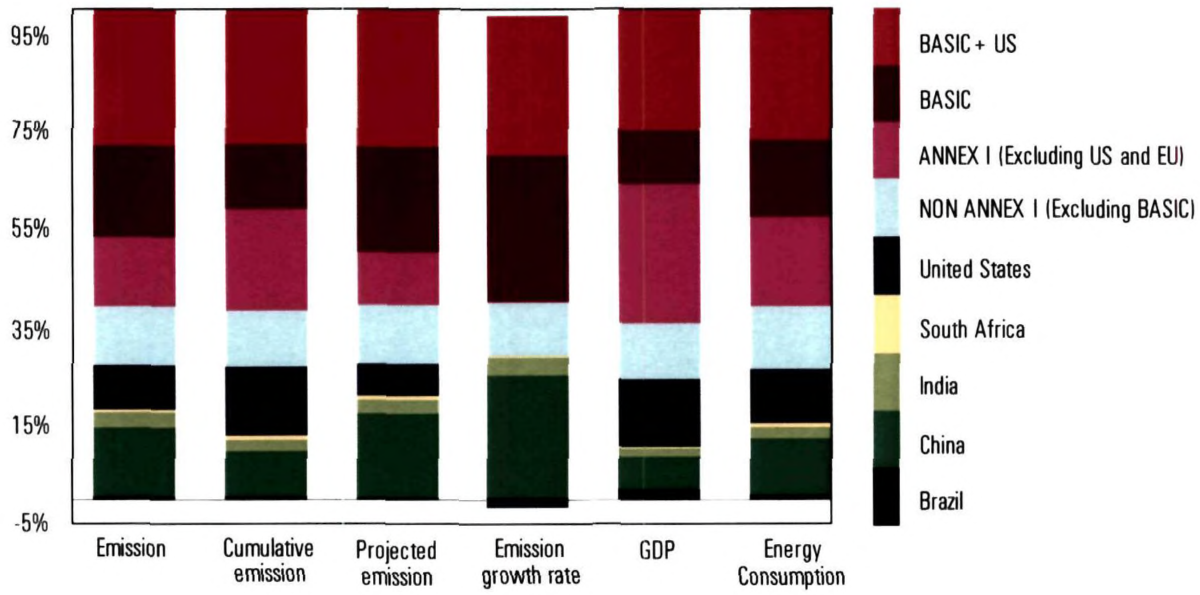


Figure 6.6. Relative contributions of Annex I, non-Annex I and BASIC countries to national aggregate CO_2 emission, cumulative emission (1980-2011), projected CO_2 emission (2020) CO_2 emission growth rate (2000-2011), gross domestic product and total energy consumption during the year 2011.

6.6.3.2. Who will share most of the carbon space in the atmosphere?

It It is a common responsibility of all countries to reduce the CO_2 emission, whether they are developed, developing or least developed nations even as the UNFCC states that there is differentiated responsibility to mean the bigger responsibility of the developed nations that have contributed more to atmospheric CO_2 concentration. Historically the developed nations shared more carbon space in the atmosphere thus contributed more to climate change. Since carbon emission is related to economic development, carbon space means the developmental space for a country. If the developed countries cut their emissions, the carbon space thus released will become available for the developing countries. Atmospheric commons should be used with equity.

During the period of 1980 to 2011, world's cumulative CO_2 emission reached 753896.1 Mt. (Figure 6.7, Tale 6.5). United States' cumulative emission during this period was 169770.5 Mt, which accounts almost 22.5% of world total. Today's big emitter, China's cumulative emission was far below that of the US and was just 15% of the global total (112815.8) which may be even less than 5% if a longer period is taken into account. Annex I countries including the US alone contributed 55.3% of world total and the non-Annex I countries (numbering more than 150 countries) excluding the BASIC countries' cumulative emission was only 21.4 % (161105.2 Mt) of the world total cumulative emission from 1980 to 2011; yet these are the countries that will take most of the brunt of global warming. India's contribution was only 3.6% (27303.0 Mt) to the world total. During 1980, the national aggregate emission in US was 4775.8Mt CO_2 (25.9% of world total) and this increased to 5490.6Mt in 2011 which was only 16.9% of the world total. China's 1980 emission was 1448.5 Mt which represents only 7.9% of the world total. It was increased to 8715.3 Mt in 2011 (around fivefold increase in 30 years) with a percentage contribution of 26.8% to the world total (Table 6.5). India's contribution was only 1.6% in 1980 and 5.6% in 2011. Projected CO_2 emission in 2020 for China showed that 33.5% of the atmospheric carbon space will be shared by China alone, provided that the present rate of growth in emission continues there. The Annex I countries including US will account only 34.8 % by then.

Today China is the top CO_2 emitter in the world, but its contribution to the historic cumulated CO_2 emission is much less when compared to US and other developed countries. So historically the most of the carbon space in the atmosphere was shared by the developed nations with a lion share by US alone. Sharing of more carbon space in the atmosphere means more contribution to climate change. Thus the developed nations contributed the most to climate change, but future climate change can be attributed a lot to China. Because Chinese economy and emissions are growing very fast and the present analysis shows that more than one fourth of the atmospheric carbon space will be occupied by China alone by 2020 year (Figure 6.8). While the present atmospheric carbon space is almost equally shared between the developed and developing nations, in future it would be mostly China that will contribute to global warming.

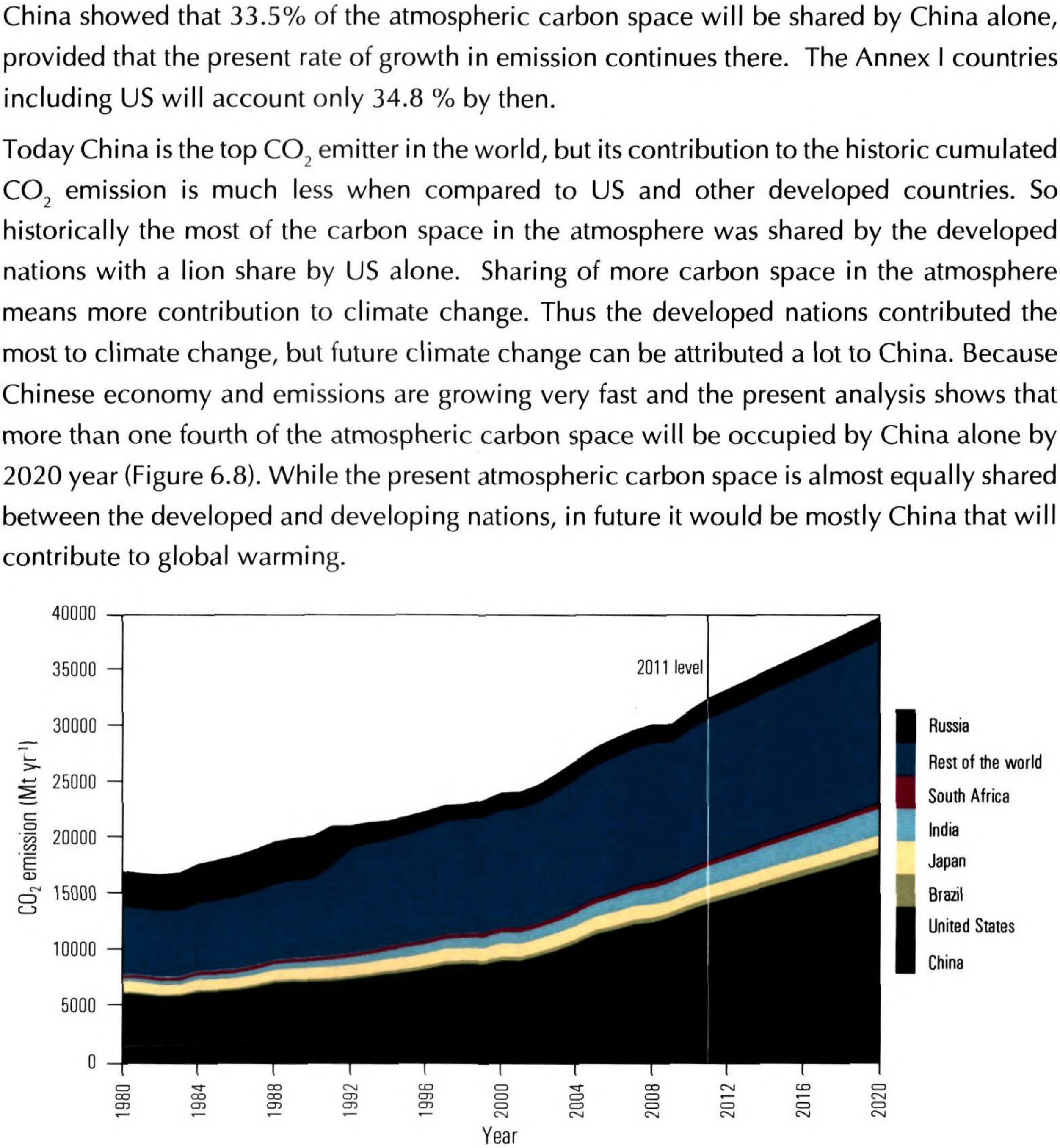


Figure 6.7. Share of atmospheric carbon space in the past and future for top CO_2 emitters in the world.

Table 6.5. Actual and percentage contribution of emission, cumulative emission, emission growth, projected emission and energy consumption of BASIC, non-annex I and Annex I countries to the world total.

Country/Region	1980 CO_2 emission (Mt)	% to World total	2011 CO_2 emission (Mt)	% to World total	Change from 1980 to 2011 (Mt)	% Change from 1980 to 2011 (Mt)	Cumulative emission from 1980 to 2011 (Mt)	% to World total	Emission growth rate (Mt yr^{-1})	% to World total	Projected emission for 2020 (Mt)	% to World total	Energy consumption (quadrillion Btu)	% to world total
Brazil	185.7	1.0	475.4	1.5	289.7	156.1	9437.1	1.3	11.7	1.5	580.6	1.5	11.3	2.2
China	1448.5	7.9	8715.3	26.8	7266.8	501.7	112815.8	15.0	509.5	64.7	13300.5	33.5	100.9	19.8
India	291.2	1.6	1725.8	5.3	1434.6	492.6	27303.0	3.6	71.9	9.1	2372.8	6.0	21.9	4.3
South Africa	235.0	1.3	461.6	1.4	226.6	96.4	11549.2	1.5	9.4	1.2	546.0	1.4	5.6	1.1
United States	4775.8	25.9	5490.6	16.9	714.8	15.0	169770.5	22.5	-26.8	-3.4	5249.3	13.2	98.0	19.2
NON ANNEX I (Excluding BASIC)	5709.6	31.0	7137.3	21.9	1427.7	25.0	135370.1	18.0	216.6	27.5	9086.4	22.9	112.8	22.1
ANNEX I (Excluding US and EU)	5787.4	31.4	8572.6	26.3	2785.2	48.1	247114.8	32.8	1.3	0.2	8584.3	21.6	160.0	31.3
BASIC	2160.4	11.7	11378.0	34.9	9217.6	426.7	161105.2	21.4	602.4	76.5	16799.7	42.4	139.7	27.4
BASIC + US	6936.2	37.6	16868.7	51.8	9932.5	143.2	330875.7	43.9	575.6	73.1	22049.2	55.6	237.7	46.6
World Total	18433.2	100	32578.7	100	14145.5	76.7	753896.1	100	787.1	100	39662.9	100	510.6	100

6.6.4. India and China in climate change negotiations

More differences than commonalities exist between India and China when it comes to energy, emission and economy. Curbing a small per cent of Chinese emissions will have more impact on world emissions than a similar cut in emissions by India. Since the carbon intensity of Chines GDP is above that of India, there is no reason why Chinese emissions cannot come down without compromising their GDP.

6.6.4.1. Difference in CO_2 emission and energy use

Global CO_2 emission in 1980 was 18433.2, increased by 76.7% during the period 1980-2011 and reached 32578.7Mt in 2011 (Table 6.5). China and India have increased their emissions by 501.7% and 492.6%, respectively in 2011 compared to 1980 level, but between 1990 to 2011, China's total emission increased by 300.2% and India's emission increased much less (198.3%). China's percentage contribution to the world total in 1980 was 7.9% and this increased to 26.8% in 2011. India's contribution to the world total was only 1.6 and 5.3% in 1980 and 2011, respectively (Table 6.5).

During 2000-2011 world CO_2 emission increased at the rate of 787.1Mt a year and 64.7% of this was contributed by China alone (509.5 Mt yr^{-1}). India's rate of increase was 71.9 Mt yr^{-1} with a percentage contribution to the world total of 9.1% during the same period. With the current rate of emission growth rate, India will take several decades to reach today's emission from China.

BASIC countries alone have a rate of growth in emission that is as high as 602.4 Mt yr^{-1} which is 76.5% of the world total emissions. US aggregate national emission decreased at a rate of 26.8Mt yr^{-1} during the period of 2000-2011. China's historic cumulative CO_2 emission from 1980 to 2011 was 112815.8 Mt (15.0% of world total for the same period) and projected emission for 2020 will be 13300 Mt (33.5% of the world total in 2020). India's contribution in cumulative emission and projected emission is almost five times less (27303.0 Mt since 1980-2011 and 2372.8 Mt in 2020) compared to China. Per capita emission of China is markedly higher than that of India (Table 6.4). India's per capita CO_2 emission (1.5Mt $person^{-1}$ yr^{-1}) is four times below that of China (6.5Mt $person^{-1}$ yr^{-1}).

The primary energy consumption was also huge in China compared to India. China consumed 19.8% (100.9 quadrillion Btu) of the total energy consumed by the world in 2011, contributing 26.8% of the global emission. India's energy consumption and emission were very less (21.9 qBtu and 1725.8Mt in 2011; 4.6% and 5.3% of the world total) compared to China. India's percentage energy consumption and emission to the world total were almost equal indicating that its economy is less energy intensive than China's. This means China's energy sector is much more emitting than India's. China's consumption of fossil fuel energy to its total energy consumption was 88% (Figure 6.8). Around 50% of world's total coal was consumed by China alone which is the most emitting form of fossil fuel.

During 2011 China consumed 7178.2 Mt coal while the consumption of coal by the whole world was 14416.3Mt in the same year (Table. 6.6). India's percentage of fossil fuel energy consumption to the total energy is 73% only and it is below than the world average of 81%. During 2011 India consumed 1149.6Mt coal with a growth rate of 48.5 Mt yr^{-1} while China's rate of coal consumption for the period of 2000-2011 was 433.1 Mt yr^{-1}, almost ten times higher than India's. Petroleum consumption was also higher in China which accounted for 11% of the world total.

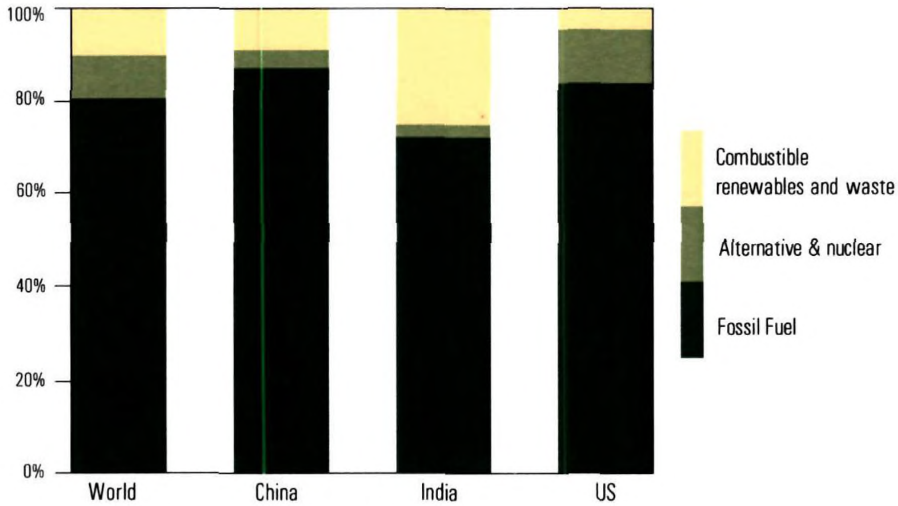


Figure 6.8. Relative contributions of different energy sources to the total energy consumed by China, India, US and the world in 2011.

6.6.4.2. Difference in GDP, carbon intensity and energy intensity between India and China

Economic development is the main factor which determines human development in a country. World's biggest economy (14991.3 bUS$ in 2011) is United States and its economy grew at a rate of 488.6 bUS$ yr^{-1} (Table 6.8). China is the second largest economy (7329.1 bUS$) and its economy grew by 535.4 bUS$ yr^{-1} during the period 2000-2011, which is faster than United States. India's position is tenth in the world with a national GDP of 1872.8 bUS$ in 2011. China contributes world's 10.4% GDP while India contributes only 2.7% to the world total. The growth rate of Indian GDP was also very small compared to China. India's economy grew by 129.2 bUS$ yr^{-1} during the period 2000-2011. Per capita GDP was also very high in China compared to India (Table 6.4). India's per capita GDP in 2011 was 1533.7 US$ per person in 2011, while in China it was 5447.3 US$ per person.

Table 6.6. Consumption different types of fossil fuels and renewable energy sources in 2011 and their growth rate in consumption (2000-2011) in BASIC, non-annex I and Annex I countries.

Country/Region	Coal		Petroleum		Natural gas		Renewable energy		Biofuel	
	2011 (Mt)	Growth (Mt yr^{-1})	2011 (000' barrels day^{-1})	Growth (000' barrels $day^{-1} yr^{-1}$)	2011 (bCF yr^{-1})	Growth (bCF yr^{-1})	2011 (bKWh yr^{-1})	Growth (bKWh yr^{-1})	2011 (000' barrels day^{-1} yr^{-1})	Growth (000' barrels day^{-1} yr^{-1})
Brazil	49.60	0.40	2721.62	48.33	884.99	48.30	459.28	15.55	377.42	28.07
China	7178.19	433.07	9852.08	462.55	4623.55	322.37	797.42	53.20	45.00	4.63
India	1149.63	48.50	3410.54	117.43	2260.51	138.60	162.00	7.74	8.00	0.24
South Africa	366.96	7.28	595.00	10.83	161.74	9.24	1.93	0.01	0.13	0.01
United States	1874.00	-19.26	18949.43	-78.18	24385.00	119.98	524.46	12.98	898.89	79.59
NON ANNEX I (Excluding BASIC)	1321.03	49.97	27948.59	580.31	37455.87	1546.06	548.38	11.08	88.99	7.57
ANNEX I (Excluding US and EU)	2476.84	-4.36	25090.56	-93.40	48938.08	539.29	1642.74	32.63	401.37	38.56
BASIC	8744.37	489.25	16579.25	639.13	7930.80	518.51	1420.64	76.50	430.55	32.95
BASIC + US	10618.37	469.99	35528.68	560.95	32315.80	638.48	1945.10	89.48	1329.44	112.54
World Total	14416.25	515.60	88567.82	1047.87	118709.74	2723.83	4136.22	133.19	1819.80	158.67

Table 6.7. Comparison of 2011 actual and projected (for 2020) gross domestic product, carbon intensity and energy intensity in BASIC, non-annex I and Annex I countries. The growth rates are calculated for the period 2000-2011.

Country/Region	GDP (bUS$)					Carbon Intensity (Mt CO2/bUS$)					Energy Intensity (Btu/UD$)				
	2011	% to world total 2011	Rate of increase (bUSD y^{-1})	Projection 2020	% to world total 2020	2005	2011	Rate of change	Projection 2020	% change from 2005	2005	2011	Rate of change	Projection 2020	% change from 2005
Brazil	2476.7	3.5	175.1	4052.9	3.9	0.42	0.42	-0.003	0.39	-6.80	10610.9	10312.0	-68.9	9692.2	-8.66
China	7321.9	10.4	535.4	12140.4	11.8	2.42	2.08	-0.020	1.90	-21.44	30092.4	26130.8	-239.7	23973.3	-20.33
India	1872.8	2.7	129.2	3035.4	2.9	1.41	1.29	-0.031	1.01	-28.62	19505.0	17581.1	-415.0	13846.0	-29.01
South Africa	401.8	0.6	24.9	625.6	0.6	1.75	1.55	-0.026	1.32	-24.57	20734.3	19183.2	-284.2	16625.2	-19.82
United States	14991.3	21.3	488.6	19388.6	18.8	0.48	0.41	-0.010	0.32	-31.62	7944.3	7164.9	-138.7	5916.4	-25.53
Non Annex I (Excluding BASIC)	12377.4	17.6	735.7	18998.4	18.5	0.95	0.82	-0.020	0.64	-32.29	17162.1	14563.8	-385.9	11091.1	-35.37
Annex I (Excluding US and EU)	30929.5	44.0	1532.0	44717.4	43.4	0.74	0.64	-0.022	0.45	-39.10	11757.4	9261.0	-405.0	5616.1	-52.23
BASIC	12073.2	17.2	864.6	19854.2	19.3	1.50	1.33	-0.020	1.16	-23.01	20235.6	18301.8	-252.0	16034.2	-20.76
BASIC + US	27064.5	38.5	1353.1	39242.8	38.1	0.99	0.87	-0.015	0.74	-25.08	28180.0	25466.7	-390.7	21950.6	-22.11
World	70371.4	100	3620.8	102958.6	100	0.62	0.62	0.001	0.63	2.05	10031.0	9842.4	-15.4	9703.8	-3.26

Carbon intensity is the ratio of the amount of carbon dioxide produced per unit of GDP. Less carbon intensity of a country means more GDP is made with less emission. The economy of a country is said to be clean or green if the carbon intensity is minimum. All major economies try to reduce their carbon intensity by reducing the fossil fuel use and using more renewable energy sources and also by improving technology with better energy use efficiency. Most developed countries had an average carbon intensity of less than 1.0 Mt CO_2/ bUS$ for a long period of years (Figure 6.9a). Even though the carbon intensity of China showed a big reduction from 1980 to 2011, in the recent years the rate of reduction has slowed down and still it showed a big carbon intensity of 2.08 Mt CO_2/ bUS$. India's carbon intensity was 1.3 Mt CO_2/ bUS$ during 2011.

During 2000-2011 period China's economy decarbonized at a rate of 0.02 Mt CO_2/ bUS$ while in India this was 0.03 Mt CO_2/ bUS$ (Table 6.7). China's voluntary emission reduction commitment through nationally appropriate mitigation action in CoP 15 at Copenhagen was it will reduce its carbon intensity of the economy by 40-45% of 2005 level by 2020. India's commitment was only 20-25% reduction in carbon intensity of 2005 level by 2020. With the current rate of reduction in the carbon intensity of China, the projected carbon intensity for 2020 would be 1.9 Mt CO_2/ bUS$ with a reduction of 21.4% of 2005 level which is much below the commitment made by China at CoP 15. India will reduce 28.6% of 2005 level by 2020 which is more than the commitment made at CoP 15. United States' agreed for a voluntary cut in emission through economy wide emission reduction target of 17% of 2005 national emission. With an emission reduction rate of 26.8 Mt CO_2 yr^{-1}, United States' projected national aggregate emission for 2020 would be 5249.3 Mt (Table 6.5) with a percentage reduction of 12.5% of 2005 level emission (5999.3 Mt).

6.6.4.3. Difference in scientific and technological development between India and China

China invests 1.7%of its GDP in scientific research while in India it is only 0.8% of its national GDP (Table 6.8). United States spends 2.9% of its national GDP for research and development purposes. While calculating the actual amount from the percentage it will be huge amount for China and US when compared to India because the national GDP of China and United States are very big compared to India. India and China are having 1.19 and 1.35 billion population, respectively. In India from this total population, the number of researcher's working in research and development during the year 2009 was only 136 persons per million people. In China this was as large as 863 persons per million people, a number which is almost 6 fold greater than in India. In US this was even bigger (4673 persons per million people) because the total money spending in US for research is 2.9

percent of its GDP, which is almost equal to 25% of the annual GDP of India. The output of all these research works and innovations are measured in terms of scientific publications and the patents which applied for. Number of scientific and technical articles published by China during 2009 was 74019, which accounted for 10% of world total (Table 6.8). In United States the number was 208601, almost 27% of the world total. India's total number of scientific and technical journal articles published during 2009 was only 19917, which represented only 3% of the world total.

Similar was the case of the number of resident patent applications form the country. It was only 8841 patent applications in India during 2011 which was only 0.7% of the world total. But in China this number was as big as 415829 patent applications in 2011, which accounted for 33% of the world total (Table 6.9). With a higher GDP, faster growth in GDP and much higher scientific and technology vibrancy, China still has a much bigger carbon intensity on its economy.

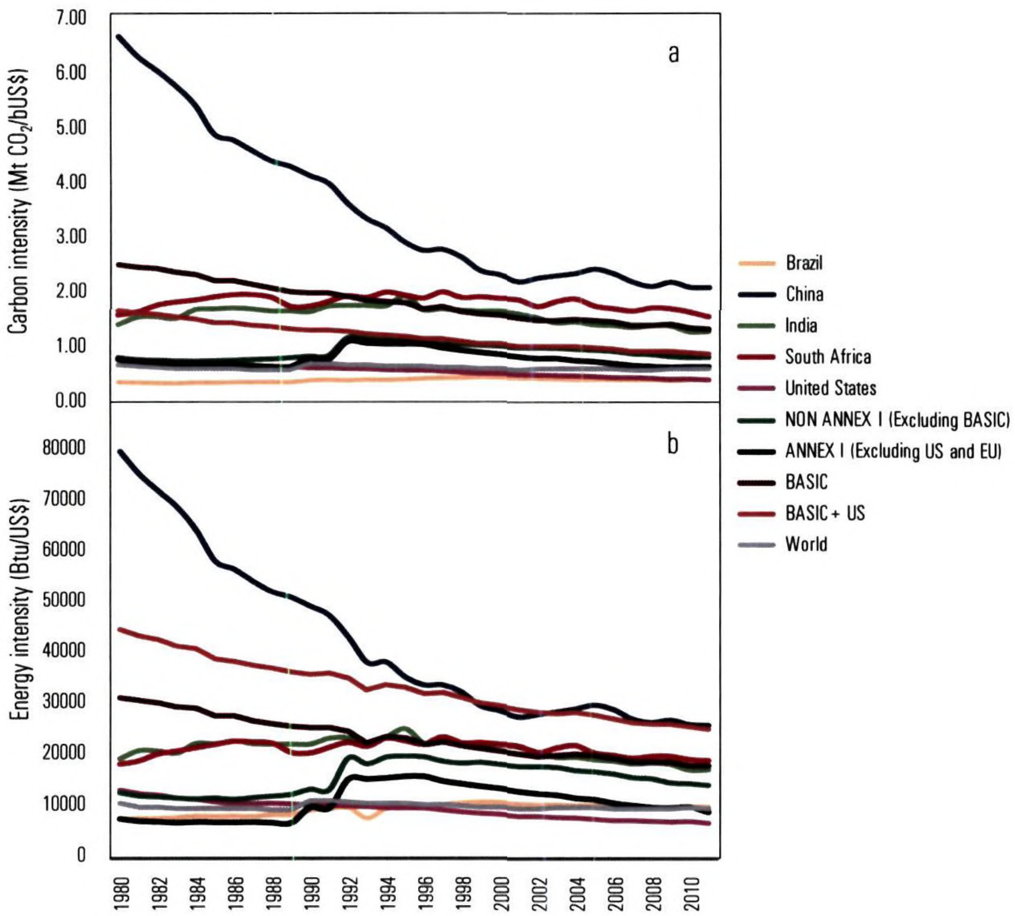


Figure 6.9 (a&b). Trends in historic (a) carbon intensity and (b) energy intensity between 1980-2011 for BASIC, non-annex I and Annex I countries.

Table 6.8. Comparison of scientific development in terms of research expenditure, number of researchers and number of publications from China, India and United States during the year 2009.

Country Name	Reserch expenditure (% of GDP)[a]	Reserchers in R&D (per million people)[a]	Number of scientific and technical journal articles[a]	Number of patent application (resident)[b]
India	0.8	136	19917	8841
China	1.7	863	74019	415829
United States	2.9	4673	208601	247750
World	2.2	1272	788333	1264981

[a]Values for the year 2009; [b]Value for the year 2011

6.6.4.4. Trees alone cannot be the answer to climate change

The analyses given above show that CO_2 emission is on the rise and may continue to rise for many more years due to our dependence on fossil fuels. Accumulation of CO_2 in the atmosphere is a dynamic function of the balance between the amount of CO_2 emitted by the world and the total amount of CO_2 sequestered by the planet (through photosynthesis) during a given period of time.

Atmospheric CO_2 concentration = CO_2 Emission – CO_2 Sequestration Eqn. (1)

From the above equation, it is evident that growing more trees can reduce atmospheric CO_2 concentration. Globally, the rate of deforestation is much larger than that of reforestation. The rate of forest destruction in the Amazon rainforests which has come down markedly in recent years is still as large as about 5000-6000 $Km^2\ yr^{-1}$ (Carrington, 2010). Recent studies estimated a net emission of GHGs from the Mato Grosso region of Brazilian Amazon, ranging from 2.8 to 15.9 Gt CO_2-eq from 2006 to 2009 (Galford, 2010; Gillian et al., 2010). It was reported that between 1996 and 2005, the Brazilian Amazon rainforest was deforested by 19,500 km^2 per year and converted to pastures and farmland releasing 0.7 to 1.4 Gt CO_2-eq yr^{-1} to the atmosphere (Daniel et al., 2009). Avoided deforestation is the best means of afforestation, even as new and massive efforts at planting more trees should be a parallel strategy in order to reduce build-up of CO_2 in the atmosphere.

Many governments around the world, including India have taken up massive tree planting programmes with the slogan that trees are the answer to global warming. While growing trees is a good idea and tree planting programmes should continue with greater zeal for their numerous ecosystem services, the present analyses show that as long as the present emission trends continue, even if we manage to convert the entire land on the planet into a forest, that will not be adequate to completely offset the current rate of build-up of CO_2 in the atmosphere and prevent or limit global warming. It has been reported earlier that if all countries in the world emitted GHGs into the atmosphere at the same rate as some developed nations did, we would need nine planets to keep the atmospheric concentration of GHGs at the present level (HDR, 2007). Analyzing published data on the global carbon budget, we show in the present study that build-up of CO_2 in the atmosphere is determined more by the amount of global CO_2 emission rather than the CO_2 sequestration by the planet and therefore, proactively reducing emission is more effective than planting more trees in reducing and stabilizing the concentration of CO_2 in the atmosphere.

Long term data on CO_2 emission and atmospheric CO_2 concentration were obtained from authentic published sources (Table 6.3). Data on terrestrial and ocean CO_2 fluxes were taken from the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007). Using these data, rate of increase in GHG emission and removal from the atmosphere and increase in the concentration of CO_2 in the atmosphere were calculated through regression analysis. The present rate of terrestrial and oceanic removal of CO_2 and the rate of build-up of CO_2 concentration in the atmosphere were used to estimate the area of land and ocean that is required to fully offset the rise of CO_2 in the atmosphere.

Linear regression analysis shows that the annual rate of increase in CO_2 emission between 1950 and 2008 was 411.30 Mt CO_2 per year (R^2 = 0.98) and the atmospheric CO_2 concentration increased at the rate of 1.30 ppm per year which is equivalent to 10151.06 Mt CO_2 per year (R^2 = 0.97) (Figure 6.10). Between 1950 and 2008, CO_2 emission (including fossil fuel combustion and land use changes) increased from 9450 Mt to 34939 Mt. During the same period, atmospheric CO_2 concentration increased from 311 ppm to 386 ppm (Figure 6.10). The increase in CO_2 emission was 270% while atmospheric CO_2 concentration increased only to the tune of 24%. Despite the huge increase in CO_2 emission, the atmospheric CO_2 did not increase to the same extent and this indicates that the amount of CO_2 sequestered by the planet must have increased at a rate greater than the rate at which CO_2 increased in the atmosphere between 1950 and 2008.

Terrestrial removal of CO_2 during 2000-2005 was 0.9 Gt C yr^{-1} (IPCC,2007) and this is equal to 3303.0 Mt CO_2 per year. Total vegetation area on earth surface is about 15000 M ha (Dixon et.al., 1994). From this I calculated the terrestrial carbon fixation rate which comes to 220 Kg CO_2 per hectare per year. At this rate, we need an additional land area of around 46141.0 M ha for planting trees so as to fully offset the current rate of increase in atmospheric CO_2 concentration (which is roughly 1.30 ppm yr^{-1}, averaged for the period 1950-2008, Figure 6.11). This is equal to the terrestrial vegetation area of three planets.

From the emission and atmospheric CO_2 concentration data, I calculated the amount of CO_2 sequestered as the difference between the former two. The rate of CO_2 emission (including fossil emissions and land use changes) from 1950-2008 was 0.12 Gt C yr_{-1}. The rate of removal of CO_2 from the atmosphere (including land and ocean sinks of CO_2) and the rate of addition of CO_2 to the atmosphere were identical (0.06 Gt C yr_{-1}) (Figure 6.11). The rate of emission was much greater than the rate of removal and the difference was 0.06 Gt C yr^{-1}. This indicates that even if we take the sequestration capacity of the land and ocean together, we will still require one more additional planet to remove the current rate of CO_2 emission to maintain equilibrium between the present emission and removal and thus keep the atmospheric CO_2 concentration stabilized at the present level.

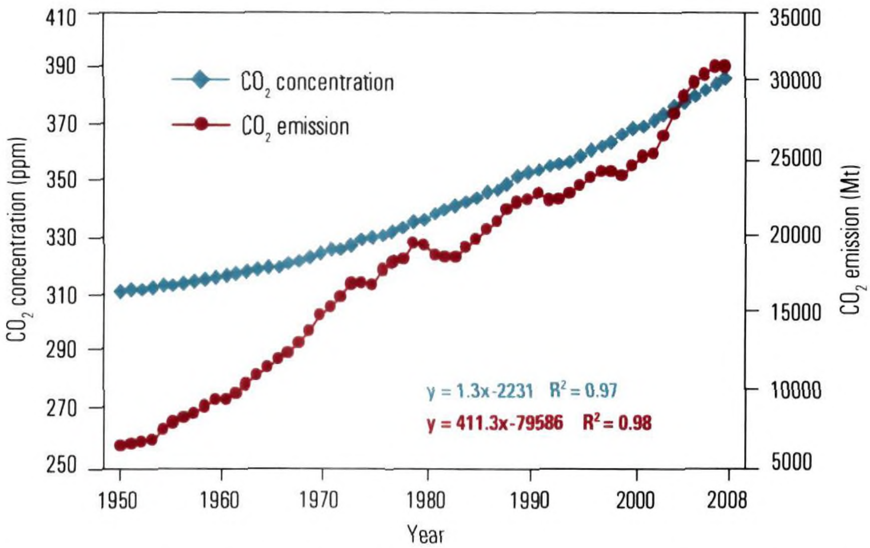


Figure 6.10. Rate of increase in the world CO_2 emission and atmospheric CO_2 concentration between the period 1950 and 2008. (*calculated based on the data from Carbon dioxide information analysis center (CDIAC) and World Resource Institute (WRI) available at http://cait.wri.org*).

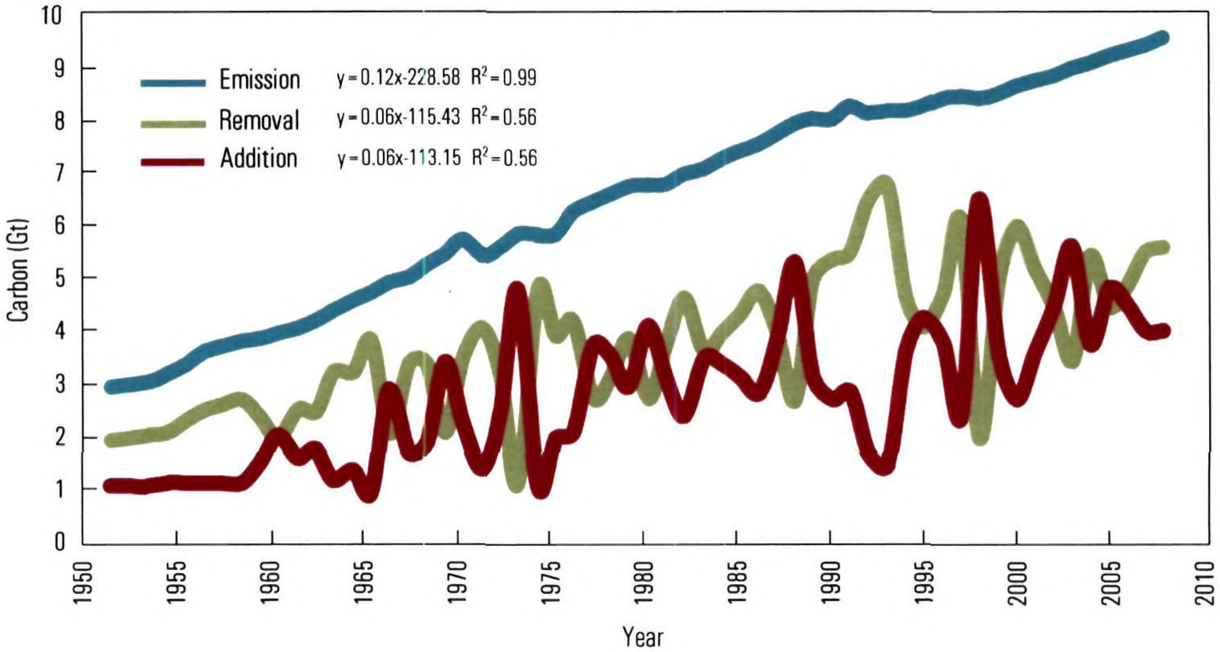


Figure 6.11. Global carbon balance sheet between 1950 and 2008

Over the years, concentration of CO_2 in the atmosphere has been increasing at an increasing rate. For example, atmospheric CO_2 concentration had been increasing at the rate of 2.07 ppm per year between 2000 and 2008 as against 1.30 ppm per year between 1950-2008. Therefore, afforestation programmes will be even more inadequate to offset the build-up of CO_2 in the atmosphere today than in the past. We would require a terrestrial vegetation area equivalent to 4.9 planets and a combined area of land and ocean equivalent to 1.6 planets to fully offset the recent rate of increase in atmospheric CO_2 concentration.

What are the policy implications of this finding in the Indian and global contexts? Renewed efforts to green more land area is one of the major national action plans to mitigate global warming. The annual rate of sequestration of CO_2 by Indian forest cover is calculated as 1.94 tons per hectare per year (Jagadish et al., 2009). At this rate, the presently existing total forest and tree cover in the country (76.87 M ha) can sequester 138.15 Mt of CO_2 every year. The total fossil fuel emission from India was 1494.88 Mt CO_2 in 2008. To offset this amount of CO_2 emission, India should have a forest area of 770.55 M ha and all of that should fix carbon at the same efficiency of 1.94 tons per hectare per year. This additional area is equivalent to 2.3 times the geographical area of the country. In other words, going by the present emission and sequestration rates, the world will not sequester what it emits nor will India sequester what it emits.

At the present rate of anthropogenic CO_2 emission, our planet will not be able to sequester enough CO_2 through the natural process of photosynthesis to prevent further rise in its concentration in the atmosphere, even if we manage to plant trees in every bit of land on the planet and they all fix carbon with the same efficiency. Indian scenario is also not any different; planting trees alone will not take care of our rising emissions. Once Mahatma Gandhi reflected on how many planets might be needed to sequester the total emission if India were to follow Britain's pattern of industrialization. Carbon capture and storage (CCS), which amounts to physically trapping CO_2 at its source and storing it in large underground geological formations is perhaps the only way we can continue to emit CO_2 at the present levels and yet stabilize its atmospheric concentration at some specified level, but this technology is yet to be fully harnessed. While planting trees is a no regret option which should be promoted and deforestation prevented, both nationally and globally - and these will certainly have positive impacts on regional and global climate and other ecosystem benefits - but reducing or even stabilizing the concentration of CO_2 in the atmosphere at the present level cannot be achieved, unless there are deliberate efforts in reducing the amount of anthropogenic CO_2 emission into the atmosphere.

6.7. Conclusion

Developed countries were not able to meet their emission reduction commitments under the Kyoto Protocol as on this date (Table 6.9). Deeper cuts are needed to keep global warming within 2 ^{0}C. Under the Kyoto protocol, there were no emission reduction targets for developing nations so as not to constrain their economic growth.

Historically developing countries have not contributed much to the buildup of atmospheric CO_2, but today they are also responsible. Because of this reason, the developed nations put immense pressure at every international climate meets to make binding emission reduction targets on the big emitters in the developing nations like China and India. This was so strong at CoP15 at Copenhagen in 2009 when the big economies in developing nations like China, India, Brazil and South Africa created a negotiation group with several Annex I countries including United States. Climate change can reduce global GDP by 5–20 percent each year (Stern, 2007).

Table 6.9. Present situation of the quantified emission limitation or reduction commitment (QELRCs) given to the Annex I countries.

Annex I Country	CO_2 Emission (Mt yr^{-1})		QELRCs	Present condition (% change from 1990)
	1990	2011		
Australia	267.6	392.3	8	46.6
Austria	55.7	67.2	-8	20.6
Belarus*	91.6[a]	67.2	--	-26.7
Belgium	125.3	131.1	-8	4.6
Bulgaria*	76.2	52.4	-8	-31.2
Canada	470.6	552.6	-6	17.4
Croatia*	16.6[a]	22.4	-5	34.8
Cyprus	5.1	9.5	--	86.8
Czech Republic*	116.8[b]	92.4	-8	-20.9
Denmark	57.1	46.7	-8	-18.3
Estonia*	25.8[a]	20.3	-8	-21.6
European Union	4545.6	4305.2	-8	-5.3
Finland	53.2	54.1	-8	1.6
France	367.7	374.3	-8	1.8
Germany	990.6	748.5	-8	-24.4
Greece	81.5	91.3	-8	12.0
Hungary*	66.8	49.6	-6	-25.7
Iceland	2.4	3.8	10	61.4
Ireland	25.7	36.6	-6	42.1
Italy	415.4	400.9	-8	-3.5
Japan	1047.0	1180.6	-6	12.8
Latvia*	12.8[a]	8.5	-8	-33.5
Liechtenstein	0.2	0.2	-8	15.6
Lithuania*	23.3[a]	16.0	-8	-31.0
Luxembourg	10.7	11.9	-8	10.7
Malta	2.4	6.8	--	188.0
Monaco	0.1	0.1	-8	-15.8
Netherlands	211.1	253.0	-8	19.8
New Zealand	28.8	37.2	0	29.2
Norway	34.8	45.9	1	31.9
Poland*	333.8	307.9	-6	-7.8
Portugal	43.9	54.2	-8	23.4
Romania*	176.1	86.2	-8	-51.1
Russian Federation*	2020.2[a]	1788.1	0	-11.5

Slovakia	42.9[b]	34.9	-8	-18.6
Slovenia	12.4[a]	15.8	-8	27.5
Spain	224.1	318.6	-8	42.2
Sweden	57.1	53.1	-8	-6.9
Switzerland	43.5	43.4	-8	-0.3
Turkey	129.5	296.3	-8	128.9
Ukraine*	533.1[a]	304.5	0	-42.9
United Kingdom of Great Britain and Northern Ireland	601.8	496.8	-8	-17.5
United States of America	5040.4	5490.6	-7	8.9
Kyoto Non compliance				
Annex I			-6.0	+10.6
Non- EIT			-6.0	+23.3
EIT			-5.9	-22.4

*EIT- Economies in transition (Countries that are undergoing the process of transition to a market economy.) [a]Emission data starting from 1992; [b]Emission data starting from 1993

The adverse effect of climate change will hit harder on poor countries than rich. As a developing country, India faces many challenges due to climate change. India's first priority among these challenges is the eradication of poverty by assuring food security through sustainable development.

India's economy is one of the biggest in the world, but we should also accept that the per capita income in India is not even coming in the first 100 position. This almost the same case of per capita emission also. In international climate meets, treating China and India together is not fair. China is far ahead of India by several folds in emission, economy, energy consumption, carbon intensity, energy intensity or even in scientific development. China is the second biggest economy in the world with a faster GDP growth. With world's more than half of the emission rate, China ranks first in global CO_2 emission. In every respect India is several orders of magnitude below China. Even when the population of both countries is similar, there is a big difference in the per capita income and emission. China's economy is highly carbon intensive because its fossil fuel consumption is very high and is mainly from coal. Recently China signed an agreement with Australia for import of coal worth 60 bUS$ (Jacob, 2010). China may not lose its top rank in emissions in the near future.

During Copenhagen meet, India and China committed for voluntary emission cuts through nationally appropriate mitigation actions. India's commitment was 20-25% reduction in carbon intensity of its economy by the year 2020 (compared to 2005) which India is set to achieve. India targets generating 20,000 MW of solar power in 2020 and implemented cess on use of coal which currently yields US$ 500 million a year, which is dedicated to the promotion and development of clean energy (National Action Plan on Climate Change-NAPCC, http://www.moef.nic.in/downloads/home/Pg01-52.pdf). With all these actions, India's current rate of reduction in carbon intensity is very fast and India will definitely achieve its ambitious goal 20-25% reduction in carbon intensity by 2020. China has pledged at Copenhagen to cut the amount of carbon dioxide produced for each unit of GDP by 40-45 percent by 2020, compared with 2005 levels. At the current rate, China is unlikely to achieve this goal in 2020.

Finally, my analyses clearly show that the world is emitting much more than it can sequester and this inequilibrium is on the rise. The result is that CO_2 concentration in the atmosphere is increasing at an increasing rate. Planting trees on the whole planet will not bring this equilibrium back. Planting trees is a no regret option which should be promoted and deforestation prevented, both nationally and globally. But this will not achieve the objective of stabilizing the concentration of CO_2 in the atmosphere at the present level cannot be achieved, unless there are deliberate efforts in reducing the amount of anthropogenic CO_2 emission into the atmosphere.

6.8. References

Andrasko, K. (1990). Global warming and forests: an overview of current knowledge. Unasylva. 4: 3-11.

Blasing, T.J. (2013). Carbon Dioxide Information Analysis Center (CDIAC). Recent Greenhouse Gas Concentrations. Available at http://cdiac.ornl.gov/pns/current_ghg.html

Carrington, D., Amazon deforestation in dramatic decline, official figures show. Guardian Newspapers Limited, United Kingdom, Friday 23 July 2010.

Chu, S. (2009). Carbon Capture and Sequestration. Science. 325: 1599.

Conway, T.J., Tans, P.P., Waterman, L.S., Thoning, K.W., Kitzis, D.R., Masarie, K.A. and Zhang, N. (1994). Evidence for interannual variability of the carbon cycle from the NOAA/CMDL global air sampling network. Journal of Geophysical Research. 99: 22831-22855.

Daniel, N., Britaldo, S. S., Frank, M., André, L., Paulo, M., John, C., Maria, B., Andrea, C., Hermann, R., Stephan, S., David, G. M., Claudia, M. S., Ruben, L., Pedro, P., Sergio, R., Ane, A., Oriana, A., and Osvaldo, S., The end of deforestation in the Brazilian Amazon. Science 4 December 2009: 326, 1350-1351.

Davis, S. J., CaldeiraK. and Matthews, H.D. (2010). Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure. Science. 329 (5997): 1330-1333.

Dixon, R.K., Solomon, A.M., Brown, S., Houghton, R.A., Trexier, M.C. and Wisiniewski, J. (1994). Carbon Pools and Flux of Global Forest Ecosystems. Science, 263 (5144): 185-190.

Dlugokencky, E.J., Steele, L.P., Lang, P.M. and Masarie, K.A. (1994). The growth rate and distribution of atmospheric methane. Journal of Geophysical Research. 99: 17021-17043.

Dutt, G. (2009). A Climate Agreement beyond 2012. Economic and Political WEEKLY. XLIV (45): 39-49.

Ehrlich, P.R. and Holdren, J.P. (1971). Impact of Population Growth. Science. 171(3977): 1212-1217.

Fiala, N. (2008). Meeting the demand: An estimation of potential future greenhouse gas emissions from meat production. , Ecological Economics (2008), doi:10.1016/j.ecolecon. 2007.12.021.

Galford, G.L., Melillo, J.M., Kicklighter, D.W., Cronin, T.W., Cerri, E.P.C., Mustard, J.F. and Cerri, C.C., Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon. Proceedings of the National Academy of Science. November 16, 2010, 107 no. 46, 19649-19654.

Gillian, L.G., Jerry, M.M., David, W.K., Timothy, W.C., Carlos, E.P.C., John, F.M. and Carlos, C.C. (2010). Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon. Proceedings of National Academy of Science. January 2010: 34-42.

Houghton, J. (1997). Global warming : The complete briefing. Cambridge University Press, Cambridge, U.K. : 251.

Houghton, R.A. (2005). In: Moutinho, P. and Schwartzman, S. (Eds). Tropical deforestation and climate change. Amazon Institute for Environmental Research (IPAM), Belem, Para, Brazil. pp. 13-21.

Human Development Report 2007/08 (2007). Fighting climate change: Human solidarity in a divided world. By United Nations Development Programme (UNDP), 1 UN Plaza, New York, 10017, USA.

IEA (2008). Energy Technology Perspectives. Paris.

IPCC, Fourth Assessment Report (AR4), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Jacob, J. (2005). The science, politics and economics of global climate change: Implications for the carbon sink projects. Current science. 89(3): 464-474.

Jacob, J. (2010). Copenhagen and the 'BASIC' countries: some basic differences between the Indian and Chinese emission. Current Science. 99 (4): 439-443.

Jagadish, K., Rajiv, P. and Dadhwal, V.K. (2009). India's Forest and Tree Cover: Contribution as a Carbon Sink. Technical paper by Indian Council of Forestry Research and Education, available at www.envfor.nic.in.

Jenkinson, D. S., Adams, D. E. and Wild, A. (1991). Model estimates of CO_2 emissions from soil in response to global warming. Nature. 351(6324):304-306.

Keeling, C. D., Whorf, T. P., Wahlen, M. and Van der Plichtt, J. (1995). Interannual extremes in the rate of rise of atmospheric carbon dioxide since 1980. Nature. 375 (6533): 666-670.

Keeling, C.D., Bacastow, R.B., Bainbridge, A.E., Ekdahl, C.A., Guenther, P.R. and Waterman, L.S. (1976). Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. Tellus. 28: 538-551.

Keeling, C.D., Bacastow, R.B., Bainbridge, A.E., Ekdahl, C.A., Guenther, P.R. and Waterman, L.S. (1976). Atmospheric carbon dioxide variations at Mauna Loa Observatory, Hawaii. Tellus. 28: 538-551.

Kindermann, G., Obersteiner, M., Sohngen, B., Sathaye, J., Andrasko, K., Rametsteiner, E., Schlamadinger, B., Wunder, S. and Beach, R. (2008). Global cost estimates of reducing carbon emissions through avoided deforestation. Proceedings of the National Academy of Sciences of the United States of America.

Knopf, B., Edenhofer, O., Barker, T., Bauer, N., Baumstark, L., Chateau, B., Criqui, P., Held, A., Isaac, M., Jakob, M., Jochem, E., Kitous, A., Kypreos, S., Leimbach, M., Magne, B., Mima, S., Schade, W., Scrieciu, S., Turton, H. and van Vuuren, D. (2009). The Economics of low stabilization: impolications for technological change and policy. In: M. Hulme, H. Neufeldt (*Eds.*). *Making climate change work for us – ADA M synthesis book. ambridge: Cambridge* University Press.

Lal, R. and Bruce, J. (1999). The potential of world cropland soils to sequester C and mitigate the greenhouse effect. Environmental Science and Policy. 2: 177-185.

McKinsey (2009). Pathways to a Low-Carbon Economy. Version 2 of the Global Greenhouse Gas Abatement Cost Curve.

Meinhausen, M., Meinshausen, N., Hare, W., Raper, S., Frieler, K., Knutti, R., Frame, D. and Allen, M. (2009). Greenhouse-gas emission targets for limiting global warming to 20C. Nature. 458: 1158 –1163.

NOAA (2013). *Trends in Atmospheric Carbon Dioxide*. Available at http://www.esrl.noaa.gov/gmd/ccgg/trends/

NOAA (2013). Trends in Atmospheric Carbon Dioxide. Available at http://www.esrl.noaa.gov/gmd/ccgg/trends/

Novelli, P.C., Steele, L.P. and Tans, P.P. (1992). Mixing ratios of carbon monoxide in the troposphere. Journal of Geophysical Research. 97: 20731-20750.

Pandey, D. N. (2002). Global climate change and carbon management in multifunctional forests. Current Science. 83 (5): 593-602.

Pieter, T. and Keeling, R. (2013). NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

Ragunandan, D., Purkayastha, P. and Jayaraman, T. (2009). Breaking the climate Deadlock. The Hindu. 23 June 2009.

Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G. and Field, C. B. (2007). Global and regional drivers of accelerating CO_2 emissions. Proceedings of the National Academy of Sciences. 104: 10288-10293.

Rogelj, J., Nabel, J., Chen, C., Hare, W., Markmann, K., Meinshausen, M., Schaeffer, M., Macey, K. and Hohne, N. (2010). Copenhagen Accord pledges are paltry. Nature. 464 (7292): 1126-

1128.

Rosa, E. A. and Dietz ,T. (2012). Human drivers of national greenhouse-gas emissions. Nature Climate Change. 2: 581–586.

Stern, N. (2009). Managing climate change and overcoming poverty: facing the realities and building a global agreement. Policy paper. Centre for Climate Change Economics and Policy Grantham Research Institute on Climate Change and the Environment. pp 1-28.

Stern, N., Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S., Crane, D., Cruickshank, S., Dietz, S., Edmonson, N., Garbett, S.L., Hamid, L., Hoffman, G., Ingram, D., Jones, B., Patmore, N., Radcliffe, H., Sathiyarajah, R., Stock, M., Taylor, C., Vernon, T., Wanjie, H. and Zenghelis, D. (2006). Stern Review: The Economics of Climate.Executive Summary. Change, HM Treasury, London. pp. i-xxvii.

Thoning, K.W., Tans, P.P. and Komhyr, W.D. (1989). Atmospheric carbon dioxide at Mauna Loa Observatory 2. Analysis of the NOAA GMCC data, 1974-1985. Journal of Geophysical Research-Atmospheres. 94: 8549-8565.

Trolier, M., White, J.W.C., Tans, P.P., Masarie, K.A. and Gemery, P.A. (1996). Monitoring the isotopic composition of atmospheric CO_2: measurements from the NOAA Global Air Sampling Network. Journal of Geophysical Research. 101: 25897-25916.

Weyant, J.P., de la Chesnaye, F.C. and Blanford, G.F. (2006). Overview of EMF-21: Multigas Mitigation and Climate Policy. The Energy Journal, Special Issue 3: 1-32.

CHAPTER 7

GENERAL CONCLUSION

"Peace be to the Earth and to the Air! Peace to be Heaven, peace to the Waters! By this invocation of peace, may peace bring peace"

Atharva Veda

SEVEN GENERAL CONCLUSION

General Conclusion

The central theme of this thesis has been to examine how climate has changed in the plantation crops growing regions of India, and how these changes have impacted them with special reference to natural rubber, a strategic industrial raw material that is essentially needed for the economic growth of the country. The major objectives of the present work were as follows:

1. To assess the historic climate change that has happened in the plantation crops growing regions of India
2. To assess the impact of climate change on natural rubber plantations in India
3. To evaluate the ecosystem services provided by natural rubber plantations
4. To review international climate change negotiations and analyze GHG emissions by major nations

In the first two introductory chapters I have discussed the importance of major plantation crops and the science and signs of climate change. In chapter three, I have analyzed the extent of climate change that has happened in the plantation crops growing regions of India. Chapter four examines how climate change has affected productivity of natural rubber. In chapter five, the rate of CO_2 sequestration and evapotranspiration of water by rubber plantations are presented. International climate change negotiations and a comprehensive treatment of global emission data of different countries with specific reference to India and China are given in chapter six. The salient findings of this thesis are summarized below.

Analyses of the historic climate change that has happened in the past one century in the country as a whole and in the various rainfall subdivisions and homogeneous (temperature) regions of the country where most of the plantation crops are grown showed an increasing trend in temperature, both annually and seasonally. Minimum and maximum temperatures showed an increasing trend in most of the plantation crops growing regions of India, but a cooling trend was noticed in some seasons in a few regions. Central Kerala, the traditional rubber cultivating region of India where this crop is widespread has been warming faster (average of 0.45 ^{0}C per decade) than the rest of the country as a whole which has major implications for the cultivation of this crop. Number of hot days and warm nights occurring per year showed an increasing trend and that of cool days and cold nights showed a decreasing trend in most of the rubber growing areas in India which may affect yields.

Compared to the warming trend that was clearly seen in the present analyses, changes in annual rainfall, both in quantum and distribution were much less obvious. Amount of annual precipitation over India as a whole or in the plantation growing regions did not show any significant trend, except in some regions. Extreme rainfall events also did not show any significant trends or pattern. Even though the amount of annual rainfall showed no significant change, tri-decadal analysis of rainfall showed a decreasing trend during the South West monsoon while it showed an increasing trend during North East monsoon in the Kerala division for the last several decades. This has implications for the crop calendar of this crop which is usually planted during the monsoon season.

Impact of regional climate change on rubber yield was analyzed with the help of multiple linear regression (MLR) models in which mean annual temperature (T_{ann}), mean annual maximum temperature (Tmax), mean annual minimum temperature (Tmin), mean annual rainfall (RF_{ann}) and mean number of annual rainy days (RD_{ann}) were used as the independent variables and rubber yield (either on a per tree per day basis or a per ha per month basis) was the dependent variable. It was found that Tmax and Tmin alone explained most variability in yield. MLR models were developed separately for each rubber growing region coming under the traditional and non-traditional rubber growing tracts of India and for individual rubber clones. Future changes in rubber productivity for unit degree rise in Tmax and Tmin and also after one decade from now were also estimated.

The long term changes (up to five decades in Kottayam) in the historical climate of the rubber growing regions and mean commercial yields from growers' fields during the same period were available. Historic climate changes could have been regressed against the changes that have happened in rubber productivity over the same period to examine how yield was affected by climate change. But this was not done, because during the same period, apart from any changes in climate, several other known and unknown factors influencing growth and productivity of rubber also would have changed. These include adoption of high yielding clones, changes in agro-management practices, especially rubber harvesting techniques, changes in occurrence of diseases etc. which would have had a direct impact on yield masking the impact of climate change. Over the years, rubber productivity in the country had gone up substantially due to widespread adoption of high yielding clones and better agro-management practices. Therefore, historic yield data and the corresponding climate data were not regressed together. Instead, yield from known clones of the same age grown in the research farms of the Rubber Research Institute of India in the different agro-climatic regions where rubber is cultivated were used. The locations from where data were taken were Kottayam in central Kerala, Padiyoor in northern Kerala, Dapchari in the North Konkan (Maharashtra), Agarthala in Tripura and Tura in the Western Gharo hills of Meghalaya. This ensured that the data were taken from sources where the same scientific management practices were adopted and other externalities were the least. Daily yields of different clones and daily weather data were used in the analysis which gave wide variations in the independent and dependent variables and one-to-one correspondence between the variables.

Three different approaches were adopted to examine how changing climate has affected rubber yield. In the first approach, yield and climate data from all the rubber growing regions were put together to develop a single model to represent all regions and clones together. The different regions represented a wide range of climatic conditions ranging from extreme dry and hot conditions (in North Konkan, a non-traditional rubber growing area) to severe winter conditions (in NE India, again an important non-traditional area) and the more traditional regions of Kerala where the agro-climatic conditions fall in between the two non-traditional regions mentioned above. The mean Tmin and Tmax in the North Konkan and the North East were in the range of 25 to 42 ^{0}C in the summer season and 5 to 26 ^{0}C in winter season. India is perhaps the only rubber growing country where this crop is cultivated in such extremely diverse agro-climatic conditions. The purpose of pooling data from all these regions was to ensure that the available wide range of climatic variables can be captured and regressed against yield in the model. This approach had a fundamental flaw. A close examination of the data from the different regions revealed that climate variables had qualitatively and quantitatively different impacts on yield of different rubber clones in the different agro-climatic regions, although this was not originally thought to be so. This differential response became evident when MLR analyses were separately done for the different regions and clones.

In the second approach, daily dry rubber yields of individual trees for two years were regressed with the weather parameters for the corresponding years separately for the different agro-climatic regions. Each region yielded different MLR models. From these models, productivity was calculated for all regions and changes in yield when both Tmax and Tmin concomitantly increased by 1^{0}C were also calculated.

In the third approach, I regressed yield (per hectare per month) with Tmax and Tmin for Kottayam, Kanjirapally and Thaliparamba regions of Kerala where rubber is widely grown and estimated the impact of rising temperature on rubber productivity. These results were comparable with the results obtained from the respective regions where per tree yield was used as the dependent variable as studied in the second approach. Potential yield reductions after 10 years (with the current warming trends prevailing) in all regions were also calculated. Regression models for individual clones for different regions were also prepared and the projected yield loss for 1 °C rice in Tmax and Tmin and yield after 10 years with the current warming rates were estimated.

Results of this study categorically prove that as climate warms, rubber yield will decline in the traditional rubber growing regions. Because, both Tmax and Tmin had a negative impact on rubber yield in Kerala. Similar impact was noticed in the Konkan region also. The prevailing summer temperatures in Kerala, and certainly in the north Konkan are already at the higher side of the optimum temperature threshold for rubber cultivation and therefore any further warming can become harmful in these regions as evidenced by the model results. Both Tmax and Tmin had a negative impact on yield in Kerala and the Konkan region. However in Northeast India, climate warming can improve rubber yield, because Tmax had a positive impact on rubber yield there. Thus climate warming will have different effects in different agro-climatic regions and this appears to follow the law of limiting factors. It is generally considered that the severe winter condition is a limiting factor for growth and productivity of rubber in the Northeast and therefore, a warming trend (at least to some small extent) may only improve rubber yield in this region. Additionally, more areas in the Northeast may become conducive for rubber cultivation if the present warming trend continues.

The prevailing temperatures in Kerala and the North Konkan are relatively higher than in the North East and hence further warming may inhibit rubber yield in the former regions. However, it is not clear why the models predicted more inhibition in yield in Kerala than in the Konkan with unit rise in temperature even as Kerala had lower temperatures than the Konkan. Even though the relative inhibition in yield was more in Kerala as temperature rises, the absolute yields would still be higher in Kerala, at least for some more years than in the other two regions.

The results of my analyses of how climate warming is happening in Kerala and what is in store for future paint a rather bleak picture for Kerala, especially the erstwhile Travancore region which is the bastion of rubber cultivation in the country. Kottayam has registered markedly higher rates of warming, both in Tmax and Tmin compared to the rest of the rubber growing regions. These warming trends will have a greater inhibitory effect on rubber yield in Kottayam (representing the erstwhile Travancore region) than Malabar or the Konkan regions. The results clearly indicate that Northeast India may hold better prospects for growing rubber in future than Kerala or the Konkan regions, if the current warming trends continue. Presently, government of India is giving special focus on expanding rubber cultivation in the Northeast as compared to other regions such as the Konkan and the results of this thesis indicate that this is a correct step.

Rubber growers have been adapting to climate warming in Kerala in recent years. Many growers from central Kerala resort to giving lifesaving irrigation at least once to their newly planted rubber during the first year which was something that was unheard of a decade ago. Some rubber estates have resorted to tapping much early in the morning when the ambient temperature is low. These are practical ways of adaptation, but what is required is to develop climate-resilient clones and agronomic practices to cope with climate warming.

Simulated yield data for the past and future reveal important information. If large scale adoption of RRII 105 had not happened and the area under this high yielding clone had not increased, there was every possibility that rubber productivity would have gone down over the years as a result of climate warming that has already happened in the traditional areas. The MLR models clearly suggest that the potential rubber productivity must have come down in the recent decades owing to climate warming and in fact this did actually happen. During the late 1970s and early 1980s, the mean productivity of RRII 105 under the best management practices of RRII research farms located in the traditional regions have been in the range of 60-65 g t^{-1} t^{-1}, but of late this is mostly in the range of 50-55 g t^{-1} t^{-1} or even less in plantations of similar age. Since the genetics (clone) was the same and the management practices were as constant (as can be expected as the trials were in RRII's own experimental farms where management practices did not undergo any substantial changes over the years), the most convincing reason for this reduction in productivity seems to be the appreciable temperature warming that has happened in the traditional regions during this period. There might have been other factors too, such as likely deterioration in soil productivity or other unknown factors or even a gap between research findings and extension, but the remarkable increase in maximum and minimum temperature that has happened in the past strongly indicates the significant role of these parameters would have played in reducing productivity. This underlines the importance of developing high yielding climate-resilient clones.

Had there been no climate warming and if the current clone composition and agro-management practices were existing in the past, the productivity of rubber would have been much higher than what was actually achieved by the Indian growers in the past. Because, temperatures were more congenial in the past than today for higher rubber yields. Over the years, due to reasons explained above, rubber productivity did increase overcoming the inhibitory effects of climate warming, but the same increasing trend in yield is highly unlikely to continue in future. My estimates based on temperature sensitivity of rubber yield and projected future temperatures (based on the current warming rates as per the data from Kottayam) clearly indicate that rubber productivity will take a big beating in the years to come. My results also clearly indicate that warming-induced loss of yield will be the highest in the erstwhile Travancore region of Kerala which has perhaps close to half of the yielding plantations in the country and hence this will make a major dent not only in productivity of local growers, but also in total amount of rubber produced in the country in the near future. Rubber Board's estimated deficit of rubber supply in the country can go even bigger due to climate warming. However, my results also suggest that this can be averted to some extent by more rubber being produced from Northeast, because climate warming may not decrease rubber yield in this part of the country. Therefore, improving the present productivity and extending area under rubber in Northeast assumes importance. Possibilities of growing alternative sources of natural rubber such as Guayule which grows in hot arid climate could be explored to bridge the expected deficit of natural rubber in future.

My results indicate that climate change will restrict realizing the full potential of high yielding clones in farmers' fields in future. This points to the need to evolve smart clones that are climate resilient. From the present study, it cannot be categorically stated that any particular clone will have better yield performance in a future warmer world. However, more work is needed to elucidate if there are clonal variations in their response to climate warming and exploit such variations for genetic improvement of this crop.

The present results clearly indicate how maximum and minimum temperatures have been increasing in the past, how this would have adversely affected rubber productivity in the past and what rising temperatures might do to rubber productivity in future in different agro-climatic regions of India where this crop is cultivated today. Climate change is obviously much more complex than daily variations in weather parameters such as daily maximum or minimum temperature. Changes in cloud formation, wind, rainfall pattern, occurrence of extreme weather events like storms, floods, long dry spells, unexpected breaks in monsoon, spread of new pests and diseases etc. are important factors that can seriously influence not only rubber yield, but different aspects of growth of rubber plants which needs to be studied.

Eddy covariance system was used in India for the first time in this study to measure ecosystem level fluxes of CO_2 and water vapour in a rubber plantation. The advantage of this method is that it allows accurate and continuous (non-destructive) measurements of CO_2 sequestration and water loss at the ecosystem level in real time. The present results show that rubber plantations are a good sink for atmospheric carbon dioxide as the CO_2 sequestration rate was about 44 tons of CO_2 per ha per year in a 4-6 year old plantation. This is a remarkably large rate, much higher than natural forests. Estimates show that Indian rubber plantations offset about 8% of the total amount of CO_2 emitted by the Indian automobile sector. The present calculations show that world's presently existing 12.2 M ha rubber plantations must be fixing almost 372 Mt CO_2 every year, which is equal to 1.4% of the total CO_2 emission from consumption and flaring of fossil fuels during 2010. This can offset the current rate of buildup of CO_2 in the atmosphere (1.9 ppm CO_2 yr_{-1}) to the tune of 2.5%. This is a remarkable ecosystem service provided by the rubber plantations that should be appreciated in international climate negotiations. The possibilities of earning carbon credits or some other payments for this significant ecosystem service are also discussed.

Global warming is the result of accumulation of CO_2 and other greenhouse gases in the atmosphere. Present analyses show that the CO_2 sequestration potential of the planet has also gone up since the industrial revolution, possibly due to CO_2 fertilization effect and extended growing season. *However, clearly the world has been emitting much more than what it can* sequester from the atmosphere resulting in rising concentration of CO_2 in the atmosphere. In fact CO_2 concentration in the atmosphere has been rising at an increasing rate. I have also analyzed the close relationship between economic growth, fossil fuel consumption and emission in major economies and compared India and China which are the two large emitting developing countries. China is far ahead of India as far as economy, emission and energy consumption are concerned which is a strong argument for not including India along with China in any climate negotiations or taking up emission reduction commitments. China is today the largest GHG emitter in the world and indications are that it will remain so for many more years.

In the final part of my thesis, I show that afforestation alone cannot be the right solution for managing the CO_2 concentration in the atmosphere or global warming. In addition to planting trees, deliberate reduction in CO_2 emission is needed to mitigate global climate change. Thus, international climate negotiations assume great importance, but unfortunately, these negotiations are sometimes more of political gimmicks and escapism and there appears to be no political will on the part of the developed (or even some of the highly emitting and fast developing) nations to reduce their GHG emissions. World economy is still largely carbon-dependent and no nation is willing to compromise its economic growth for the sake of reducing emissions. New technologies for decarbonizing the economy are needed to sustain economic growth without concomitant increase in GHG emission. It is highly likely that the poor and developing nations, which experience the brunt of climate change which they did not create at the first place, will have to depend on the developed nations to have access to such clean (and expensive) technologies; the same countries that have contributed the most to global warming.

To conclude: Climate has warmed in the traditional and non- traditional rubber growing tracts of India and this will have qualitatively and quantitatively different impacts on rubber productivity. Traditional rubber growing regions of Kerala have warmed more than the other regions. Kerala may be relatively more affected by the adverse effects of climate warming than Northeast India where warming conditions may increase productivity even as the prevailing cold conditions may be a limiting factor at present. Rise in temperature would have a positive impact on rubber cultivation in Northeast India. Extrapolating the present warming trends, present models clearly indicate that rubber productivity will be relatively more affected in Kerala than any other rubber growing regions in the coming decade, although absolute productivity may still remain high in Kerala. However, rubber productivity may see an improvement in Northeast in the coming decade as the region continues to get warmer which may also make more areas in Northeast suitable for rubber cultivation. Apart from several unfavorable socio-economic factors such as small holding size, absentee growers, unavailability of labors, high labor and input costs, high living costs, high land value and alternate land use options, environmental concerns etc. climate warming will be an additional burden on Kerala's rubber plantation sector. It may be only a matter of time before Kerala losing its prime position in rubber cultivation to Northeast India.

List of Journal publications, Conference papers and Awards

Journal Publications

Satheesh, P.R. and Jacob, J. (2011). Impact of climate warming on natural rubber productivity in different agro-climatic regions of India. *Natural Rubber Research.* 24(1): 1-9.

Raj, S., **Satheesh, P.R.** and Jacob, J. (2011). Evidence for climate warming in some natural rubber growing regions of South India. *Natural Rubber Research.* 24(1): 10-17.

Annamalainathan, K., **Satheesh, P.R.** and Jacob, J. (2011). Ecosystem flux measurements in rubber plantations. *Natural Rubber Research.* 24(1): 28-37.

Sumesh, K.V., **Satheesh, P.R.**, Annamalainathan, K., Krishnakumar, R., Thomas, M. and Jacob, J. (2011). Physiological evaluation of a few modern *Hevea* clones for intrinsic drought tolerance. *Natural Rubber Research.* 24(1): 61-67.

Annamalainathan, K., Joseph, J., Alam, B., **Satheesh, P.R.** and Jacob, J. (2013). Seasonal changes in xylem sap flow rate inmature rubber plants. *Journal of Plantation Crops.* 41(3): 343-349

Thomas, M., Sathik, M.B.M ., Luke, L.P., Sumesh, K.V., **Satheesh, P.R.**, Annamalainathan, K. and Jacob, J.(2012). Stress responsive transcripts and their association with drought tolerance in *Hevea brasiliensis. Journal of Plantation Crops.* 40(3): 180-187

Sathik, M.B.M., Kuruvilla, L., Thomas, M., Luke, P.L., **Satheesh, P.R.**, Annamalainathan, K. and Jacob, J. (2012). Quantitative expression analysis of stress responsive genes under cold stress in *Hevea brasiliensis. Rubber Science.* 25(2): 199-213.

Molly Thomas, Mohammed Sathik, M.B., Lisha P. Luke, Linu Kuruvilla, Sumesh, K.V., **Satheesh, P.R.**, Annamalainathan, K., Krishnakumar, R. and James Jacob. (2011). Analysis of drought responsive gene expression in *Hevea brasiliensis. Natural Rubber Research.* 24 (2): 247-252.

Conference papers

Jacob, J. and Satheesh, P.R. (2012). Climate warming in the plantation belt of kerala and its impact on natural rubber productivity. Proceedings of Kerala Environment Congress 2012, organized by Centre for Environment and Development, Trivandrum in association with Rajiv Ghandi Centre for Biotechnology. Pp 99-108.

Jacob, J. and Satheesh, P.R. (2012). Climate Change, Economy and Sustainable development. Proceedings of the International Seminar on Climate Change, Sustainable Development and Society (CLIMATE CONCLAVE-2012) organised by British Council, Association of British

Scholars & TKM Institute of management on February 2012 at Trivandrum, Kerala, India. Pp 23-36.

Annamalainathan, K., Satheesh, P.R. and Jacob, J. (2012). Measurements of CO_2 and Water Flux in Natural Rubber Ecosystem. Proceedings of The International Conference on Climate Change and CO_2 Management: Mitigation, Separation and Utilization organised by Anna University, Chennai, India. pp. 35-40.

Satheesh, P.R. and Jacob, J. (2012) Trees are not the answer to climate change. Proceedings, 24th Kerala science congress 2012. 08-04, pp. 459.

Satheesh, P.R., and Jacob, J. (2010). Kalavastha vyathiyanam: chila yadharthyangal. Published in Rubber magazine (Malayalam) special edn. for rubber and climate change. March 2010, by Rubber Board, Kottayam. pp. 15-17.

Jacob, J., Shammi, R. and Satheesh, P.R. (2010). Kalathinte chuvarezhuthukal. Published in Rubber magazine (Malayalam) special edn. for rubber and climate change. March 2010, by Rubber Board, Kottayam. pp. 8-11.

Sumesh, K.V., Satheesh, P.R., Annamalainathan, K., Krishnakumar, R., Thomas, M. and Jacob, J. (2010). Physiological evaluation of modern *Hevea* clones for drought tolerance using gas exchange and chlorophyll fluorescence techniques. Proceedings of International conference on climate change and rubber cultivation: R&D priorities, 28-30 July 2010, conducted by RRII in collaboration with IRRDB. p 55-56.

Annamalainathan, K., Satheesh, P. R. and Jacob, J. (2010). Rubber plantation As potential sink to mitigate rise in atmospheric carbon dioxide: An ecosystem flux approach. Proceedings of International conference on climate change and rubber cultivation: R&D priorities, 28-30 July 2010, conducted by RRII in collaboration with IRRDB. p76-77 .

Jacob, J. and Satheesh, P. R. (2010). Impact of Climate Change on Natural Rubber Productivity in Different Agro-Climatic Regions in India. Proceedings of International conference on climate change and rubber cultivation: R&D priorities, 28-30 July 2010, conducted by RRII in collaboration with IRRDB. p 8-11.

Jayasree, G., Thomas, M., Preenu, A. A., Sumesh, K.V., Satheesh, P.R., Annamalainathan, K. and Jacob, J. (2010). An analysis of intrinsic water use efficiency (WUE) in RRII 400 series clones of Hevea. Proceedings of International conference on climate change and rubber cultivation: R&D priorities, 28-30 July 2010, conducted by RRII in collaboration with IRRDB. p 57-58.

Sathik, M.B.M., Kuruvilla, L., Luke, L.P., Satheesh, P.R., Thomas, M., Annamalainathan, K. and Jacob, J. (2010). Genes associated with cold tolerance in *Hevea* and their relevance to climate change. Proceedings of International conference on climate change and rubber cultivation: R&D priorities, 28-30 July 2010, conducted by RRII in collaboration with IRRDB. p 44-45.

Shammi, R., Satheesh, P.R. and Jacob, J. (2010) Has climate changed in the natural rubber growing regions in India? Proceedings of International conference on climate change and rubber cultivation: R&D priorities, 28-30 July 2010, conducted by RRII in collaboration with IRRDB. p 3-6.

Thomas, M., Sathik, M.B.M., Kuruvilla, L., Luke, L.P., Sumesh, K.V., Satheesh, P.R., Annamalainathan, K., Krishnakumar, R. and Jacob, J. (2010). Quatitative gene expression analysis of stress responsive genes in *Hevea* under drought stress. Abstracts, 19th Biennial symposium on plantation crops, Placrosym XIX in Rubber research institute of India, Kottayam on 7-10 December, 2010).

Jacob, J. and Satheesh, P. R. (2010). Climate change and natural rubber productivity. Abstracts, 19th Biennial symposium on plantation crops, Placrosym XIX in Rubber research institute of India, Kottayam on 7-10 December, 2010, p 19-20.

Satheesh, P. R. and Jacob, J. (2010). Carbon dioxide emission, GDP growtn and climate change: A comparison between the US, China and India. Abstracts, 19th Biennial symposium on plantation crops, Placrosym XIX in Rubber research institute of India, Kottayam on 7-10 December, 2010, p 31.

Annamalainathan, K., Satheesh, P. R. and Jacob, J. (2010). Eddy covariance measurements of CO_2 and water flux in natural rubber plantation. Abstracts, 19th Biennial symposium on plantation crops, Placrosym XIX in Rubber research institute of India, Kottayam on 7-10 December, 2010, p 32.

Jacob, J. and Satheesh, P. R. (2010). Carbon sequestration by natural rubber plantations for a low carbon growth trajectory. Abstracts, 19th Biennial symposium on plantation crops, Placrosym XIX in Rubber research institute of India, Kottayam on 7-10 December, 2010, p 33-34.

Thomas, M., Sathik, M.B.M., Luke, L.P., Kuruvilla, L., Sumesh, K.V., Satheesh, P.R., Annamalainathan, K., Krishnakumar, R. and Jacob, J. (2010). Analysis of drought responsive gene expression in *Hevea brasiliensis.* Abstracts, 19th Biennial symposium on plantation crops, Placrosym XIX in Rubber research institute of India, Kottayam on 7-10 December, 2010, p 80-81.

Awards

Won the third best research paper award given in 2012 by Rubber Research Institute of India during the 25th anniversary of its research journal *Natural rubber Research* (now *Rubber Science*).

Natural Rubber Research, **24**(1): 1-9, 2011

IMPACT OF CLIMATE WARMING ON NATURAL RUBBER PRODUCTIVITY IN DIFFERENT AGRO-CLIMATIC REGIONS OF INDIA

P.R. Satheesh and James Jacob

Rubber Research Institute of India, Kottayam-686 009, Kerala, India

Received: 12 January 2011 Accepted: 20 May 2011

Satheesh, P.R. and Jacob, J. (2011). Impact of climate warming on natural rubber productivity in different agro-climatic regions of India. *Natural Rubber Research*, **24**(1): 1-9.

Long term changes in climate of major natural rubber (NR) growing tracts of India were quantified and their impact on NR productivity was estimated using multiple linear regression models. Day-to-day variations in productivity in terms of dry rubber yield per tree per tap (g/t/t) could be best explained based on the variations in daily maximum temperature (Tmax) and daily minimum temperature (Tmin) and variations in other weather variables did not contribute much to the variations in daily productivity. For unit rise in Tmax and Tmin, NR productivity was affected differently in different agro-climatic regions. If both Tmax and Tmin rose by 1 °C, NR productivity will reduce by 9-16% in the agroclimatic conditions of Kerala and by 11% in the hot and drought-prone North Konkan region. On the other hand, in the cold-prone North Eastern India, there is hardly any reduction in NR productivity if both Tmax and Tmin went up by 1 °C. Our analysis show that if the present warming trend continues, NR productivity in Kerala could be reduced by 4-7% and that in North East India could go up by as much as 11% in the next decade. North Konkan region may also register about 4% reduction in NR productivity in the next decade if the present warming trend continues; however, absolute yields will continue to remain high in Kerala.

Key words: Climate warming, Maximum temperature, Minimum temperature, MLR models, Natural rubber productivity.

INTRODUCTION

It is very likely that greenhouse gases (GHGs) accumulating in earth's atmosphere from anthropogenic emissions are warming the world's climate system (IPCC, 2007a). Climate change as a result of global warming can influence the growth and productivity of agricultural crops (Cynthia and Parry, 1994). Climate change can affect crop productivity in various direct and indirect ways (Cynthia *et al.*, 2001). For example, an extreme weather event like drought or storm directly impacts growth and productivity. Changes in weather pattern can affect the incidence of pests and diseases and thus indirectly affect the crop.

Natural rubber (NR) is mostly grown in South and South East Asia which is highly vulnerable to climate change (IPCC, 2007b). Studies show that temperatures have generally gone up in this part of the world in the recent decades (Manton *et al.*, 2001). Number of rainy days and number of cool nights per year showed a declining trend and that of hot days per year increased. While we may be able to understand and appreciate

Correspondence: James Jacob (james@rubberboard.org.in)

to what extent climate has changed in the traditional rubber growing regions of the world in the recent past, it is extremely difficult to predict how exactly these changes will continue in the years ahead and how these changes will affect growth and productivity of NR. Thus, the impact of change in future climate on natural rubber growth, productivity and supply will be complex and difficult to predict.

While warming conditions and associated changes in climate may adversely affect growth and productivity in the traditional NR growing tracts of the world, it is likely that new regions and countries could become suitable for NR cultivation in future. For example, regions where low temperature is presently a limiting factor for cultivating NR, such as parts of North East (NE) India could become suitable for NR cultivation in a future warmer world. Changes in climate may lead to changes in incidences of old and new pests and diseases in ways unknown today.

Between 2001 and 2008, consumption of NR in India increased at the rate of 0.035 million tons/year while its supply increased by 0.036 million tons/year (IRSG, 2009). Almost all studies show that in the years ahead, this kind of near-perfect harmony between demand and supply may not continue to exist even as consumption of NR is expected to increase at a faster rate than its supply, both nationally and globally (IRSG, 2009), provided there is sustained economic growth. Since 2006, India ranks first in the world in terms of NR productivity (IRSG, 2009). Despite the recent global economic crisis, India remained reasonably buoyant and the Indian economy is expected to grow at impressive rates in the coming years, and thus, the demand for NR also will be on the rise. But climate change is one important factor that may seriously jeopardize NR availability in India and other major NR producing countries in South and South East Asia, a region particularly vulnerable to the adverse impacts of climate change (Manton *et al.*, 2001). The present study examines how rising temperature may influence NR productivity in the different agro-climatic regions of India where NR is cultivated.

MATERIALS AND METHODS

Long term daily weather data collected from the weather station at the Rubber Research Institute of India (RRII) located in Kottaym, a typical traditional rubber growing region in Kerala, since 1957 were analysed for long term trends. Long term daily weather data were collected from the Regional Research Stations (RRSs) of RRII at Agartala, Tura and Dapchari (non traditional regions), and Central Experimental Station (CES) of RRII at Chethackal and RRS, Padiyoor (traditional region) representing the diverse agro-climatic regions in India where NR is cultivated (Jacob *et al.*, 1999) and their changing trends were worked out.

The climatic conditions of these regions range from extreme dry and hot conditions in Dapchari to severe winter conditions in NE. Dapchari is situated at 20^{0}04'N, 72^{0}04'E with an average elevation of 48 m above MSL in the North Konkan region of Maharashtra. During the monsoon season, this region gets around 2400 mm rainfall. During peak summer days, the maximum temperature goes above 38 ^{0}C and during winter, the minimum temperature can be as low as 15.5 ^{0}C (Jacob *et al.*, 1999).

Agartala and Tura are situated in NE India, at 23^0 50′N, 91^0 16′E and 25^0 30′N, 90^0 13′E, with an altitude of around 30 and 1100 m above MSL, respectively. The annual rainfall in these regions ranges from 2000-2400 mm. During peak winter days, the minimum temperature may be as low as 5 °C or less and the maximum temperature during summer is 31 °C (Jacob *et al.*, 1999). Compared to these two non traditional regions, the weather conditions in the traditional NR growing regions of India are more moderate. These traditional regions are situated at a latitudinal range of 8^0 15′N to 12^0 5′N and longitudinal range of 74^0 5′E to 77^0 30′E with an altitude of approximately 20-500 m above MSL and are represented by RRII, Kottayam, CES, Chethakkal and RRS, Padiyoor. Mean annual rainfall in these regions ranges from 2000-4500 mm. The mean maximum and minimum temperatures during the summer months are 33 °C and 25 °C and for the winter months, 31 °C and 22 °C, respectively. India is perhaps the only country where NR is cultivated in such extremely diverse conditions. In all cases, we regressed NR yield with different weather parameters to determine the quantitative effect of each weather parameter on yield.

Three different approaches were adopted in analyzing the data. In the first approach, we regressed mean annual productivity in these diverse agro-climatic regions together with the prevailing weather parameters and made one single multiple linear regression model (MLR) for all the locations. In the MLR model, we used weather parameters like mean annual temperature (Tann), mean annual maximum temperature (Tmax), mean annual minimum temperature (Tmin), mean annual rainfall (RF) and mean number of annual rainy days (RFday) as independent variables and mean yield over the year *i.e.* g/t/t as the dependent variable. Variables from all the different experimental locations representing the diverse agro-climatic regions were regressed together in one single MLR model so as to get maximum variability in the independent (weather) variables. In the second approach, daily per tree yield (g/t/t) for several years was regressed with the corresponding daily weather parameters for these years, separately for the different agro-climatic regions. In a third approach, we regressed the per hectare productivity with maximum and minimum temperatures for three locations from within the traditional areas, namely Kottayam, Kanjirapally and Taliparamba and estimated the impact of rising temperature on productivity. After getting a model for each location, we predicted the yield for 1 °C rise in Tmax and Tmin. We also predicted the yield for the next 10 years by incorporating the current warming trends in these regions in the models.

RESULTS AND DISCUSSION

Long term temperature trends

The mean Tmax and Tmin on almost every day in an year during 2005-2009 have been higher than the same for the period 1957-1961 at RRII, Kottayam (Fig. 1). Liner regression analyses showed that the mean annual Tmax and Tmin have been increasing at the rate of 0.05 °C per year and 0.03 °C per year, respectively since 1957 at RRII, Kottayam (Table 1). At the Regional Research Station of RRII in Agartala, Tmax and Tmin increased at the rate of 0.02 °C per year and 0.06 °C per year, respectively since 1986. In every study location there was a warming trend, but the extent of the warming was different (Table 1).

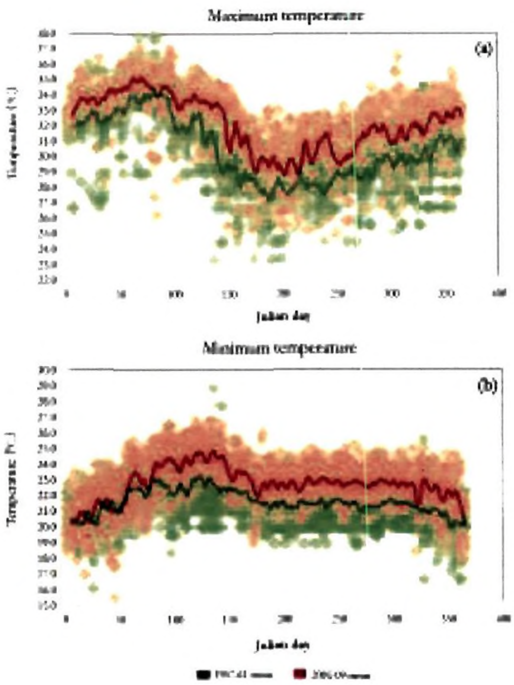


Fig. 1. Mean daily Tmax (a) and Tmin (b) in RRII, Kottayam during the periods 1957-61 (green) and 2005-09 (red)

Multiple liner regression analysis of annual yield data and different weather parameters (all locations together)

Mean annual weather data (mean temperature, mean Tmax, mean Tmin, mean rainfall and mean number of rainy days/ year) were used as the independent variables (X variables) and mean annual productivity of the tree (g/t/t) was taken as the dependent variable (Y variable) to work out a single MLR model in which data from all study locations were pooled together in order to catch maximum variations in the independent variables (approach 1). In the last step of MLR, only three independent variables were left in the model, namely, mean annual Tmax, mean annual Tmin and mean annual RF (Y = 96.94 - 7.05 Tmax + 7.45 Tmin + 0.008 RF, R^2=0.71) (Table 2). This model (in which the independent variables from various agro-climatic regions were pooled and incorporated in one single MLR model) had a fundamental flaw; in the different regions, the different independent variables had

Table 1. **Climate warming trends based on liner regression analysis in different locations of the study representing different agro-climatic regions where NR is cultivated in India**

Station	Period	Annual mean temperature (^{0}C)		R^2	Warming rate (^{0}C/year)
Tura	1995-2008	Tmax	29.3	0.30	0.12
(NE)		Tmin	16.9	0.30	0.05
Agartala	1984-2007	Tmax	30.6	0.07	0.02
(NE)		Tmin	19.9	0.30	0.06
Padiyoor	1998-2009	Tmax	32.8	0.05	0.01
(Traditional)		Tmin	21.8	0.60	0.11
Dapchari	1987-2009	Tmax	33.2	0.40	0.08
(Non-traditional)		Tmin	20.6	0.16	0.03
Kottayam	1957-2009	Tmax	31.2	0.66	0.05
(Traditional)		Tmin	22.7	0.30	0.03
Chethackal	1987-2009	Tmax	32.5	0.10	0.02
(Traditional)		Tmin	21.8	0.21	-0.03

Table 2. **MLR (backward) models obtained between the annual yield and different weather parameters for all stations together (approach 1).**

Model		Unstandardized coefficient		Standardized coefficients	t	p
		B	Std. Error	Beta		
1	(Constant)	-26.4	152.224		-0.173	0.871
	Tann	2.787	2.628	0.284	1.061	0.349
	Tmax	-4.922	6.459	-0.607	-0.762	0.488
	Tmin	6.203	5.56	1.145	1.116	0.327
	RF	5.68E-03	0.009	0.449	0.625	0.566
	RFday	8.94E-02	0.305	0.21	0.293	0.784
2	(Constant)	-0.195	111.345		-0.002	0.999
	Tann	2.642	2.333	0.269	1.132	0.309
	Tmax	-6.419	3.572	-0.791	-1.797	0.132
	Tmin	7.647	2.327	1.412	3.286	0.022
	RF	8.13E-03	0.003	0.643	2.58	0.049
3	(Constant)	96.938	72.647		1.334	0.23
	Tmax	-7.053	3.61	-0.869	-1.954	0.099
	Tmin	7.452	2.375	1.376	3.138	0.02
	RF	8.11E-03	0.003	0.641	2.515	0.046

qualitatively and quantitatively different impacts on yield (see approach 2 below). For example, in the NE where very low winter temperatures prevail, an increase in Tmax had a positive effect on yield unlike in other places where the effect was the opposite. This became evident when MLR analysis was made separately for the different regions (see approach 2 below). Therefore, approach 1 was rejected.

Multiple linear regression analysis of daily yield data and daily weather data separately for different locations

Upon realizing that the weather parameters had different impacts on yield in the different study locations, MLR analysis was done for each study location separately (approach 2). For obtaining variations in yield (Y) and weather (X), daily data were collected round the year for several years. The MLR models obtained for the individual regions had only two independent variables in the last step, namely daily Tmax and daily Tmin. The MLR models for the different study locations were: Y = 433.43 - 7.87 Tmax - 4.83Tmin (CES, 9^0 26'N to 76^0 48'N), Y = 171.01 - 2.54Tmax - 1.71Tmin (Padiyoor, 11^0 58'N to 75^0 36'N), Y = 204.98 - 1.01Tmax - 5.51Tmin (Dapchari, 20^0 04'N, 72^0 04'E), Y = 41.25 + 0.67Tmax - 1.13Tmin (Agarthala, 23^0 50'N, 91^0 16'E) and Y = -24.85 + 3.58 Tmax - 2.59Tmin (Tura, 25^0 30'N, 90^0 13'E). From these five models, the change in yield when both Tmax and Tmin concomitantly increased by 1 ^{0}C was calculated (Table 3). Reduction in yield in CES, Chethackal was to the tune of 16% for 1 ^{0}C rise in Tmax and Tmin. In Dapchari, the yield reduction for 1 ^{0}C rise in Tmax and Tmin was 11% followed by 9% in Padiyoor. But in the other two regions, namely Agartala and Tura in NE India where winter temperatures are very low, the impact of warming was found to be negligible. In Agartala, the yield reduction was about 1% and in the case of Tura there was an increase in the yield by 3% for 1 ^{0}C rise in Tmax and Tmin. Thus, small rise in temperature in this region may not have much adverse impact on rubber yield. Sometimes this may increase the yield just like what happened in the Tura region. Warming of the region may help to expand NR cultivation to more parts of NE where low temperature is a limiting factor today.

During the last 52 years (1957-2009) Tmax and Tmin in RRII have increased at the rate of 0.05 ^{0}C/yr and 0.03 ^{0}C/yr, respectively at RRII, Kottayam (Table 1). Extrapolating this data, the rise in Tmax and Tmin in the next 10 years was calculated and the same was used to estimate the expected reduction in productivity after 10 years at the nearby CES, Chethackal using the MLR model developed for CES (Table 3). The yield reduction after 10 years will be about 7% in CES. In Padiyoor, the rate of increase in Tmax and Tmin during the period 1998-2009 were 0.01 ^{0}C/yr and 0.11 ^{0}C/yr, respectively (Table 1) and this may result in the reduction of yield by 4% after 10 years based on the MLR model for Padiyoor (Table 3). In the case of Dapchari, during the period 1987-2009 the rate of increase in Tmax was much higher (0.08 ^{0}C/yr) but the minimum temperature increased by only 0.03 ^{0}C/yr (Table 1). The reduction in the yield in this region will be 4% for the next decade. In Agartala, the reduction in yield in the next ten years will be very small going by the present warming trend (1%) which is 0.02 ^{0}C/yr for Tmax and Tmin 0.06 ^{0}C/yr for Tmin (during the period 1984-2007). For the period 1995-2008 Tmax in Tura increased by 0.12 ^{0}C/yr (Table 1). But the minimum temperature increased by 0.05 ^{0}C/yr in this region (Table 1). The cumulative effect of the expected changes in Tmax and Tmin in this region could lead to an increase in the yield by 11% in the next ten years (Table 3).

Table 3. **MLR (backward) models, percentage change in NR productivity (on a per tree per day basis) for 1^{0}C rise in Tmax and Tmin and predicted yield depression in the next 10 years with the current warming trends in the different study locations (approach 2)**

Station			MLR			% Change (for 1 ^{0}C rise)	% Change (in next 10 years)	Estimated present productivity from MLR (g/t/t)
			Coeff.	Intercept	R^2			
Tura	2003-08	Tmax	3.58	-24.85	0.23	**3**	**11**	**35.8**
(NE)		Tmin	-2.60					
Agartala	2003-08	Tmax	0.67	41.25	0.07	**-1**	**-1**	**37.9**
(NE)		Tmin	-1.13					
Chethackal	2003-08	Tmax	-7.87	433.43	0.29	**-16**	**-7**	**73.0**
(Traditional)		Tmin	-4.83					
Padiyoor	2007-08	Tmax	-2.54	171.01	0.19	**-9**	**-4**	**48.6**
(Traditional)		Tmin	-1.71					
Dapchari	2007-08	Tmax	-1.01	204.98	0.50	**-11**	**-4**	**57.7**
(Non-Traditional)		Tmin	-5.51					

Table 4. **MLR (backward) models, percentage change in the future productivity of rubber (on a per ha per month basis) for 1°C rise in Tmax and Tmin and estimated present productivity (kg/ha/yr) from the MLR models for three locations in Kerala**

Region			MLR			% Change (for 1°C rise)	Estimated present productivity from MLR model (kg/ha/yr)
			Coeff.	Intercept	R^2		
Kottayam	2008-09	Tmax	-6.14	999.53	**0.24**	**-19**	**1965**
(close to RRII)		Tmin	-27.68				
Taliparamba	2008-09	Tmax	6.14	-7.30	**0.12**	**-4**	**1950**
(close to Padiyoor)		Tmin	-1.37				
Kanjirapally	2008-09	Tmax	-11.33	798.36	**0.25**	**-15**	**1902**
(close to CES)		Tmin	-12.68				

Multiple linear regression analysis of per hectare productivity and temperature

The MLR model obtained for per hectare productivity (kg/ha/month) was Y = 999.53 - 6.14Tmax - 27.68Tmin for Kottayam (close to RRII), Y = 789.36 - 11.33Tmax - 12.68Tmin for Kanjirapally (close to CES) and Y = 281.91 + 4.13Tmax - 11.26Tmin for Taliparamba (close to Padiyoor). These MLR models were made using monthly mean values of the Y and X vaiables for the whole year for several years. While mean yields were obtained from growers' fields in these three regions, the weather data were obtained from nearby RRII, Kottayam (for the Kottayam region), RRS, Padiyoor (for the Taliparamba region) and CES, Chethakkal (for the Kanjirappally region). The percentage reductions in productivity (for 1 °C rise in both maximum and minimum temperatures) were 19%, 15% and 4% for Kottayam, Kanjirapally and Taliparamba, respectively. These results were comparable to the results obtained from the respective regions when per tree per day yield was used as the dependent variable (Tables 3&4).

Our analyses clearly indicate that climate has warmed in the traditional and non traditional rubber growing tracts of India and that this will have qualitatively and quantitatively different impacts on NR productivity in the different regions. Kerala and the Konkan regions are going to be relatively more affected by the adverse effect of climate warming than NE India (Table 3) where warming conditions may increase productivity even as the prevailing cold conditions are a limiting factor at present (Jacob *et al.*, 1999). Rise in temperature, especially in Tmax would have a positive impact on NR cultivation in NE India, unlike in other places. For these reasons, approach 1 was rejected. Extrapolating the present warming trends, the MLR models clearly indicate that NR productivity will be relatively more affected in Kerala than any other NR growing regions in the next one decade, although the absolute productivity may still remain high here. However, NR productivity may see an improvement in NE in the coming decade as the region continues to get warmer.

In this context, it is pertinent to ask the question if the past warming has had in fact adversely affected NR productivity. Going by the MLR models, such an impact must have happened already. But it may be noted that statistical data clearly indicate that NR productivity in the country has gone up in the past decades (Rubber Board, 2009). This has been due to increased adoption of high yielding clones, particularly RRII 105, the flagship clone released by RRII during 1980. RRII 105 has been one of the highest yielding clones anywhere in the world. As a large share of the mature plantations came under RRII 105, NR productivity (based on statistical data from growers' fields) also increased over the years, masking the actual impact of climate warming on productivity.

However, if large scale adoption of RRII 105 had not happened and the area under this high yielding clone had not increased, there was every possibility that NR productivity would have gone down over the years as a result of climate warming. The MLR models clearly suggest that the potential NR productivity must have come down in the recent decades; thanks to climate warming. During the late 1970s and early 1980s, the mean productivity of RRII 105 under the best management practices of our research farms in the traditional regions have been in the range of 60-65 g/t/t, but of late, this is mostly in the range of 50-55 g/t/t or even less (RRII, 1988 & 2010). Since the genetics (clone) was the same and the management practices were constant (as can be expected as the trials were in our own experimental farms where management practices did not under go any substantial change over the years), the most persuasive reason for this reduction in productivity seems to be the appreciable temperature warming that has happened during this period. There might have been other factors too, such as likely deterioration in soil productivity or other unknown factors, but the high rate of rise in both Tmax and Tmin in the traditional

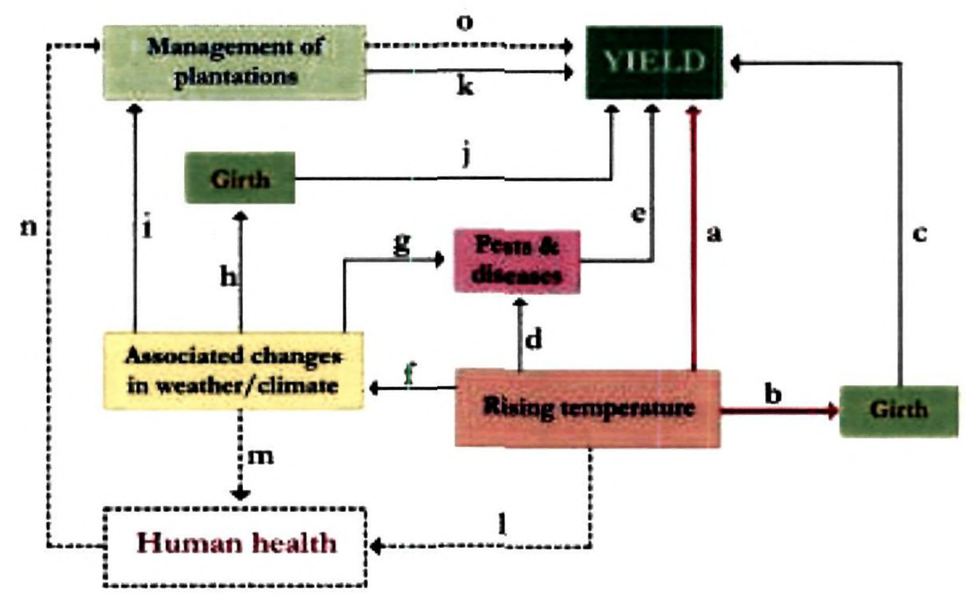


Fig. 2. Flow chart showing the direct and indirect effects of climate warming on growth and yield of rubber

regions strongly indicates the significant role climate warming must have played in reducing productivity in the past.

This could have been true for other crops too – had it not been for the genetic and agronomic improvements, productivity might have been adversely affected, or at least the potential productivity of a new variety might not have been fully realized in the field as temperature rose. This points to the need to evolve cultivars and clones that are climate (temperature) resilient.

The present analysis has been the first attempt of its type to assess the direct impact of climate warming on NR productivity. Our results clearly indicate how Tmax and Tmin have been increasing in the past, how it has adversely affected productivity in the past and what rising temperatures might do to NR productivity in future in the different agro-climatic regions of India where this crop is cultivated today. Climate change is obviously much more complex than daily variations in weather parameters such as daily Tmax or Tmin (See Fig. 2). Changes in cloud formation, wind, rainfall pattern, occurrence of extreme weather events like storms, floods, long dry spells, unexpected breaks in monsoon, spread of new and old pests and diseases *etc.* are important factors that can seriously influence NR cropping calendar in unknown ways which are the subject of our current research.

REFERENCES

Cynthia, R. and Parry, M.L. (1994). Potential impact of climate change on world food supply. *Nature,* **367**:133-138.

Cynthia, R., Iglesias, A., Yang, X.B., Epstein, P.R. and Chivian, E. (2001). Climate change and extreme weather events: Implications for food production, plant and pests. *Global Change & Human Health,* **2**(2): 90-104.

IRSG, (2009) *Rubber Statistical Bulletin, April-June 2009* International Rubber Study Group, 111 North Bridge Road #23-06 Peninsula Plaza, Singapore 179098. **63**:10-12.

IPCC. (2007a). *Fourth Assessment Report (AR4), Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2007b). *Fourth Assessment Report (AR4), Climate Change 2007: Impacts Adaptation and Vulnerability.* Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jacob, J., Annamalainathan, K., Alam, B., Sathik, M.B.M., Thapliyal, A.P. and Devakumar, A.S. (1999). Physiological constraints for cultivation of *Hevea brasiliensis* in certain unfavourable agroclimatic regions of India. *Indian Journal of Natural Rubber Research,* **12**(1&2): 1-16.

Manton, M.J., Della-marta, P.M., Haylock, M.R., Hennessy, K.J., Nicholls, N., Chambers, L.E., Collins, D.A., Daw, G., Finet, A., Gunawan, D., Inape, K., Isobe, H., Kestin, T.S., Lefale, P., Leyu, C.H., Lwin, T., Maitrepierre, L., Ouprasitwong, N., Page, C.M., Pahalad, J., Plummer, N., Salinger, M.J., Suppiah, R., Tran, V.L., Trewin, B., Tibig, I. and Yee, D. (2001). Trends in extreme daily rainfall and temperature in Southeast Asia and the South Pacific: 1961-1998. *International Journal of Climatology,* **21**:269-284.

RRII. (1988). *Annual Report 1986-87.* Rubber Research Institute of India, The Rubber Board, Kerala, 23p.

RRII. (2010). *Annual Report 2008-09.* Rubber Research Institute of India, The Rubber Board, Kerala, 28-32.

Rubber Board. (2009). *Indian Rubber Statistics.* The Rubber Board, Kerala, **32**: 7-8.

Natural Rubber Research, **24**(1): 28-37, 2011

ECOSYSTEM FLUX MEASUREMENTS IN RUBBER PLANTATIONS

K. Annamalainathan, P. R. Satheesh and James Jacob
Rubber Research Institute of India, Kottayam- 686 009, Kerala, India

Received: 6 February 2011 Accepted: 28 April 2011

Annamalainathan, K., Satheesh, P.R. and Jacob, J. (2011). Ecosystem flux measurements in rubber plantations. *Natural Rubber Research*, **24**(1): 28-37.

Perennial trees like natural rubber plants sequester large quantities of atmospheric CO_2 into biomass and therefore, mitigate the increase in greenhouse gas (GHG) emission. In the present study measurements of CO_2 and water vapour flux of a natural rubber ecosystem were attempted for one continuous year. An eddy covariance (EC) flux measurement system was installed on an 18 meter tower inside a rubber plantation (4-5 years old) at the Central Experimental Station of the Rubber Research Institute of India (RRII) which is situated in the traditional rubber growing region of Kerala. The daily net ecosystem exchange (NEE) of CO_2 by the rubber ecosystem was in the range of 1-25 g/m²/day during the study period. Most of the days recorded a net CO_2 sequestration. However, a few days recorded a net CO_2 efflux (R_{eco}) from the plantation to atmosphere. The mean annual NEE of the 4-5 years old rubber plantation was 11 g CO_2/m²/day which works out to 33.5 tons CO_2/ha/year indicating that rubber plantation is a potential sink for atmospheric CO_2. The amount of carbon sequestered by the plantation as calculated from the EC data was compared with carbon sequestration of the trees calculated from biomass inventory method. The annual mean evapotranspiration was 3.5 mm/day as calculated from the EC data indicating the high efficiency of sequestering carbon per unit amount of water consumed.

Keywords: Atmospheric flux, Biomass, Carbon sequestration, Eddy Covariance, NEE.

INTRODUCTION

CO_2 is the most important anthropogenic greenhouse gas (GHG) causing global warming (Solomon *et. al.*, 2007). Agricultural and forest ecosystems act as major sinks for atmospheric CO_2 as these ecosystems can sequester large quantities of CO_2. The term "sink" is used to describe agricultural and forest lands or other systems that absorb and store CO_2 from atmosphere. Carbon sequestration is the removal and storage of atmospheric CO_2 by photosynthesizing organisms including terrestrial and aquatic vegetation, algae *etc.* in plant or algal biomass and soils (Kumar *et al.*, 2009). Sequestration of CO_2 by terrestrial plants helps prevent global warming (Suruchi and Singh, 2002). Marine algae are also a potent sink for atmospheric CO_2 (Takahashi *et al.*, 2002); however, terrestrial vegetation is obviously more amenable to human intervention than marine algae are.

Roughly between 45 and 55% of plant biomass is carbon (Malhi *et al.*, 2001). Some of this stored carbon in plants is transferred into soils when vegetation, litter and roots decay. In fact, there is more carbon stored in below ground biomass and soils than above

Correspondence: K. Annamalainathan (Email: annamalainathan@yahoo.co.in)

ground biomass in boreal forests (Roger, 2001). In tropics, more carbon is stored in above ground vegetation than in soils (IPCC, 2000). Carbon stored in various components of an ecosystem can return to the atmosphere as CO_2 when the soil is cultivated. Agricultural tillage operations stir up soils resulting in oxidation of biomass carbon into CO_2. Decay or combusting of biomass also results in emission of CO_2 into the atmosphere. The movement of carbon in and out of trees and soils is integral part of the earth's carbon cycle.

While annual agricultural crops also sequester large amounts of CO_2 from the atmosphere, almost the entire amount of carbon stored in them is returned to the atmosphere at the end of the crop cycle when the crop is consumed by man or animal and the crop residues are used as cattle feed or they are incorporated into soil or burnt. This is not so in forestry or plantation agriculture with perennial tree species. For example, a plantation like natural rubber (*Hevea brasiliensis*) has an economic life cycle of 25- 30 years and therefore, the carbon sequestered in the biomass in rubber plantations will stay for this long.

Automobile tyres, whether they are made of natural or synthetic rubbers, are indispensable to man. Automobiles are responsible for emission of roughly 14% of the global GHGs (Stern, 2006). Natural rubber plantations help to mitigate the atmospheric CO_2 concentration in two different ways. First, it supplies natural rubber which can be used in place of synthetic rubbers that are produced from petroleum stocks. Production of synthetic rubbers results in huge emission of CO_2. Secondly, natural rubber plantations have the capacity to sequester significant quantities of CO_2 from the atmosphere. This study attempts to measure the capacity of a rubber plantation to sequester atmospheric CO_2.

There are several methods to study the CO_2 sequestration potential of a perennial plantation crop like natural rubber. Biomass inventory method is the most easily available and commonly used method which gives an estimate of the total amount of carbon stored in the various components over a period of time (Jacob and Mathew, 2004; Jacob, 2005). In the present study a state-of-the-art method known as eddy covariance (EC) technique was used for measuring CO_2 and water flux in a 4-5 year old natural rubber plantation in central Kerala continuously for a period of one year.

MATERIALS AND METHODS

Experimental site

The experimental site was situated at the Central Experimental Station (CES) of Rubber Research Institute of India (RRII) at Chethackal, Pathanamthitta District, Kerala (Fig. 1). The location is 9^0 26'N and 76^0 48'E. The study was carried out in an immature (4-5 year old) rubber plantation, with different *Hevea* clones namely, RRII 105, PB 260, RRII 430 and ten ortet selections, spread over more than five hectare area with almost uniform growth. The average height of the trees was 10 m and girth was 35 cm at 150 cm above the bud union of the plant when the study began in March 2009. Results given here are based on the measurements made between April 2009 and March 2010.

Eddy covariance technique for atmospheric flux analysis

Eddy covariance (EC) method is a sophisticated micro-meteorological method in which the fluxes of CO_2 and water vapour and three-dimensional wind velocities are measured on real time basis (Baldocchi, 2003). The EC system comprises of a three dimensional sonic anemometer (CSAT3, Campbell, USA) which is used together with an open path infra red gas analyzer (Li-7500, Li-Cor, USA). Additionally the system is equipped with a net radiometer (NR-Lite, USA) and temperature and relative humidity (RH) sensors (HMP 45, Vaisala, Finland) (Fig.2). Other weather parameters namely, rainfall, maximum and minimum temperatures, sunshine hours, *etc.* were collected from an adjacent weather station at CES, Chethackal. Carbon dioxide (Fc) and water vapour fluxes of the rubber plantation were continuously measured by eddy covariance technique for the above period. The EC equipments were commissioned on a flux tower of 18 m height and the various sensors were fixed on the tower at 4 m above the canopy (Fig. 2).

Raw data were collected and corrected by Edi Re software and processed into half-hourly values. There are several parameters necessitating correction of the measured signals (Massman and Lee, 2002). The planar fit corrections have been done for averaging the mean vertical wind by using Edi Re software. Data on CO_2 flux (Fc) and the water vapour flux which is measured as latent heat of vapourisation (LE) were corrected for density effects (Webb *et al.*, 1980). Daily diurnal net ecosystem exchange of CO_2 (NEE) and day and night flux rates were also calculated. The latent heat of vapourization (LE) was used to calculate evapotranspiration (ET) on a per day basis. The downloaded and corrected data table contains half hourly mean values of net radiation, air temperature, relative humidity (RH), fluxes of CO_2 (Fc), water (LE) and sensible heat (H). The rates of ecosystem photosynthesis, respiration and decomposition will vary diurnally and seasonally in response to interactions between the physical environment like irradiance, moisture and temperature and biotic factors like plant phenology, soil microbial metabolism and heterotrophic CO_2 release (Goulden *et al.*, 2004). Therefore, attempts were also made to correlate the CO_2 flux values with prevailing environmental conditions.

Net ecosystem level flux of CO_2 and water vapor in real time was calculated. The net CO_2 exchange obtained from the EC system is the difference between photosynthetic assimilation by the vegetation and the total respiratory CO_2 efflux from the foliage, roots and soil (Lalrammawia and Paliwal, 2010). In the present study, ecosystem level net CO_2 sequestration rates (photosynthesis and respiration, including litter decomposition) and evapotranspiration for a one year period in a 4-5 year old rubber plantation is described.

Accounting of tree biomass

The above ground dry weight of a rubber tree was calculated using the Shorrock's regression model:

$W= 0.002604\ G^{2.7826}$ (Shorrocks *et al.*, 1965)

where, G is trunk girth (cm) at a height of 150 cm from bud union. 15-20% of the shoot biomass was taken as the root biomass.

RESULTS AND DISCUSSION

Diurnal pattern of net ecosystem exchange of CO_2 (NEE) clearly indicates two phases namely, a net fixation of CO_2 occurring during day time (influx) and net release of CO_2 from the system into the atmosphere during night time (efflux) (Fig. 3). By default,

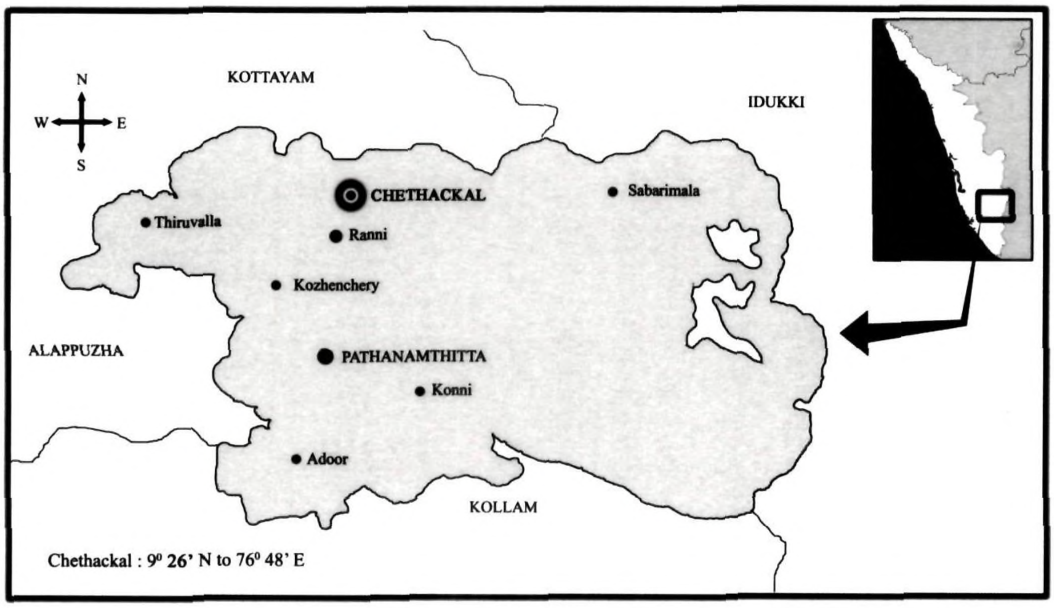


Fig. 1. Map showing the location of the study area (Chethackal, Pathanamthitta District, Kerala, India, 9^0 26'N ; 76^0 48'E)

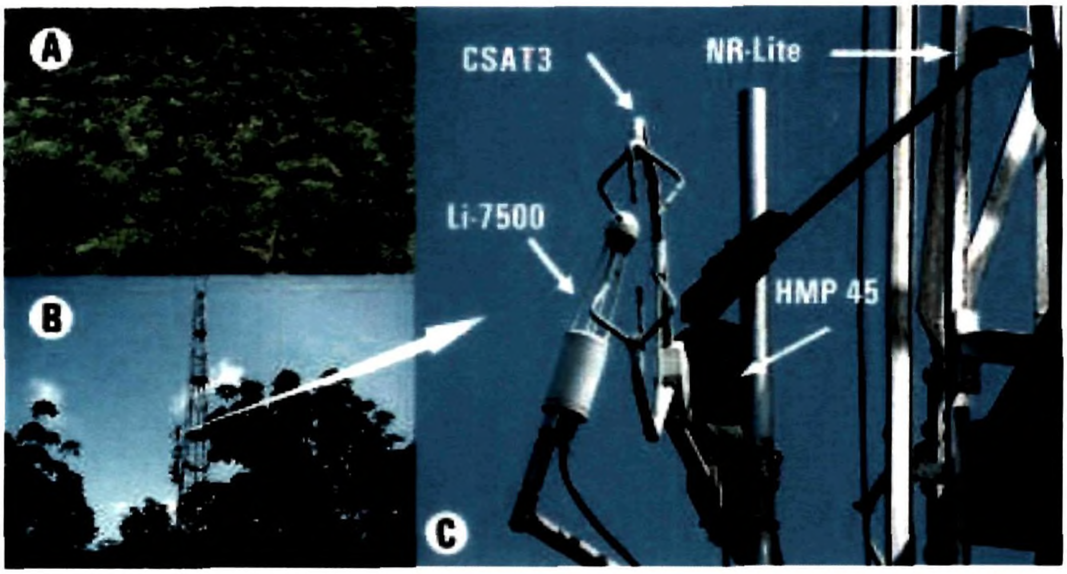


Fig. 2. (A) A bird's eye view of the young rubber canopy at Central Experimental Station (CES), Rubber Research Institute of India, Kottayam, Kerala State, India. (B) Eddy covariance system installed on an 18 meter tower inside a rubber plantation. (C) Various sensors of eddy covariance measurement system are indicated, CSAT3, Campbell's three dimensional sonic anemometer; Li 7500, Li COR's open path infra red gas analyzer; NR- Lite, Kipp and Zonen's net radiometer and HMP 45 temperature and RH sensors

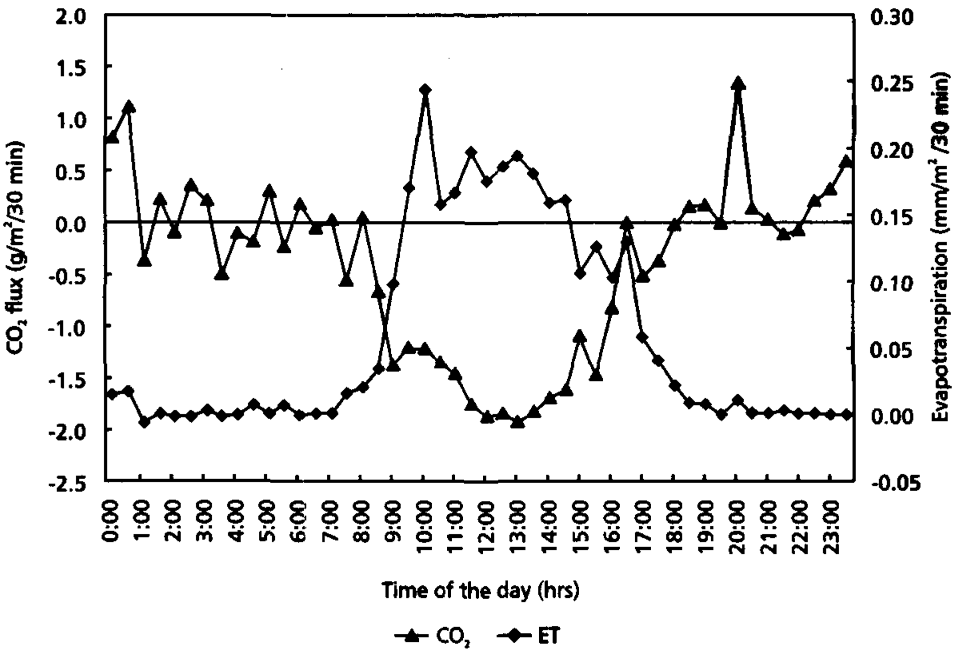


Fig. 3. A typical diurnal CO_2 and water flux (25[th] July 2009) pattern in an immature rubber plantation (4-5 years old)

net influx of CO_2 into the ecosystem (net photosynthesis) is shown as negative flux and net efflux of CO_2 (net respiration) is shown as positive flux which includes respiration from all living components and decomposition, collectively termed ecosystem respiration (R_{eco}). The difference between the amount of net fixation during day time and the CO_2 lost as R_{eco} during night time is the net fixation of CO_2 by the ecosystem for a given day. As sunlight intensity increases, net CO_2 flux gradually becomes negative (indicating net photosynthesis or CO_2 influx or sequestration into the ecosystem) and this generally remains negative until sunset. In the evening as light intensity declines R_{eco} becomes greater than CO_2 fixation (Fig. 3). Evapotranspiration followed an opposite pattern as that of CO_2 flux (Fig. 3).

During the study period, the daily NEE by the rubber ecosystem ranged 1-25g CO_2/m^2/day (Fig. 4). Most of the days recorded CO_2 influx in to the plantation; however, a few days (around 25 days during the one year study period) recorded net carbon efflux from the plantation to atmosphere. On those days, around 1-7g CO_2/m^2/day was released to atmosphere and during these days there was rain and relatively fewer sunshine hours. The net efflux on certain days would have included the possible high rate of total soil respiration (R_s) both by autotrophic (R_a) and heterotrophic (R_h) components of the soil in addition to the net CO_2 release from leaf respiration. The soil respiration rate generally depends on the soil moisture, temperature, organic composition, density of microbial population and rate of decomposition of organic contents (Stephen

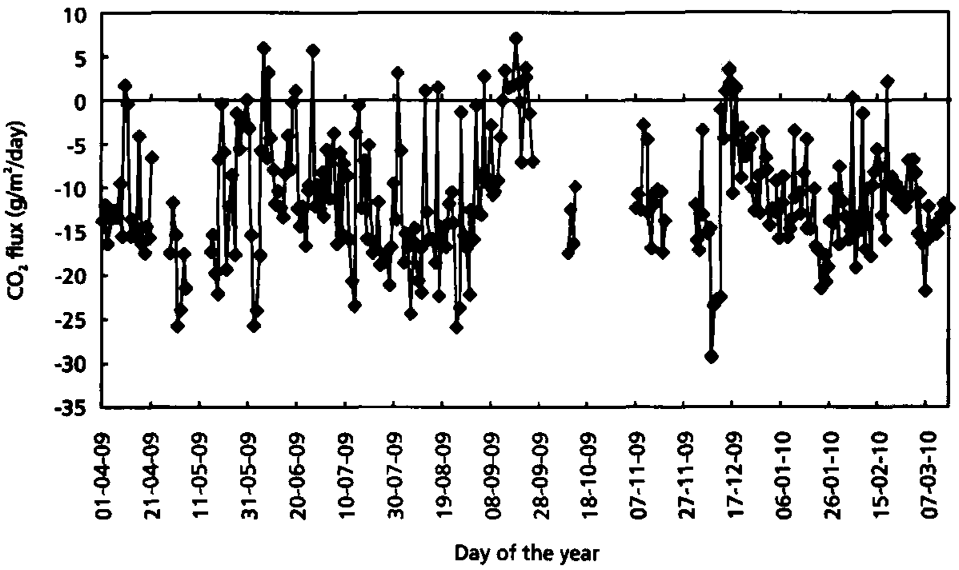


Fig. 4. Daily net CO_2 flux (Fc) in a 4-5 year old immature rubber plantation in central Kerala for a continuous one year period. Short gaps in the data are due to equipment failure from thunder storm, power failure *etc.*

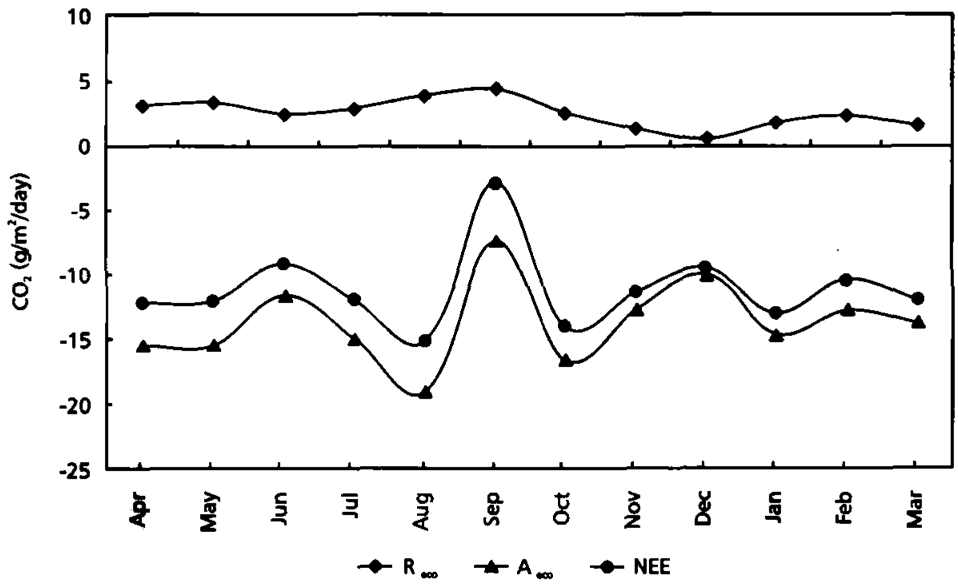


Fig. 5. Mean monthly ecosystem exchanges of CO_2 in a 4-5 year old rubber plantation. The mean ecosystem respiration (Reco), ecosystem CO_2 assimilation (A_{eco}) and net ecosystem CO_2 exchange (NEE) on per day basis are depicted

and Theodore, 1979). Intermittent heavy rainy days witnessed a net efflux of CO_2 to atmosphere, most probably, due to a low rate of canopy photosynthesis due to poor solar light and possible sudden spurts in release of locked up CO_2 from the air space in the soil. Sunny days (when soil moisture level was not deficient) were more favourable for sequestration of carbon by the rubber plantation. On an annual average, the NEE was 11g CO_2/m^2/day during the study period which is equivalent to 33.5 tons of CO_2/ha/year.

The net CO_2 assimilation (A_{eco}) and net respiratory CO_2 efflux (R_{eco}) were calculated for the entire year. While the mean R_{eco} was 2.5g CO_2/m^2/day, the net assimilation rate (A_{eco}) recorded was 13.5g CO_2/m^2/day (Fig. 5). Though there was considerable rate of ecosystem respiration at night, the CO_2 assimilation during daytime was much higher in rubber plantation making it a net sink of CO_2. In a study with mature rubber plantation in Thailand, Thaler *et al.* (2008) got similar rates of sequestration and they have suggested that ecosystem level EC measurement of CO_2 and water fluxes could be used to model gas exchange of rubber plantation according to prevailing climate and other environmental parameters.

The daily flux data were analyzed in relation to prevailing maximum temperature (Tmax) and sunshine hours of the day, but a clear relationship was not observed throughout the study period, most likely due to other factors such as soil moisture and VPD interfering with photosynthesis and respiration (Stephen and Theodore, 1979; Orchard and Cook, 1983). In general, days with lengthy sunshine hours recorded high rate of net ecosystem exchange (Fig. 6).

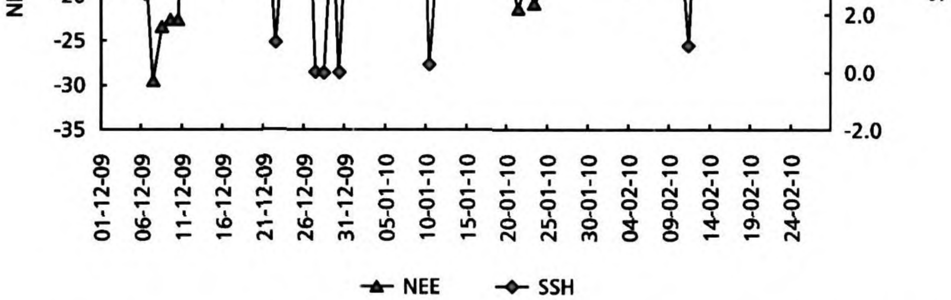


Fig. 6. Sunshine hours (SSH) and net ecosystem exchange of CO_2 (NEE). Days with lengthy sunshine hours recorded high rate of net ecosystem exchange (NEE)

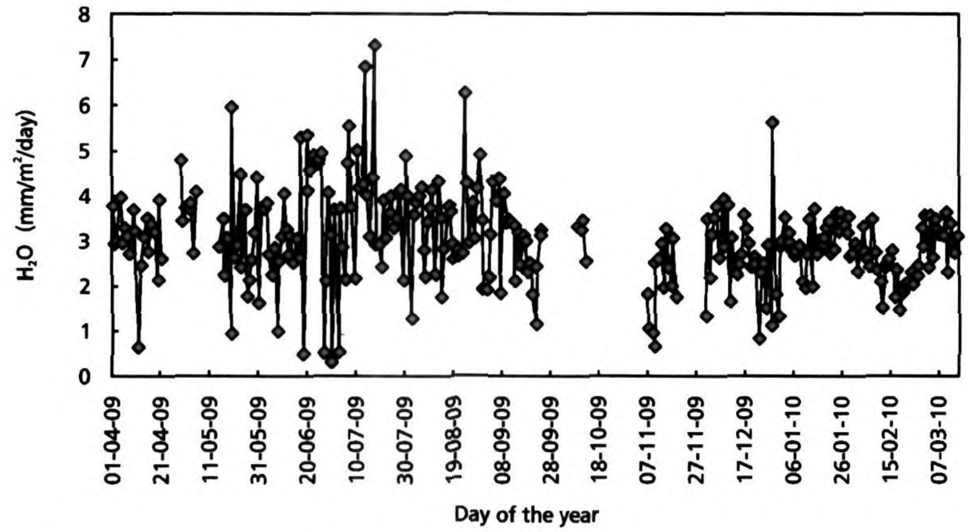


Fig. 7. Water flux in a 4-5 year old rubber plantation in central Kerala for a continuous one year period

During summer months sunlight was plenty but soil moisture deficit and high atmospheric VPD could restrict canopy photosynthesis and hence NEE. The NEE was relatively higher during pre-monsoon period when the soil is fully recharged with moisture after the initial showers. During continuously cloudy and incessant rainy days, either NEE was very low or the net ecosystem respiration rate was higher than net assimilation.

The rate of evapo-transpiration (ET) was calculated from the downloaded data on latent heat of vapourization (LE). The mean ET was 3.5 mm/day during the study period (Fig. 7). Earlier studies with lysimetric method in the traditional rubber growing areas of Kerala showed that the mean ET was 4.4 mm per day (Jessy *et al.*, 2002).

The amount of carbon sequestered by the rubber plantation was estimated during the same period by estimating the annual shoot biomass increment during this period using Shorrock's method. From the shoot biomass estimation, the amount of CO_2 sequestration was calculated as 13.5 t CO_2/ha/yr which does not include root biomass, soil respiration, litter decomposition and sequestration by weeds and other vegetation inside the plantation such as cover crops. Carbon stock in rubber plantations has been worked out earlier by biomass inventory method (Jacob and Mathew, 2004; Wauters *et al.*, 2008). The amount of carbon stored in one hectare of a 33 year-old stand was 596 mt. Total carbon sequestered by rubber plantations under Kerala conditions for a 21 year period was estimated to be 67 t C/acre and it was reported that the sequestration capacity of rubber plantation was much higher than most other terrestrial ecosystems (Jacob and Mathew, 2004). A 14 year old rubber holding had a carbon stock of 76 t C/ha in its above ground biomass which is equivalent to 19.9t CO_2/ha/yr (Wanters *et al.*, 2008). The contribution of the soil organic carbon pool amounted to 135 t C/ha (Wauters *et al.*, 2008).

Our studies show that natural rubber plants are a good sink for atmospheric CO_2 round the year. Cultivation of rubber trees on non forested land is a good land use option to mitigate rising concentration of CO_2 in the atmosphere. Under Kyoto Protocol, forestry or plantation activities that sequester atmospheric carbon into biomass can generate CO_2 offset credits that could further help in reduction of fossil fuel use (Suruchi and Singh, 2002), but existing plantations are not eligible for this credit. However, there are alternative carbon markets where carbon credits from existing plantations are also getting greater acceptability.

ACKNOWLEDGEMENTS

The authors thank Dr. Mallinath Priyadarshan, Deputy Director, Central Experimental Station for his help in maintenance of the eddy covariance tower. Thanks are also due to Dr. R. Krishnakumar, Joint Director, Crop Physiology Division, RRII for his support in commissioning the tower.

REFERENCES

Baldocchi, D.D. (2003). Assessing ecosystem carbon balance. Problems and prospects of the eddy covariance technique. *Global Change Biology*, **9**: 476-492.

Goulden, M.L., Miller, S.D., Da Rocha, H.R, Menton, M.C., De Freitas, H.C., E Silva Figueira, A.M., and Dias De Sousa, C.A. (2004). Diel and seasonal patterns of tropical forest CO_2 exchange. *Ecological Applications*, **14**(4): 42-54.

Intergovernmental panel on climate change 2000. (IPCC 2000). *Methodological and technological issues in 'Technology Transfer'*, ISBN 92-9169-112-7.

Jacob, J. (2005). The science, politics and economics of global climate change: Implications for the carbon sink projects. *Current Science*, **89**(3): 464-474.

Jacob, J. and Mathew, N.M. (2004). Eco-friendly NR plantations can tap vast global funding. *Rubber Asia*. March-April, 2004.

Jessy, M.D., Dey, S.K, Prathapan, K., Joseph John, Mathew, T.P and Punnoose, K. I. (2002). Effect of drip irrigation on growth of immature rubber. *Journal of Natural Rubber Research*, **15**(2): 182-186.

Kumar, G.P., Ashutosh, A.M, Gupta, S. and Singh, S.B. (2009). Carbon sequestration with special reference to agro forestry in cold deserts of Ladakh. *Current Science*, **97**: 1063-1068.

Lalrammawia, C. and Paliwal, K. (2010). Seasonal changes in net ecosystem exchange of CO_2 and respiration of *Cenchrus ciliaris* L. grassland ecosystem in semi-arid tropics: an eddy covariance measurement. *Current Science*, **98**(9): 1211-1218.

Malhi, Y., Phillips, O. and Grace, J. (2001). Are Amazonian rain forests absorbing carbon and increasing in biomass? A comparison of evidence and insights from measurements of carbon dioxide fluxes and forest biomass change. In: *Tropical Ecosystems: Structure, diversity, and Human Welfare. Proceedings of the International Conference on Tropical Ecosystems*. Oxford-IBH, New Delhi, 27-28 p.

Massman, W. J. and Lee, X. (2002). Eddy covariance flux corrections and uncertainties in long term studies of carbon and energy exchange. *Agriculture and Forest Meteorology*, **113**: 121-144.

Orchard, V.A. and Cook, F. J. (1983). Relationship between soil respiration and soil moisture. *Soil Biology and Biochemistry*, **15**: 447-453.

Roger, S.S. (2001). Sequestration of carbon by soil. *Soil science*, **166**(11): 858-871.

Shorrocks, V.M. (1965). Mineral nutrition, growth and nutrient cycle of *Hevea brasiliensis*. Growth and nutrient content. *Journal of Rubber Research Institute of Malaysia*, **19**: 32-47.

Solomon, S., Dahe, Q., Martin, M., Melinda, M., Kristen, A., Melinda, M.B., Tignor, H., LeRoy, M. Jr., and Zhenlin, C. (2007). Climate Change, The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Summary for policy makers. pp. 1-18.

Stephen, G.P. and Theodore, T.K. (1979). Stomatal response of populus clones to light intensity and vapor pressure deficit. *Plant Physiology,* **64**: 112-114.

Stern, N. (2006). Stern review on the economics of climate change. *Executive summary.*

Suruchi, B. and Singh, R. (2002). Carbon sequestration estimates for forestry options under different land-use scenarios in India. *Current Science,* **83**: 1380-1386.

Takahashi, T., Sutherland, C., Sweeney, A., Poisson, N., Tilbrook, N., Bates, R., Wanninkhof, R.A., Feely, C., Sabine, J., Olafsson and Nojiri, Y.C. (2002). Global sea-air CO_2 flux based on climatological surface ocean CO_2 and seasonal biological temperature effects. *Deep Sea Research II,* **49**: 1601-1622.

Thaler, P., Siripornpakdeekul, P., Kasemsap, P., Kunjet, S., Chairungsee, N., Kositsup, B., Roupsard, O., Gay, F., Chantuma, A., Thanisawanyangkura, S., Sangkhasila, K., Sathornkich, J. and Bonnefond, J.M. (2008). Rubberflux. Progress in CO_2 and water budget evaluation of rubber plantations in Thailand. *AsiaFlux Workshop 2008,* 17-19 November 2008, Seoul, Republic of Korea.

Wauters, J.B., Coudert, S., Grallien, E., Jonard, M. and Ponette, Q. (2008). Carbon stock in rubber plantation in Western Ghana and Mato Grosso (Brazil). *Forest Ecology and Management,* **255**(7): 2347-2361.

Webb, E.K., Pearman, G.I and Leuning, R. (1980). Corrections of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of Royal Meteorological Society,* **106**: 86-100.