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Evaluation of RCA & RCA GUESS and estimation of vegetation-climate

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Abstract

There is a bidirectional relation between climate and vegetation distribution at local as well as global scale. Changes in climate pattern modify the terrestrial vegetation distribution that in turn affects the climate system by altering the balance of radiation, water, momentum, CO_2 and other important atmospheric gases. The large-scale changes in vegetation structure and composition give rise to important climate relevant feedbacks (biophysical as well as biogeochemical). General circulation models that simulate future climate state do not take into account these interactions between land and atmosphere. Results from fairly recent studies bring forth the importance of including vegetation dynamics in order to predict the future climate more realistically. The physical changes in vegetation pattern such as changes in albedo, evapotranspiration, and surface roughness affect the climate pattern (i.e. through biophysical feedbacks) at regional scales, emphasizing the importance of coupling regional climate models with dynamic vegetation models. However, before applying the regional models to a large domain such as India, it is important to validate these models. Therefore, the aim of this study is to first assess the performance of RCA GUESS, a regional earth system model and RCA, a regional climate model, against observation datasets for the period 1989-2005. Later, the study examines the effect of vegetation feedbacks, more precisely biophysical feedbacks, on present climate of India. At the end, the future climate predictions will be made using RCA under IPCC's future greenhouse gas scenario (SRES-A_1B). The study found that RCA did not simulate average surface temperature and precipitation for summer as well as winter months quite reasonably. On the other hand, RCA GUESS also showed similar pattern of deviations but the biases in RCA GUESS are explained to a certain extent over some regions by including transient vegetation and in some cases the deviations were even amplified. This shows that Indian Climate is quite sensitive to vegetation change and it certainly plays a critical role in influencing the regional climate. However, still both models require significant improvement in their structural design for correctly representing the climate and vegetation pattern of tropical region. The study also discussed the reasons of significant biases present over mountainous region which was also noticed when these models are applied over different bioclimatic regions such as Europe and South America. Since both models showed considerable uncertainty in predicting the present climate variables, therefore, it is very hard to deduce the actual impact of climate on vegetation pattern and vice versa. However, the study also found that India would experience overall warming of 1^{o}C under A_1B scenario for the period 2031 to 2050 and the warming will be more pronounced over northern, western and central regions. The temperature of these regions rise as much as 1.5 to 2^{o}C. These results are comparable with the findings of other studies. But, the major shift in the precipitation pattern is not properly captured. Overall, this study not only improved our current understanding of RCA and RCA GUESS performance over tropical country such as India but also form a basis for future studies using these models over that region.

Keywords: Geography, Vegetation feedbacks, Climate Change, GCMs, RCMs, Validation, Physical Geography

Abstrakt/Sammanfattning

Det finns ett dubbelriktat samband/förhållande mellan klimat och vegetationsfördelning på lokal såväl som på global skala. Förändringar i klimatmönstret förändrar/modifierar den markbundna växtligheten som i tur påverkar klimatsystemet genom förändringar i strålningsbalansen, vatten, rörelsemängd, CO2 samt andra viktiga atmosfärsgaser. De storskaliga förändringarna i vegetationens struktur och sammansättning ger upphov till relevanta och viktiga klimat återkopplingar (biofysiska och biogeokemiska). Generella cirkulationsmodeller som simulerar framtida klimat tar inte med dessa samspel mellan land och atmosfär i beräkningen. Resultat från relativt nya studier frambringar betydelsen av att räkna med vegetationsdynamiken för att realistiskt kunna förutspå klimatet i framtiden. De fysiska förändringar i vegetationsmönstret så som förändringar i albedo, evapotranspiration och ytjämnhet påverkar klimatmönstret (dvs genom biofysiska återkopplingar) på regional skala med betoning på betydelsen av att koppla regionala klimatmodeller med dynamiska vegetationsmodeller. I vilket fall, innan de regionala modellerna appliceras på ett större landområde, som exempelvis Indien, är det viktigt att validera dessa modeller. Därför är målet med denna studie att först/främst värdera prestandan av RCA GUESS och RCA med observerade dataset från perioden 1989-2005. Studien ska också undersöka påverkan som vegetationens återkopplingar har, framförallt de biofysiska återkopplingarna, på det nuvarande klimatet i Indien. Slutligen ska det framtida klimatet förutspås genom användning av RCA med IPCCs framtida växthusgasscenario (SRES-A1B). Studien kom fram till att RCA hade svårt att simulera den genomsnittliga temperaturen för markområden och nederbörd under sommaren och vintermånaderna. Å andra sidan så visade också RCA GUESS liknande avvikande mönster men påverkan av RCA GUESS kan förklaras till en viss del för vissa regioner av att angränsande vegetation har inkluderats i modellen och i vissa fall blev avvikelserna förstärkta. Detta vittnar om att Indiens klimat är förhållandevis känsligt mot förändringar i vegetationen vilket innebär att vegetationen har en kritisk roll i hur den inverkar på det regionala klimatet. Dock behöver båda modellerna signifikant förbättras i deras strukturella design för att korrekt kunna representera klimatet och vegetationens mönster i tropiska regioner. I studien diskuteras anledningarna till den påverkan som de bergiga regionerna har vilket också uppmärksammades när dessa modeller applicerades på andra bioklimatiska regioner som Europa och Sydamerika. De större svårigheterna som studien stötte på var att kvantifiera påverkan som de biofysiska återkopplingarna har på det nuvarande klimatet eftersom båda modellerna visade betydande osäkerheter med att förutspå det nuvarande klimatets variabler. Därför är det mycket svårt att utläsa den verkliga inverkan som klimatet har på vegetationsmönstret och vice versa. Likväl så fann studien att Indien kommer att genomgå en övergripande uppvärmning på 1oC under A1B scenariot under perioden 2031 till 2050 och uppvärmningen kommer att vara som störst runt de norra, västra och centrala delarna av landet. Temperaturen i dessa delar kan komma att bli så mycket som en höjning på 1.5 till 2oC. Dessa resultaten är jämförbara med resultat av andra studier. Dock lyckades inte den övergripande förändringen av nederbördsmönstret belysas/åskådliggöras. Trots allt så lyckades inte bara denna studie att förbättra förståelsen för RCA och RCA GUESS prestationsförmåga för tropiska länder som Indien utan också skapa en grund för framtida studier som använder dessa modeller i de regionerna.

Nyckelord: Vegetationsåterkopplingar, klimatförändringar, GCM, RCM, validering

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Abbreviations

AOGCM	Atmosphere Ocean General Circulation Model
AR4	IPCC's Fourth Assessment Report
C_3	C_3 carbon fixation plants
C_4	C_4 carbon fixation plants
CH_4	Methane
CO_2	Carbon dioxide
CRU	Climate Research Unit
DFJ	December-January-February
DGVMs	Dynamic Global Vegetation Models
E_λ	Latent Heat Flux
ECHAM	European Centre Hamburg Model
ERA	ECMWF global atmospheric reanalysis
FSI	Forest Survey of India
GCMs	Global Climate Models
GDP	Gross Domestic Product
GHGs	Greenhouse Gases
GUESS	The General Ecosystem Simulator
H	Sensible Heat Flux
HadRAM	Hadley Center Regional Atmospheric Model
HIRLAM	High Resolution Limited Area Model
IBIS	Integrated Biosphere Simulator
IPCC	Intergovernmental Panel on Climate Change
JJA	June-July-August
K	Kelvin
km	Kilometer
LAI	Leaf Area Index
LINUX	Linus Unix
LLS	Land Surface Scheme
LPJ-DGVMs	Lund-Potsdam-Jena Dynamic Global Vegetation

	Models
LSS	Land Surface Scheme
LW	Long wave radiation
MAM	March April May
Mm	Millimeter
NATCOM	India's Initial National Communication to Climate Change
NPP	Net Primary Productivity
NWP	Numerical weather prediction model
^{o}C	Degree Centigrade
PFTs	Plant Functional Types
PRECIS	Providing Regional Climate Impact Studies
RCA	Rossby Center Regional Atmospheric Model
RCA-E	RCA3-Ecoclimap
RCMs	Regional Climate Models
R_{out}	Outgoing long wave radiation
SRES	Special Report on Emission Scenarios
SW	Short wave radiation
T2m	Temperature observed at 2m
VOCs	Volatile Organic Carbon
α	Albedo

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1.0 Introduction

Traditionally, it was believed that vegetation structure, composition and distribution are influenced by climate modifications (Woodward 1987, 1995 and Prentice *et al.* 1992). However, some studies recognized that there is a bidirectional relationship between climate and vegetation distribution at local as well as global scales (Charney *et al.* 1975; Bonan *et al.* 2002; Moorcroft 2003 and Foley *et al.* 2003). These studies determined that changes in climate pattern modify the terrestrial vegetation distribution that in turn affects the climate system by altering the balance of radiation, water, momentum, CO_2 and other important atmospheric gases. Small to large-scale changes in vegetation structure and composition give rise to some important climate relevant feedbacks (positive as well as negative) (Shukla *et al.* 1990; Bonan *et al.* 1992; Lean & Rowntree 1993; Foley *et al.* 1994; Sellers *et al.* 1996 and Betts *et al.* 1997). The feedbacks from terrestrial ecosystem, which are triggered through modification in physical property of vegetation, are termed as bio-geophysical feedbacks. It includes the feedbacks that originate from changes in surface albedo, surface roughness and evapo-transpiration, which alter the water, energy and momentum balance of terrestrial ecosystem. Feedbacks that are initiated as a result of modification in atmospheric chemistry due to change in trace gases such as CO_2, CH_4, Volatile Organic Carbons (VOCs), etc. are collectively known as biogeochemical feedbacks (Brovkin *et al.* 2006; Lashof 1997 and Foley *et al.* 2003).

Biophysical feedbacks have modified and shaped up the earth's climate system many times over centuries. In mid Holocene, rise in atmospheric temperature to several degrees, apart from earth orbital change, is attributed to shift in the structural property of global vegetation pattern, which predominantly happened due to initiation of biophysical feedbacks (Foley *et al.* 1994). Another study also emphasized the importance of biophysical feedbacks in shaping up the climate pattern in past. According to this study, global cooling of about 0.25 K between 1000 to 1900 centuries mainly happened due to the transformation of natural forest area to cropland over Northern Hemisphere, which in turn increased the surface albedo of the area. This change in surface albedo and other associated factors initiated the biophysical feedback, which thereby reduced the overall temperature of Northern Hemisphere (Govindasamy *et al.* 2001).

It has also been hypothesized that rapid change in land use and land cover change with associated increase in average global surface temperature as a result of anthropogenic green house gas emissions especially due to CO_2 enrichment may alter the vegetation structure and composition at large spatial scale. This shift may again give rise to some potentially important vegetation-climate feedbacks that influence the future climate globally, regionally and locally (Schaeffer *et al.* 2006; Muller *et al.* 2007 and Strengers 2010).

Earlier, many traditional vegetation-climate models did not take into account the interaction between land and atmosphere in order to predict the future climate state (Box 1981; Henderson-Sellers 1993; Foley *et al.* 1998 and Peng 2000). However, the results from subsequent studies bring forth the importance of including vegetation dynamic to realistically predict the future climate by present climate models. These models help in studying the climate relevant feedbacks, which get initiated due to the modification in vegetation pattern, and also help in examining the long-term affect of vegetation changes on climate system. Studies also pointed out that it is imperative to include biophysical feedbacks at regional level in recent climate models for better representation of regional climate behaviour. (Charney *et al.* 1975; Foley *et al.*1994; Shukla *et al.* 1990; Betts 2000 and Foley *et al.* 2003). Unlike carbon cycle feedbacks that have a global significance because CO_2 is well mixed in the atmosphere, biophysical vegetation feedbacks have a regional to local importance that can lead to influence global climate pattern (Wramneby 2010). Therefore, this issue needs to be dealt with the regional climatic models that include climate relevant feedback mechanisms generated from vegetation change. Recently, Wramneby 2010, attempted to simulate the future climate state over Europe by including vegetation-climate feedbacks into the regional model structure (RCA GUESS). The study highlighted that there would be an additional amplification and dampening of CO_2 induced warming over different locations of Europe, which thereby make a substantial difference in average regional temperature, if vegetation dynamic will be included in the model calculation.

It is projected that Indian Climate would experience drastic change in future (Kumar *et al.* 2006) but the predictions haven't taken into account the influence of vegetation dynamics on Indian Climate. Therefore, a study is required which determine the affect of vegetation on Indian Climate together with its feedbacks. However, before assessing the vegetation influence on climate and applying the regional earth system model (RCA GUESS) to a large domain such as India, it is important to validate that model against observation datasets. Thus, this study will first assess the performance of RCA and RCA GUESS for present climate from the period 1989-2005. Later, the study will examine the affect of vegetation feedbacks, more precisely biophysical feedbacks, over India for similar period. At end of the report, the future climate predictions will be made using RCA under IPCC's future greenhouse gas scenario (SRES-A_1B) and the influence of vegetation on future climate will be speculated.

2.0 Objectives

The main objectives of the study are:

- Evaluation of RCA and RCA GUESS against observation datasets
- Quantification of biophysical feedbacks from the period 1989-2005
- Future climate predictions of India using RCA

3.0 Literature Review

3.1 Vegetation and Climate feedback

There are a number of vegetation-climate feedbacks that originate from structural changes in vegetation pattern, which consequently, amplify or dampen the initial perturbations and influence the future climate state. However, focus of this study is to highlight important biophysical feedbacks that are not fully captured by the present global earth system models but they are important in determining the regional climate behaviour.

In order to understand vegetation and climate feedbacks in context of climate change, it is important to understand the concepts of radiation balance and available surface energy with respect to the earth system. Therefore, this section first describes radiation balance and available surface energy. Later, it presents the detailed discussion on individual biophysical feedbacks and the processes involved in them. However, in reality, there are both synergetic and opposing feedbacks exist in the system and it is the interaction of these feedback loops that determine the overall contribution of vegetation feedbacks to climate and vice versa.

3.1.1 Energy Balance

The main source of energy available to the terrestrial ecosystem comes from the Sun in a form of short wave (SW) radiation. Out of which, some proportion of SW radiation gets reflected as a result of surface property of land surface area which is termed as albedo (**α**) of the earth surface. The energy left after the surface reflection gets absorbed by terrestrial ecosystem which later its balances out by emitting long wave radiation back into the atmosphere. The emission of outgoing longwave radiation (R_{out}) mainly depends upon the emissivity of the surface and surface temperature. The total available surface energy partitioned in the form of sensible heat (H) and latent heat (E_{λ}) fluxes. Sensible heat is the total amount of heat absorbed by air near to the earth surface, which determines the temperature of lower atmospheric region. Sensible heat can be measured with the help of thermometer. On the other hand, latent heat is a hidden form of energy in the water molecule, which is gained during the phase change of water molecule to the vapour stage. Latent heat warms the upper atmosphere some distance above the vegetation cover by releasing absorbed energy. This energy plays a crucial role in cloud formation, upward air movement and also in other climatic processes. These energy fluxes determine the flow and movement of available surface energy from any landscape that in turn influence the surface temperature and precipitation of any region (Lashof 1997 and Campbell 1998).

The balance of incoming and outgoing shortwave and longwave radiation and the partitioning of available energy are dependent on surface property of the area and it is highly influenced by dynamic changes in vegetation structure and composition of that area. Therefore, understanding of above variables together with dynamic changes in vegetation structure becomes immensely important to study the biophysical feedbacks of the Earth system.

3.1.2 Vegetation-albedo feedbacks

Albedo is the fraction of incoming SW radiation that is reflected from the surface and the atmosphere. Differences in the surface albedo depend upon the spread of ice sheets, cloud cover and atmospheric particles. It is also influenced by the structure and properties of vegetation cover such as its colour, density, canopy height and Leaf Area Index (LAI) (Lashof 1997). As far as vegetative albedo is concerned, open land such as deforested land or agricultural fields usually have high albedo while darker vegetative surface such as areas with extensive forest cover are characterized by lower albedo. The albedo of any area determines the total net radiation available to the surface and also decides its emissivity. For example, darker surfaces, such as tropical forests, capture substantial amount of SW radiation falling upon it as a result of which, those regions capture additional energy at the surface to derive latent and sensible heat fluxes that in turn determine the overall surface temperature and precipitation of that region. On the other hand, if the surface is open due to devoid of vegetation or masked with snow, the albedo of the area increases and most of the energy return back to the atmosphere making that region cooler (Myhre and Myhre 2003). Therefore, large scale changes in vegetation cover alters the surface property of land surface area and trigger some important feedbacks as a result of change in the surface albedo which thereby modify the surface energy balance and that can lead to shift in the climate state of that area.

In the Mid Holocene about 6000 years ago, insolation from the Sun was increased because of the variation in the Earth's orbit. This orbital change altered the climate pattern and modified the ecosystem structure and composition extensively. The boreal forest invaded in modern tree line and modified the leaf surface area that in turn changed the overall albedo of northern latitudes. This resulted in approximately 4^{o}C increase in spring temperature and 1^{o}C rise in other seasons (Bonan *et al*. 1992 and Foley *et al.* 1994). Similarly, the vegetation-albedo feedback played a significant role in shaping up the climate pattern of Saharan region during Mid Holocene. The transformation of wet and fertile Saharan region, which was a response to an enhanced monsoon circulation as a result of increased solar insolation, to an arid land can only be explained after considering the vegetation albedo feedback (Claussen *et al.* 1999). Moreover, some 115,000 years ago during interglacial to glacial shift as a result of earth's orbital change and also due to lowering of CO_2 amount as compared to present level led to the expansion of glaciation (tundra expansion). The extent of the glaciation can only be explained after considering the affect of high latitude land surface albedo in the model simulation by Gallimore 1996.

Some recent studies pointed out that the surface albedo of many landscapes are going to change drastically as a result of global warming and also due to changes in other linked parameters such as rainfall pattern, evaporation rate and sea level rise. In addition to that, the present rate of large-scale deforestation over tropical countries also contributes in modifying land use patterns, which consequently makes a significant difference in the surface albedo (Foley *et al*. 1994 and 2003). The study by Bonan *et al.* 1992 showed that the future warming may significantly reduce the surface albedo of polar areas over the northern latitude due to the invasion of boreal vegetation. This situation disturbs the energy distribution pattern of snow covered tundra region. The land in response captures more incoming solar radiation making the surface air temperature higher. In the tropical regions, the effect of surface albedo feedback on surface temperature is not certain. The large scale deforestation in tropical countries will certainly reduce the surface albedo but some modelling studies presented that their surface temperature will keep on rising due to other offsetting factors generated from evapotranspiration reduction that is discussed later in the report (Henderson-Sellers 1993 and Nobre 1991).

3.1.3 Hydrological cycle feedbacks

In this section, the feedbacks associated with change in evapotranspiration that is influenced by soil water content, Leaf Area Index (LAI) and modification in the roughness length of the area will be discussed.

Dense vegetation has higher LAI and rooting depth as compare to open areas or grasslands and it can also access more water from the ground in comparison to grasses (Strengers 2010). Therefore, areas with more vegetative cover are associated with high latent cooling and lower sensible heat flux under no water stress conditions. In contrast, the rate of evapotranspiration is quite low in open areas, which are devoid of vegetation such as grassland. These areas tend to have higher surface temperature as a result of a lower latent heat flux and consequently a higher Bowen ratio[1].

Regions with high radiative transfer[2], where surface moisture availability is also not limited, the rate of evapotranspiration from the dense vegetation area increases manifold that in turn decreases sensible heat fluxes of the area and limits the increase in surface temperature. This high evapotranspiration rate also offsets the warming induced by lowering of albedo due to dense vegetation. Furthermore, associated increase in evapotranspiration leads to more cloud formation over the region, blocking the incoming solar radiation to reach the ground. More cloud cover also makes the area cooler as a result of increase in rainfall events. On the other hand, places experiencing high radiative transfer but having low surface moisture lead to an extension of dry spell associated with high surface temperature as a result of decrease in evapotranspiration and thereby decrease in precipitation (Lashof *et al.* 1997 and Betts *et al.* 2000).

Doubling of CO_2 affects the physiological response of trees by reducing the stomatal conductance which in turn decreases the evapotranspiration rate that further rise the global surface temperature but other factors such as moisture availability and carbon fertilization regulate this warming in diverse ways (Drake *et al.* 1997). According to Betts *et al.* 2000, a decline in the evapotranspiration rate as a result of reduction in stomatal conductance contributes in amplification of global surface temperature. On the other hand, high latent heat fluxes owing to higher Leaf Area Index as a result of high CO_2 level in the atmosphere leads to an increase in the precipitation rate that in turn offsets the warming induced from physiological changes. The overall combined physiological and structural changes may lead to an increase in the latent cooling but it is important to consider that actual impact of vegetation structural change lags several years or decades behind to CO_2 induced physiological response.

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[1] Bowen ratio is the ratio of energy fluxes of sensible and latent heat that tells about the amount of heat lost or gained by any system.

[2] A Physical phenomena depicting energy transfer in form of electromagnetic radiation is known as Radiative transfer.

Compared to open areas, vegetative areas are rougher which make the atmosphere more turbulent. This turbulent atmosphere has a considerable effect on surface temperature and precipitation. The vegetative roughness length first accelerates the turbulent mixing and decreases aerodynamic resistance in the Planetary Boundary Layer which thereby modifies the wind speed and vertical air movement. The increase in turbulent mixing and vertical movement of the air then increases the evaporation, making that region, cooler and wetter. But the influence of this feedback on the climate as compared to other biophysical feedbacks is not substantial (Bonan 2008).

Hydrological feedbacks play an important role in determining the surface temperature of (sub) tropical regions. The most studied Amazon basin, where around 50% of the rainfall originates from forest's own evapo-transpiration, is most likely affected by hydrological feedbacks (Lashof 1997). According to Henderson-Sellers 1996, doubling of CO_2 will increase the stomatal resistance that in turn reduces the evapotranspiration of the area up to half of its present rate and the area experience 4^oC rise in the surface temperature and -120 W/m^2 fall in latent heat flux (Pollard and Thompson 1995). It is also predicted that precipitation over the Amazon basin will further get reduced once the forest-clearing threshold is reached. This again promotes water stress condition that in turn reduces the overall evapotranspiration leading to a dry spell. However, observations and satellite studies confirmed that during the dry spell of 2005, Amazonian forests were able to maintain high evapotranspiration rate but this phenomenon is represented quite weak in many models (Rocha 2004 and Saleska *et al.* 2007). Therefore, it can be seen that a complex relation exists between atmosphere and terrestrial ecosystem which needs to be studied more carefully.

3.2 Carbon cycle feedback

For centuries, carbon cycle feedbacks both from terrestrial and ocean ecosystems have been playing a crucial role in shaping the earth's climate system. For shorter timescales relevant to human activities, feedbacks related to carbon cycle are governed by atmospheric carbon exchange between land and ocean ecosystems. It is believed that the amount of CO_2 emitted during last several decades has not only been taken up by the atmosphere alone, a sizeable quantity is equally partitioned between terrestrial and marine ecosystems. The land and ocean ecosystems are playing critical role in limiting climate change by controlling CO_2 in the atmosphere and acting as major sinks but some recent studies indicated that their capacity to sequester carbon is limited. The present rate of carbon emission by anthropogenic activities will soon affect the efficiency of both ecosystems but uncertainty in many ecological processes pose a serious challenge to accurately predict their tipping point (IPCC 2007 and Archer 2007).

At present, terrestrial ecosystem is sequestering one fourth of emitted carbon but general consensus among scientists is that, in future, it may start losing considerable amount of CO_2 as a result of warm climate and eventually become a carbon source. However, some studies pointed out that in carbon rich environment, terrestrial vegetation experiences a positive fertilizing effect that accelerates the rate of photosynthesis (mostly in C_3 plants), which in turn lead to more CO_2 being fixed on the land (Norby *et al.* 1999). This increase in CO_2 uptake accelerates the plant productivity resulting in greener surroundings, which eventually offset the CO_2

induced warming (Nowak 2004). CO_2 fertilization certainly has some positive effect on the earth's climate but at the same time, the response of this effect would not be similar on all plant function types and forests age classes. On the other hand, some studies pointed out that under warm and water limited conditions, plants close their stomata to conserve water which may hinder CO_2 uptake which significantly reduce the latent heat flux making the climate of those regions, hot and dry. Some model studies predicted that at certain threshold level, the photosynthesis rate would be strengthened due to carbon enrichment but soon it saturate, however, plant respiration rate keep on accelerating, making the terrestrial ecosystem, a carbon source (Woodward *et al.* 1995). Soil is also considered as one of the largest natural terrestrial carbon sink equivalent to atmosphere and all terrestrial vegetation in combination (Archer 2007). It is predicted that not only the biomass, which is accumulated over the centuries, decomposes quickly, releasing substantial amount of CO_2 in environment due to the increase in temperature but large stocks of methane will also be escaped into the atmosphere. This large amount of methane emissions amplifies the global average temperature very sharply (Chapin *et al.* 2008). Therefore, it can be said that in carbon rich environment, plant productivity increases that limit the global warming to a certain extent, however, after a point of time plant photosynthesis stops accelerating and finally it gets saturated. On the other hand, increase in plant and soil respiration together with methane emission from the soils reduces the capacity of land to sequester carbon and accelerate global warming. The other factors such as droughts and fire events due to increase in the global temperature might also contribute in reducing the land carbon stocks.

3.3 Earth System Modeling

Earth encompasses mainly atmosphere, cryosphere, pedosphere, hydrosphere, lithosphere and biosphere and it is the interaction between these subsystems that determines the habitable environment on terrestrial ecosystem. There are several simple to quite complex processes and mechanisms involved in the functioning of these subsystems. Numerical equations are generally used to represent the physical processes and mechanisms in model structure. These models have been improved over the years from simple to complex as details and understanding of many processes and mechanisms become stronger. However, to understand the dynamics of complete Earth system, mere complete knowledge of these subsystems, treated in isolation from each other is not sufficient. Therefore, there was an increasing need to build a robust model structure, accounting for major interactions between the subsystems of the Earth. This idea leads to a frequent use of global Earth System Models, a coupling between General Circulation Models (GCM) and Dynamic Global Vegetation Models (DGVMs) and other model components (Hill *et al.* 2004, McGuffie 2005 and Randall *et al.* 2007).

GCMs simulate the behavior of the earth's atmosphere in a detailed manner. The principles behind building these models are numerical equations of fluid dynamics and thermodynamic but later many other components were included in it. GCMs represent the earth's climate system by using a three dimensional grid with a horizontal resolution of 300-500 km and vertical resolution of 10-20 vertical layers in the atmosphere reaching up to 30 layers including ocean, which is further improved by different scientific groups. As of now, many GCMs are built with their unique numerical representations of the earth climate system but the outcomes from all of these model predictions have been indicating a startling shift in future global climate state (Stute 2001).

The horizontal resolution of GCMs is quite course and that simplifies many processes and mechanisms relevant at local to regional scale. Downscaling of GCMs yields detailed picture of that particular region. Therefore, regional climate models (RCMs) have been built to take into account those processes and mechanisms, which are relevant to small regions and are not fully captured by global circulation models. Regional climate models improved the horizontal resolution to 10-50 km representing the regional climate pattern more precisely and accurately and give meaningful predictions of future climate. The boundary conditions of regional climate models come from global climate models. However, the drawback of GCMs and RCMs is the fact that the vegetation is represented static rather than dynamic with the changing climate. Fairly recently, a growing number of studies have emphasized the importance of vegetation-climate feedbacks (Betts 2000 and Foley *et al.* 2003). However, the majority of these studies have been conducted with global GCMs coupled to global DGVMs, neglecting the regional effects of biophysical vegetation-climate feedbacks.

Static and dynamic biogeographical modelling are two general approaches to look into the potential impact of changing climate on global vegetation pattern (Prentice and Solomon, 1990). Various traditional ecosystem models used the first approach to capture the ecosystem functions or structural responses due to climate change but fail to focus on transient changes in the vegetation structure and composition, seasonality, carbon fertilization, competition based extinction and biogeochemical response. DGVMs have been constructed not only to capture large-scale responses of climate on terrestrial ecosystem but also to simulate the dynamic shift of vegetation with respect to climate that in turn modify biogeochemical and hydrological cycles. These DGVMs represent biospheric vegetation as a composition of plant functional types (PFTs) based on its physiognomic and morphological traits. The groups of vegetation having similar functional attributes, such as their carbon metabolism, gas exchange and water relations, are included under same PFTs (Box 1996). The DGVMs can comprise any number of PFTs to represent the global vegetation but are often limited to fewer categories. The significant processes such as competition based extinction, establishment, growth, mortality, carbon fluxes and nutrient cycling are embedded in the model structure, which modifies the structural properties of the vegetation. These key processes are taken from earlier vegetation models such as plant growth from biogeochemistry model and plant succession processes from gap (patch) models. DGVMs also include disturbance regimes, which are mainly limited to wildfires but can be extended to pest damage, ozone damage, human intervention to land properties etc. There are several limitations associated with dynamic vegetation models such as it is unrealistic to simulate the vegetation beyond the local scale because it requires a large number of points to be simulated. These models also require detailed information of species characterization which is quite hard to acquire for some areas. Most DGVMs have adopted a large area parameterization approach rather than a cohort (individual patch)-based approximation, however, later gives more realistic results of PFTs dynamic (Peng 2000 and Smith *et al.* 2001).

In order to understand the bidirectional relationship between terrestrial ecosystems and the Earth’s climate at global scale, a number of experiments with coupled GCMs and DGVMs have been conducted. However, to identify and assess the impacts of vegetation change on regional and local climate pattern and to understand the biophysical feedbacks at regional scale, integration of RCMs and DGVMs is required. As of now, these kinds of studies have been attempted by few researchers and more in depth research is required.

3.4 Future Climate scenarios and vegetation climate feedbacks over India

According to India's Initial National Communication to Climate Change (NATCOM I), it is predicted that there will be an abrupt shift in bioclimatic conditions over different locations across India during the period 2071-2100, some places going to be wet while other become dry, for instance, northeastern region will experience more rainfall whereas northwestern region experience dry climate conditions due to decrease in number of rainfall events. But, overall average rainfall is going to increase over India (except for some places such as Punjab, Rajasthan and Tamil Nadu) together with an associated increase in the mean surface temperature. Around 2.9^{o}C and 220 mm rainfall is predicted under SRES-B_2 scenario, while as per SRES-A_2 scenario, which depicts more extreme conditions, the increase of average temperature and precipitation is predicted around 4.2^{o}C and 300 mm respectively. It is also highlighted in the study that the number of rainy days may decrease but the intensity of the rainfall will increase, which in turn give rise to more extreme events. These climate change scenarios and projections are the results from Providing Regional Climate Impact Studies (PRECIS), an RCM developed by Hadley Centre which was applied over India using two IPCC emission scenarios i.e. SRES-A_2 and SRES-B_2 (Kumar *et al.* 2006). However, these climate change predictions for India did not include the impact of vegetation climate feedbacks that may influence the regional climate in positive as well as negative way across the country.

The latest forest report of 2009 by Forest Survey of India estimates that the forests cover of India has increased by 0.18 million hectare during the period 2005-07, which is a marginal increase of 0.23%. As of now, around 23.84% geographical land area has come under the forest cover. In the last 10 years (1997-2007), an increase of 3.13 million hectares of forest cover was recorded that shows an average increase of 0.47% per year (FSI 2009). However, abrupt changes in bioclimatic conditions may certainly influence the growth and composition of forest ecosystems in many locations. For instance, northeastern region transform in the wet forest types while northwestern become dry forest type during 2071-2100 (Ravindranath *et al.* 2006). These large changes in forest structure and composition will certainly modify the physical properties of the land surface area that in turn triggers some important vegetation-climate feedbacks. It has been reported that the evapotranspiration feedback will be more pronounced than the surface albedo feedback in the tropics (Lashof 1997) and it is more likely that the overall climate condition over India may be influenced by this feedback loop *(refer figure – 1).*

A study carried out by Chaturvedi *et al.* 2010 found that states, which are dominated by extensive forest area, will be expected to experience major change in forest composition and pattern. The study used IBIS dynamic global vegetation model and climate projections were taken from the Regional Climate Model of the Hadley Centre (HadRM3) for A_2 and B_2 scenarios. The main findings of the study indicated a 39 % change in vegetation pattern under A_2 scenario while 32 % transformation is recorded in B_2 scenario at the end of this century. The NPP was found to increase by

68.8% under A_2 while 51.2% in the B_2 scenario. The soil organic carbon will be changed by 37.5% and 30.2% for A_2 and B_2 scenario respectively. The result also predicted that the north eastern forests are better to cope with the projected change in comparison to forests of upper Himalayan regions, northern and central parts of the Western Ghats and some parts of central India. In the future, major shifts are predicted to occur in these forest regions.

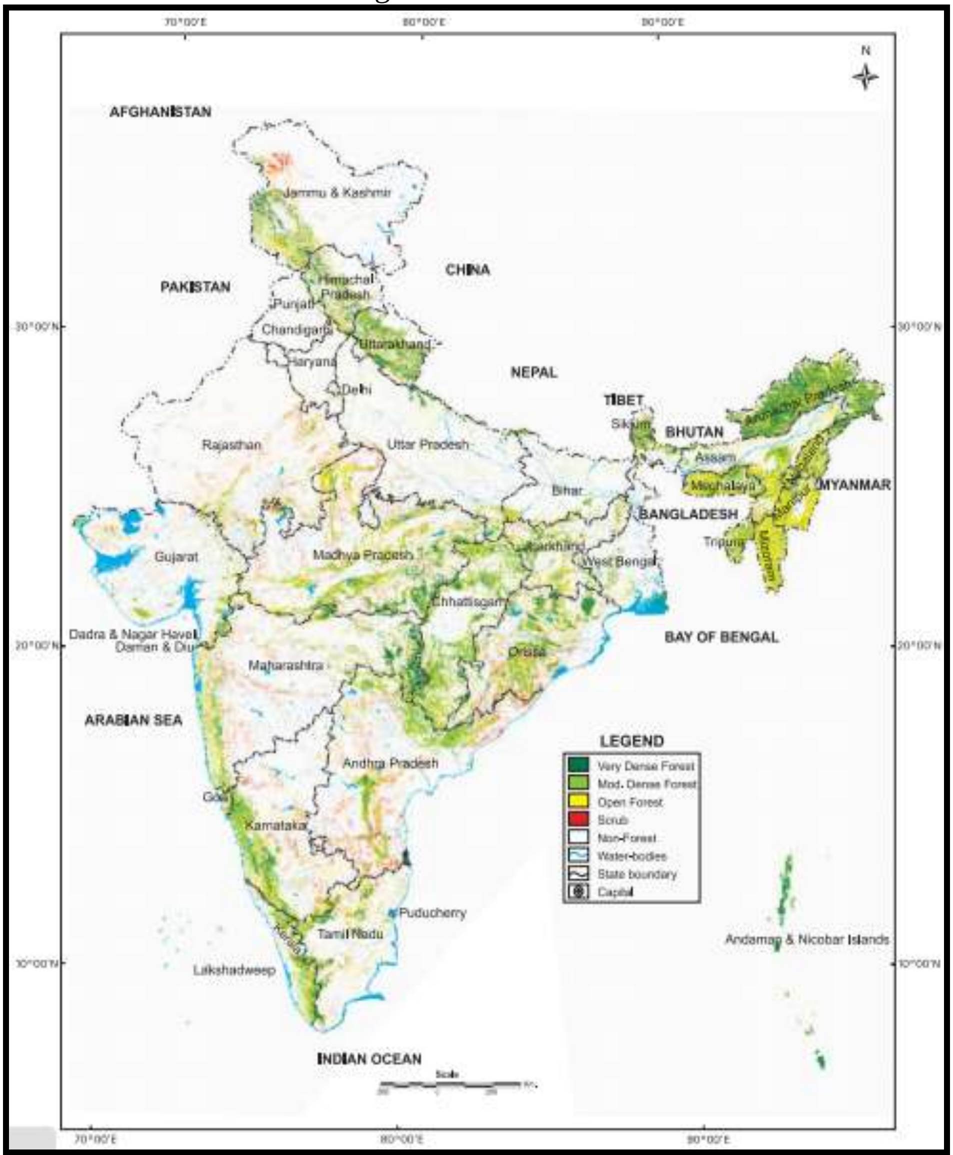

Figure 1: Forest Cover of India (2007)[3]

The study by Sellers *et al.* 1996 and Betts *et al.* 1997 shows that under a carbon rich environment, LAI of the forest will increase and thereby amplify the evapotranspiration rate and initiate the negative feedback of vegetation in India. Another study by Bhattacharya *et al.* 2009, discusses the long-term albedo change of different land use types and albedo rainfall feedback relation using satellite data over India. The study showed that there was a decreasing trend in the mean surface albedo over the India for a period of seventeen years (1982-2000).

[3] *FSI,2009*

The main reasons for the decrease in surface albedo were an increase in the wetness conditions due to a rapid increase in irrigated area that brought under the canal command as the accessibility to water for farming purpose has been improved and also because of the technological advancement in field water conservation that in turn making the land surface greener. The other reasons could be that the land surface area experiencing natural vegetation growth because of better forest management practices and programs. It is also pointed out that due to the recent warming episodes, the snow is melting before the actual time which further making the land cover wet and thereby increasing the albedo of the area. All these reasons contributed in lowering of the surface albedo over the Indian landmass, which eventually might have influenced the climatic conditions. Therefore, it is evident from the above discussion that vegetation plays a significant role in deciding future climate state over the country and it needs to be studied with the help of regional earth system models.

4.0 Methodology

4.1 Study Area

India is situated in the southernmost region in Asia covering 3,287,263 square kilometers[4]. India is a tropical country but due to its significant topographical variations, other climate conditions also exist. According to the Köppen classification which is based on average monthly values of temperature and precipitation, India mainly comprises six climate types i.e. alpine and tundra conditions in north, deserts in west, semi arid conditions in western and southern areas, tropical wet condition in south western part, tropical humid from the middle of northern part to north eastern part and tropical wet and dry in southeastern part (*figure 2*).

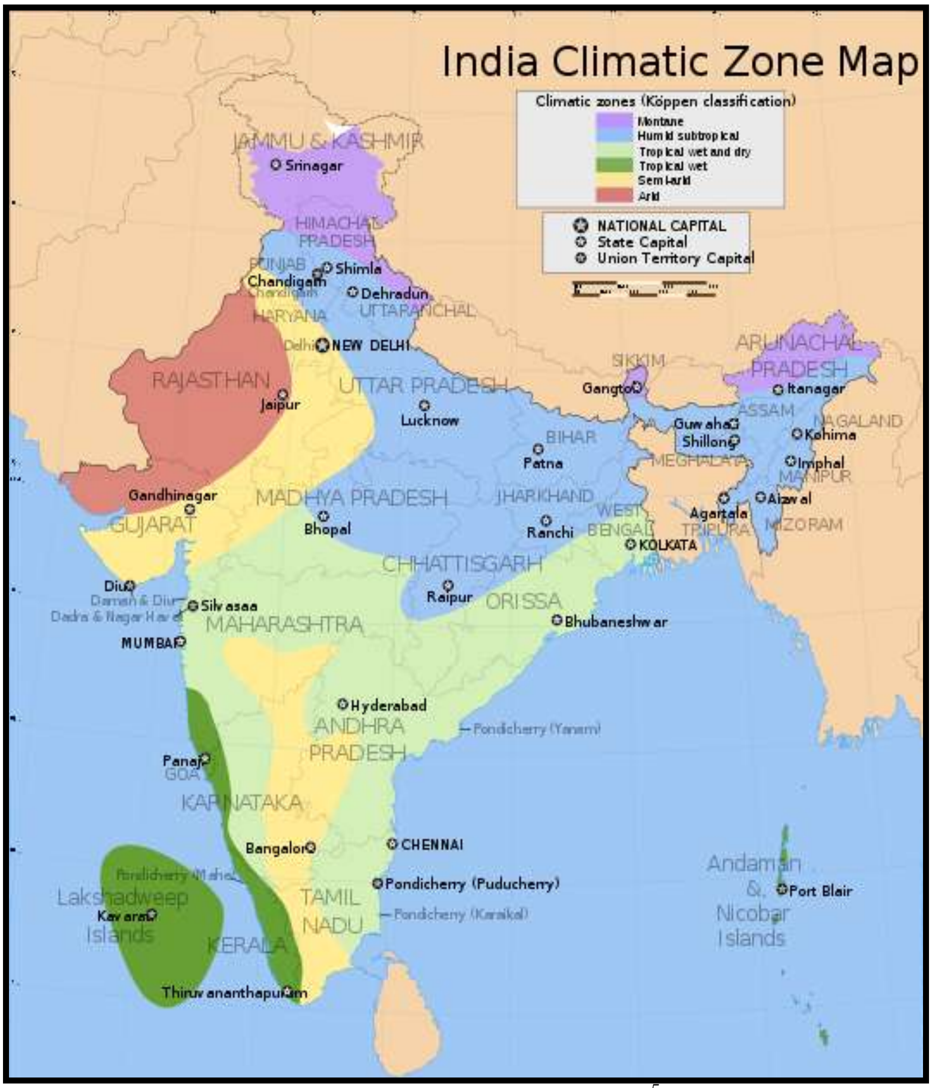

Figure: 2 India Climate Zone Map[5]

The nation experiences four seasons i.e. winter, summer, monsoon and post monsoon season. Because of varied topography and soil and climate conditions, India experience diverse vegetation pattern ranging from tropical forests to sub tropical

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[4] http://en.wikipedia.org/wiki/Geography_of_India
[5] http://it.wikipedia.org/wiki/File:India_climatic_zone_map_en.svg

forests to alpine forests. This large-scale physiographic and climatic variation also makes some regions rich in biodiversity while some areas become devoid of vegetation. The country is divided into 16 major forests types, which further grouped into 5 major classes i.e. moist tropical forest, dry tropical forests, mountane subtropical forests, temperate and alpine forests (Champion and Seth 1968) (figure 3).

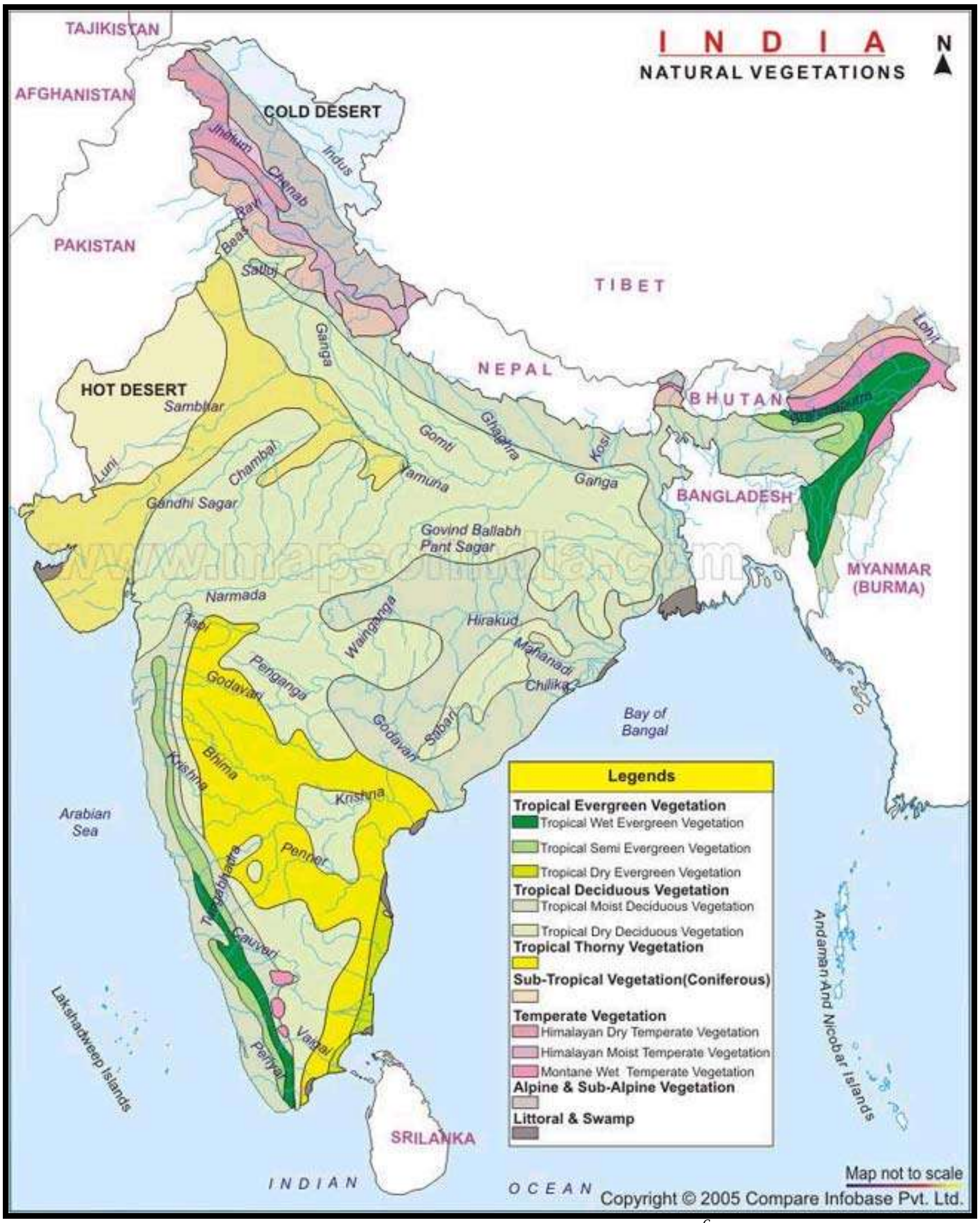

Figure 3: Natural Vegetation Map of India[6]

4.2 Model Description

For the purpose of this study, RCA GUESS, a coupled regional earth system model was used to simulate present climate scenarios over India. RCA GUESS is the

[6] http://mapsofindia.com/maps/india/natural-vegetations-india.html

combination of a regional climate model (RCA) and a dynamic vegetation model (LPJ-GUESS).

4.2.1 Rossby Center Regional Atmospheric Model (RCA)

RCA is a regional climate model that comprises a detailed description of short-term interactions between atmosphere and land, which usually gets averaged out in GCM because of the coarse horizontal resolution (Kjellstrom et al. 2005). RCA has taken most of the properties from High Resolution Limited Area Model (HIRLAM), a numerical weather prediction (NWP) model. As of now, three versions of Rossby Center Regional Atmospheric Model are released i.e. RCA1, RCA2 and RCA3. The present RCA is an improved version of regional atmospheric model, which is built upon the earlier versions of RCA series (Bringfelt *et al.* 2001 and Jones *et al.* 2004). In the new versions, there is an improvement in surface exchange processes between land and atmosphere. Also, changes are made in land surface, radiation, turbulence, cloud, precipitation, and condensation parameterizations to realistically represent the climate system. The spatial resolution of model can be as fine as 11 km and the vertical resolution reaches to 40 levels with 20-minutes time resolution. The Land Surface Scheme (LSS), also known as tiled scheme, in the RCA model handles the atmosphere and land surface exchange processes. This scheme helps in understanding the regional climate behavior as a result of modification in vegetation. The description of parameters such as LAI and albedo of different vegetation types are quite different in stand-alone version (i.e. without coupling) compared to coupled-version of the model (which is discussed later in the report). In stand-alone version, LAI and albedo of different vegetation types are represented as constant, scaled or parameterized variables while in the coupled model these processes are dynamically modeled (Samulesson *et al.* 2011).

In LSS, the land surface area is represented as grid cells which is further divided into three distinct tiles with respect to temperature and other variables i.e. forest, open land and snow. Each tile is connected to the lowest atmosphere level through its own aerodynamic resistance assuming equilibrium in local surface layer. Each tile and its sub-surfaces are distinct from each other by their own unique values of surface properties and energy balance that also makes them behave differently. The forest tile is divided into three sub tiles or sub surfaces i.e. forest canopy, forest floor soil and snow on forest floor. These sub tiles are closely linked to each other through their canopy temperature and humidity. Within the forest tile, needleleaved and broadleaved fractions are differentiated in separate groups. The albedo of open land and sub tiles of forest decide the net radiation availability for each tile. However, the partitioning of the net radiation is dependent on LAI because it modifies the aerodynamic resistance and surface air resistance to evapotranspiration that in turn affect the ratio of sensible heat and latent heat of all vegetated sub surfaces. LAI also plays an important role in total water storage and interception. The detailed description and functioning of the processes within RCA (without coupling) can be found in Samuelsson *et al.* 2011.

4.2.2 LPJ-GUESS

LPJ-GUESS is a dynamic vegetation model, which simulates vegetation structure and composition in response to a changing climate at local to global scale (Sitch *et al.*

2003; Smith *et al.* 2001 and Hickler *et al.* 2004). It is a process based model of vegetation dynamics and it also incorporates the physiological changes and biogeochemistry of terrestrial ecosystems. These key formulations are inherited from earlier vegetation models, for instance, plant growth comes from biogeochemistry models and plant succession was taken from GAP (patch) models. The atmospheric CO_2 concentration, climate parameters such as average daily or monthly temperature, precipitation; SW radiation or percentage of sunshine hours, latitude and information on soil code are required as an input data to the model. These input data together with the defined processes modifies Net Primary Production (NPP), soil water availability, carbon content in the litter and the soil, vegetation composition and structure. However, the processes in the model can also be modified by current state variables and input data. The transient vegetation composition at different spatial scale and their associated biogeochemical fluxes of water and CO_2 come as an output from the model. The model works at one day to yearly time intervals. On the daily time step, processes such as photosynthesis, respiration, stomatal regulation, water and CO_2 fluxes to atmosphere are implemented while at the annual interval processes such as NPP, carbon content in litter and soil, vegetation dynamics (establishment and mortality) are modeled (Smith *et al.* 2001). The biospheric vegetation is characterized as a composition of plant functional types (PFTs) based on their physiognomic and morphological traits. PFTs are divided in two groups, the woody group and herbaceous group. The woody PFTs are further divided into eight sub groups (of two tropical, three temperate and three boreal) whereas herbaceous PFTs split up into two sub groups (C3 and C4 grasses). The woody PFTs are represented by its crown mass and tissue pools, leaf mass, sapwood, heartwood, and fine root mass while the herbaceous PFTs are characterized by its leaf and fine root mass. The number of PFTs in the model is dependent on the knowledge of vegetation type of the study area and researcher discretion but in most cases, they are limited to 10, which mostly represent all vegetation types of the earth. Since PFTs are an important element in the model structure, they have been given different parameterization based on its physiological processes, for instance, on photosynthetic pathway, leaf thickness, allocation, phenology, stomatal conductance and rooting depth (Cramer *et al.* 2001 and Sitch *et al.* 2003).

Several significant processes and mechanisms that simulate the vegetation structure and composition are present under number of modules and sub modules in the model that operates on different time scales. Establishment and mortality processes determine the addition of tree species and their removal from the stand level. Competition based on light, water and other important resources between the plant species are also present as a significant process in the model that decides the extinction of certain species of plant at the cost of other. The carbon and water fluxes and nutrient cycling controls plant growth and establishment. The model also has a disturbance sub-module, which mainly is limited to wildfires but can be extended to pest damage, ozone damage, human intervention to land properties etc. The model runs on two modes namely Population and Cohort mode. These two modes differ on the basis of the level of detail by which vegetation dynamics and structure is stimulated. In population mode, which is based on LPJ-DGVM, vegetation is averaged out over a larger area making several state variables calculated in simpler and faster manner. Population mode simplifies several processes and ignores many processes that are relevant to smaller scales. On the other hand, in cohort mode in which calculation is done at stand level scale, the information about vegetation demography, heterogeneity within patch, size and structure of PFT_S, succession stages, and vertical stand structure does not get simplified and this mode gives more detailed information of average individual. Information about more processes and model structure can be found in Smith *et al.* 2001.

4.2.3 RCA GUESS

To study the affect of vegetation dynamics on climate and modification in climate on vegetation pattern as well as impacts of their feedback processes on each other requires a complete and robust regional Earth System model. RCA GUESS is one of the comprehensive regional Earth System models of present generation, which uses an interactive coupling between LPJ-GUESS and the Land Surface Scheme of RCA. In this study, RCA GUESS operates on a spatial resolution of 50 x 50 km with a 20-minute time interval that provides detailed and precise information of underlying vegetation mechanisms due to climate change as compared to global earth system models. The model comprises two sub models i.e. a vegetation submodel based on LPJ-GUESS and the physical submodel RCA. The vegetation submodel simulates vegetation dynamics and leaf phenology while the physical submodel simulates regional climate conditions. The physical submodel gives air temperature, soil temperature, soil water and shortwave net radiation as an input to the vegetation sub model, which in turn utilizes these data and returns daily average LAI back to the physical submodel. The information provided by the vegetation submodel on LAI and vegetation fraction affects the surface albedo of each grid area. This further affects the surface energy partitioning and thereby climate conditions. The vegetation in the model is represented as PFTs but since limitation in identifying tropical PFTs, global PFTs (Annexure III) have been used in this study. The vegetation is grouped into three classes based on their LAI and albedo (fraction of forest cover). The classes present in RCA GUESS are Open land (includes herbaceous vegetation and crops) and Forest with broadleavead and needleleavead fractions. These three classes also comprise the information on bare ground and snow cover (Smith *et al.* 2010).

The vegetation submodel of RCA GUESS model simulates the vegetation in three stages namely spin up phase, historical phase and simulation phase. In the spin up phase, the model needs to reach to an equilibrium condition starting from the bare ground. The vegetation, soil and litter carbon stocks get accumulated over the years and reach to the equilibrium with climate. The model also simulates the carbon feedback processes but since CO_2 gets well mixed into the earth's atmosphere, these feedbacks don't pose much impact on regional climate conditions. Once the equilibrium is achieved, the model utilizes observed datasets of the climate parameters and CO_2 to initialize the historical phase and then simulation phase can be carried out (Smith *et al.* 2010 and Wramneby *et al.* 2010).

4.3 Experiment & Analysis

The objectives of this study are to validate RCA and RCA GUESS simulations against observation datasets and also to identify the role of vegetation on regional climate pattern of India. To achieve these objectives, two separate simulations were carried out for 15 years period from 1989 to 2005. Smaller experiments are performed covering only 15 years due to limited time scope of the study. The limitation lies in the fact that vegetation changes normally operate on longer time scales. Covering these longer time scales would, however, require a number of long and technically demanding computer simulations. The domain of the model was set up over India on a rotated grid system with a spatial resolution of 50 x 50 km. The domain selected in the present study is large enough to generate and quantify the regional pattern that influences Indian Climate. In the first simulation, RCA was not coupled with LPJ-GUESS while the other simulation was performed by combining both the models. The boundary conditions were taken from ERA-interim[7], the reanalysis data set for the both simulations. ERA-interim is a reanalysis dataset that gives the information on the state of the atmosphere, ocean and land conditions from 1989. The dataset contains data on several parameters such as temperature, precipitation, evapotranspiration over water and soil, global radiation, snow depth, water balance, wind speed and water vapour. The data set is also used to validate the simulation results of the model. The other dataset, which is used to validate the results, is CRU high-resolution climate data set complied by the Climatic Research Unit together with Hadley Center. This data set provides values of monthly temperature, precipitation, fraction of cloud cover for the nearest 0.5 degree grid cell (New *et al.* 1999). In addition to the above experiments, a longer simulation from 1960 to 2050 with RCA was performed. The boundary conditions were taken from ECHAM5, the fifth-generation atmospheric general circulation model, under SRES-A1B greenhouse gas (GHG) emission scenario. In this experiment, the future simulated climate (2030-2049) will be analyzed keeping in mind how modification in vegetation pattern influenced the present climate pattern over India. This study gives an insight into the role of vegetation in influencing regional climate pattern and also provides useful description on validation of RCA and RCA GUESS. Neither of them has been applied over India before at regional resolutions in standalone or combined setup, therefore, this study gives important future prospects.

The vegetation sub-model under RCA GUESS set up was "spun up" for 360 years to make the vegetation to reach on a steady state with the climate. The spin up was performed using CRU05, global historical climate data set, repeating the climate of first 30 years (1901 to 1930) until the model had reached to 300 years. The interannual trend in the data was removed by linear regression method. Concentrations of CO_2 were taken from the database complied by McGuire *et al.* 2001 and for 300 spin up period, 1901 value was used. After 300 years a historical period was simulated until the first coupling year was reached. Unlike the vegetation submodel, the climate submodel requires a spin up of a few months because of the shorter climate system memory. The RCA GUESS model was set up on GIMLE[8], a LINUX based cluster that can be accessed through SSH-Secure Shell Client. In order to run the model, a file was developed for the site that contains instructions for the model regarding the information on the extent of gridcell, path for input data files and where to keep the output files, spinup time, information of PFTs, time of elevated CO_2 and how high it should reach, soil type and other important information required for model run. The output generated from the RCA GUESS, was later processed using SIMBA that can also be accessed through SSH-Secure Client. The output generated from the above two experiments will be anlaysed and mapped using SIMBA and GIMLE. In the Annexure-I and II, the information of the LINUX codes can be found.

[7] http://www.ecmwf.int/research/era/do/get/era-interim
[8] http://www.nsc.liu.se/systems/gimle/

These codes are used to run the model in GIMLE and also used for processing the output in SIMBA.

4.4 Assumptions

- Tropical areas are usually characterized by high biodiversity and their climate is influenced not only by the dominant plant functional type as specified in the model structure but other species also play important role in influencing the climate state. However, in the model for simplification, a limited number of PFTs were chosen to represent the vegetation types of the area. It is therefore assumed that only dominant PFTs are going to modify the climate state of the region, which is not the case in reality.

- The model is a simplification of the reality and in this model many processes and mechanisms are not included which could be relevant for the climate state of tropical countries, particularly for India. The model doesn't take into account many significant activities such as land use and land management change, grazing effect, pest outbreak, wildfires, human intervention etc., which may amplify or dampen the present condition.

- Though, one objective of the study is to ascertain the impact of biophysical feedback on present Indian Climate, but in reality these feedback processes don't affect the climate in isolation. Other feedback processes also present in the earth's climate system, which changes and modify the climate state of any region. Therefore, the combined effect of all positive and negative feedback processes, ultimately decides the regional climate state.

- CRU05 dataset provides mean annual temperature, precipitation and solar radiation to each grid cell from 1901- 1960. The model also requires past climate data for the spin up phase but due to unavailability of the past climate dataset, the CRU dataset for the first 30 years was recycled for initial 300 years.

5.0 Results

In this section, the results from the first experiment that includes variables such as temperature, precipitation and cloud cover for present climate will be examined and LAI, albedo, sensible and latent fluxes observations will also be briefly discussed. In the second experiment, variables generated from RCA for future climate will be evaluated and discussed. Results are presented in the form of maps focusing over South Asia. This domain covers entire India with some other countries as well. Two seasons i.e. summer and winter are taken into the consideration for the analysis. For summer, June, July and August (JJA) months are selected while for winter, December, January and February (DJF) months are considered.

5.1 Validation of RCA and RCA GUESS and estimation of vegetation feedbacks

5.1.1 Average Surface Temperature

In this part, two different observation datasets are used for validation i.e. ERA Interim and CRU. Temperature data observed at 2 meter (T_2m) for 16 years period is compared with the simulated results. The simulation results are obtained from RCA and RCA GUESS.

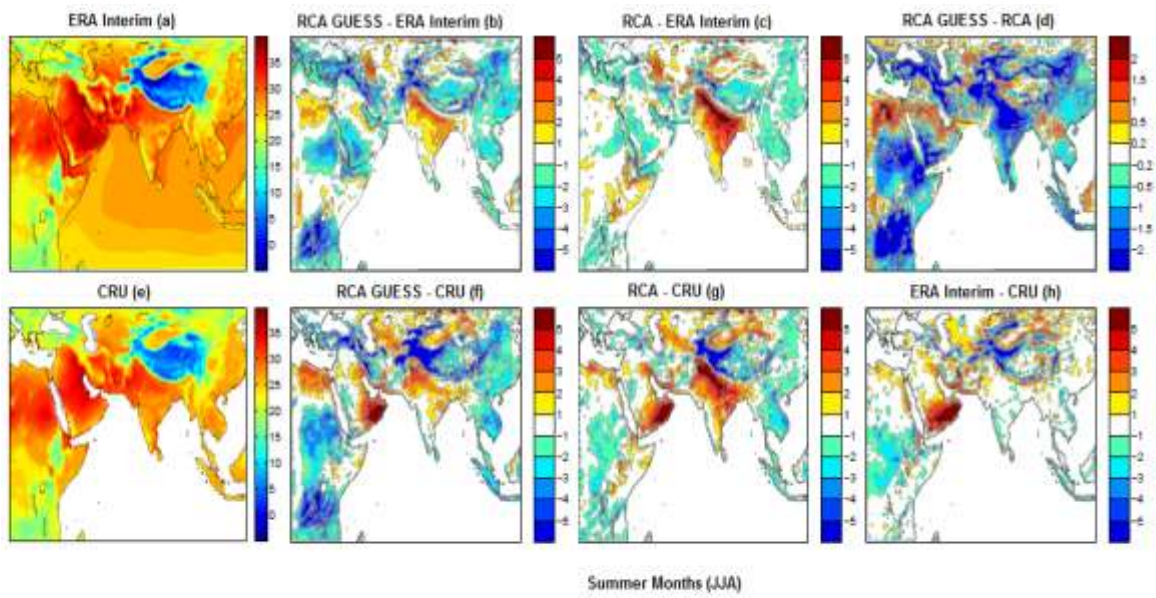

Figure 4: Average 2m temperature (^oC) from 1989 to 2005 for summer months, results from a) ERA Interim, b) difference between RCA GUESS and ERA Interim and c) difference between RCA and ERA Interim, d) difference between RCA GUESS and RCA, e) CRU, f) difference between RCA GUESS and CRU, g) difference between RCA and CRU and h) difference between ERA Interim - CRU

Figure 4 (a & e) depicts the observed average temperature (JJA) over India from the period 1989 to 2005. It can be seen from the *figure 4 (b)* that RCA GUESS is showing warm bias in summer months over northern part of India. The bias is more intense and concentrated near the Himalayan belt and moderate warm bias of 1-2^oC can also be observed over central regions of India. When compared with CRU dataset (*figure 4 (f)*), the warm bias can be clearly noticed near the Himalayan belt but it is more intense over Jammu and Kashmir and Himachal Pradesh. However, some underestimation of the temperature is also visible over Western Ghats. It is clear from the above results that RCA GUESS is simulating Indian summer climate quite reasonably with some warm bias.

On the other hand, results from RCA, in which the vegetation represented as a static parameter, show strong positive bias over entire country and the temperature is overestimated upto 4 to 5^{o}C in northern and eastern regions when compared with both the observation datasets. It can be noted from the above results that some bias which was present in southern and northern part of India can be explained by including dynamically simulating vegetation but there are some bias that still exists in RCA GUESS over northern part (refer *figure 4 (c & g)*).

The difference between RCA GUESS and RCA can be viewed as a vegetation response to climate because this is the only factor that differs between both of them. From *figure 4 (d)*, it can be observed that the influence of vegetation on Indian Climate actually made the environment 1 to 2^{o}C cooler in the northern and eastern regions while 0.2 to 0.5^{o}C in southwestern regions. However, since RCA GUESS is also overestimating the temperature over certain parts of the country, therefore, before accounting feedbacks affect on Indian Climate, it is important to correct these biases which are present in the results.

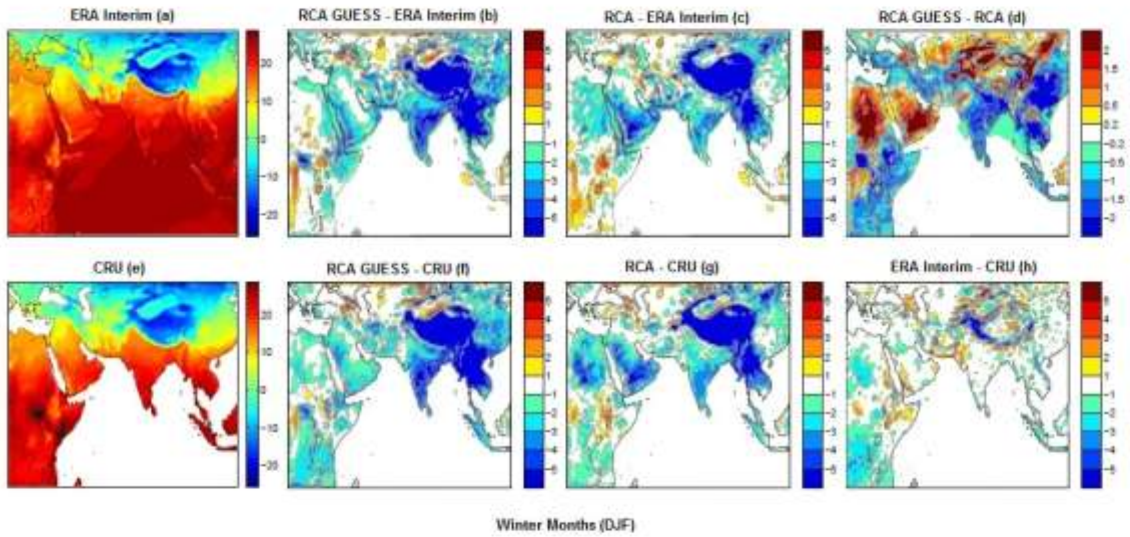

Figure 5: Average total temperature (^{o}C) from 1989 to 2005 for winter months, results from a) ERA Interim, b) difference between RCA GUESS and ERA Interim and c) difference between RCA and ERA Interim, d) difference between RCA GUESS and RCA, e) CRU, f) difference between RCA GUESS and CRU, g) difference between RCA and CRU and h) difference between ERA Interim - CRU

From *figure 5 (b & f)*, it is obvious that RCA GUESS is showing strong cold bias over entire India during wintertime. The underestimation of surface temperature in order of 3 to 5^{o}C is visible over central, southern and northeastern part of India. Almost similar response can be observed in RCA simulations when compared with both observational datasets. *Figure 5 (c & g)* depicts negative bias of 1 to 2^{o}C throughout entire country but not as pronounced over central and northeastern regions as in RCA GUESS. Since pattern of the deviation is very similar in both the simulations, it could be interpreted that biases from RCA are inherited to RCA GUESS. Some regions showed very strong bias in RCA GUESS due to vegetation response. It can be seen as uncertainty which gets amplified by vegetation. As far as vegetation feedbacks in winter months are concerned, it can be noticed that the country experienced dampening of surface temperature by 1 to 2^{o}C but here also some caution needs to be exercised while interpreting the results. RCA and RCA GUESS are again not simulating the winter temperature well. Therefore, the feedbacks observed in *figure 5 (d)* can be seen as a product of vegetation response to climate that in some case amplified by the errors and deficiencies in the models.

CRU dataset is developed from the worldwide observations of meteorological stations. On the other hand, ERA Interim dataset is prepared both from the satellite observations and meteorological readings. Since the dataset is partially derived from model, therefore, it is also known as quasi observations (Kjellstrom and Lind 2009). *Figures 4 (h) and 5 (h),* show the difference between both observational datasets for summer and winter months. It is clearly evident from the figures that both datasets depicts almost similar temperature over India with some deviations in summer and winter months over mountainous regions.

5.1.2 Average Precipitation

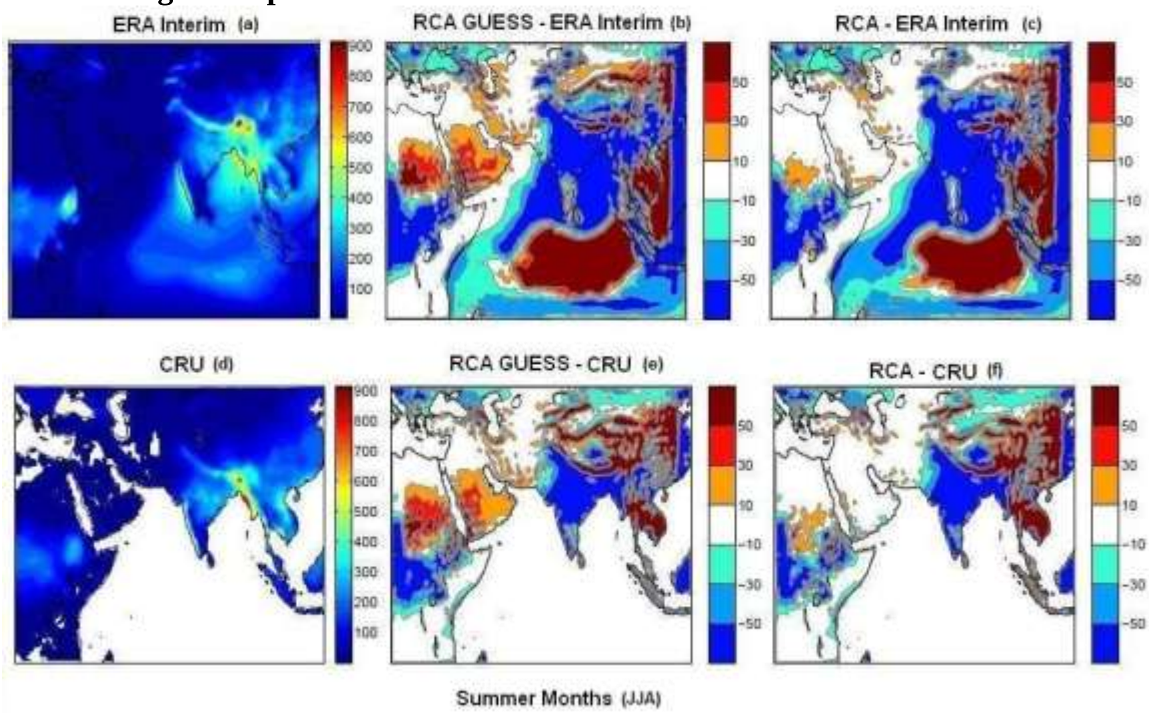

Figure 6: Average total precipitation (mm) from 1989 to 2005 for summer months, results from a) ERA Interim, b) difference between RCA GUESS and ERA Interim, c) difference between RCA and ERA Interim, d) CRU, e) difference between RCA GUESS and CRU and f) difference between RCA and CRU

Total precipitation in both the models is calculated by adding convective and large-scale precipitation. The *figure 6 (a&d)* presents the total average precipitation distribution for summer months by ERA Interim and CRU respectively. It is clear from the *figure 6 (b, c, e & f)* that RCA and RCA GUESS is highly underestimating the total precipitation in order of 50mm or more over almost entire country when compared with the observation datasets. Similarly, the rainfall is overestimated in order of 50mm or more over the regions falling under Himalayan belt in both models when compared to CRU dataset while comparison with ERA interim shows less bias over that region. However, precipitation over some areas near to eastern parts and western India are giving reasonable predictions. One thing is quite evident from the results that the pattern of deviations of rainfall is very similar in both model simulations. This again led to the reasoning that most of the deviations might be inherited from the RCA to RCA GUESS. These findings also give the information that the underestimation of precipitation in summer months can be viewed as another reason for warm bias in RCA GUESS and RCA results.

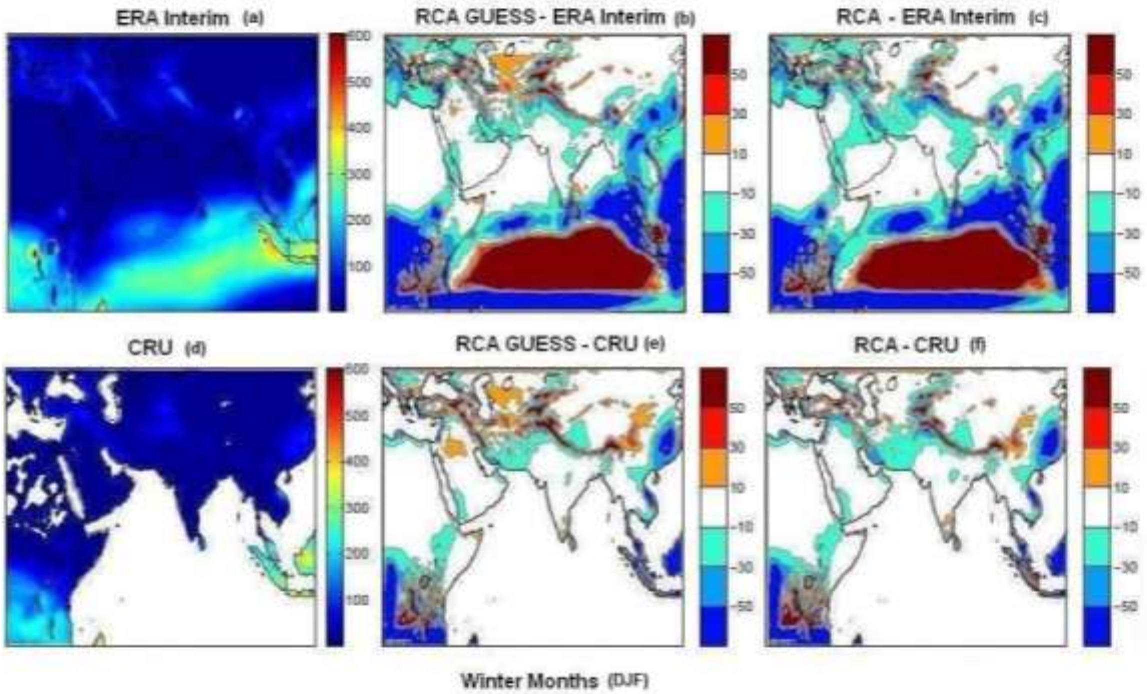

Figure 7: Averaged total precipitation (mm) from 1989 to 2005 for winter months, results from a) ERA Interim, b) difference between RCA GUESS and ERA Interim and c) difference between RCA and ERA Interim, d) CRU, e) difference between RCA GUESS and CRU and f) difference between RCA and CRU

In winter months, RCA GUESS (*figure 7 b & e*) and RCA (*figure 7 c & f*) simulated total precipitation over entire country quite reasonably. In comparison to ERA Interim dataset, both models show some underestimation of precipitation in order of 10 to 30mm in northern and northeastern part of India (*figure 7 b & c*). Similarly, both models are giving quite realistic results when compared to CRU dataset. Only around Himalayan belt, models are overestimating the precipitation by 50 mm or more (*figure 7 e & f*). It is also clear from the results that the underestimation of surface temperature that was observed in winter months over entire country might be marginally influenced by deviation in wintertime precipitation.

5.1.3 Cloud Cover

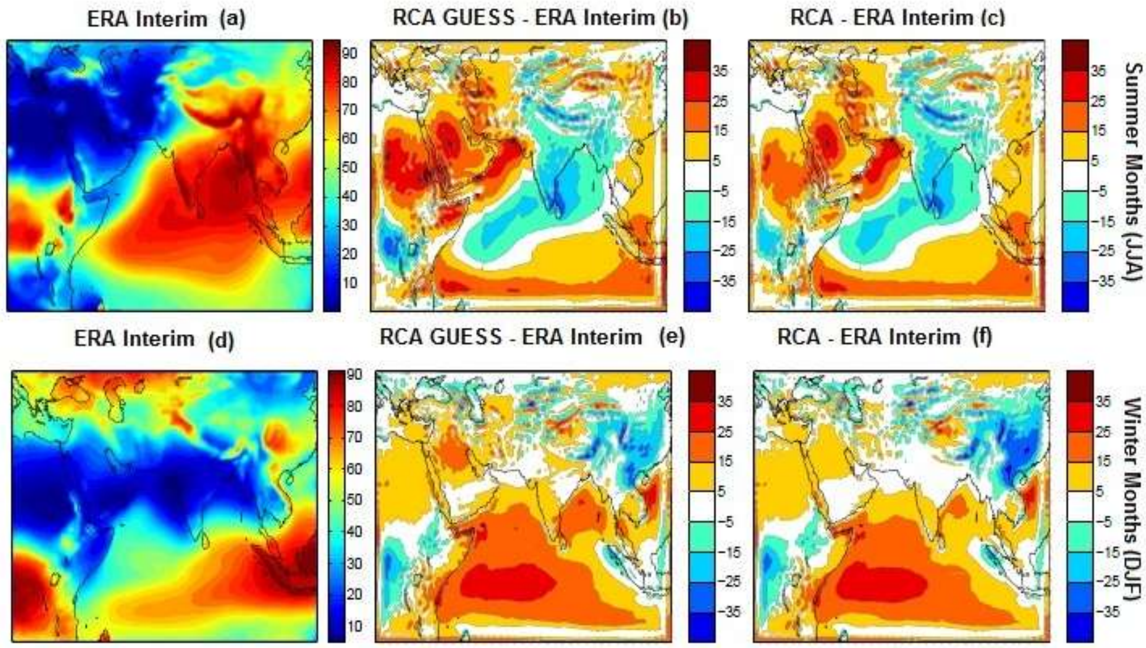

Figure 8: Average total cloud cover (%) from 1989 to 2005 for summer months, results from a) ERA Interim, b) difference between RCA GUESS and ERA Interim, c) difference between RCA and ERA Interim; average cloud cover for winter month results from d) ERA Interim, e) difference between RCA GUESS and ERA Interim, f) difference between RCA and ERA Interim

As far as cloud cover over Indian region is concerned, it is clear that the simulations of both models are underestimating the cloud cover in summer months by 5 to 25 % and in some places, for instance, over southern India and Upper Himalayas the underestimation was as much as 25 to 35% (*figure 8 (b & c)*). This, in a way, can be seen as an underestimation of Indian Summer Monsoon. During these months, India receives most of the rainfall and deviation in predicting Indian summer monsoon might have given a reduced precipitation pattern in summer and which also contributed in a positive bias. Apart from that, cloud cover distribution also affects the energy distribution and strong underestimation of cloud cover would definitely suggest that more SW radiation fall on the ground making the region warmer.

On the other hand, both models quite reasonably reproduced wintertime cloud cover but some deviations can be noticed in southern part. Some difference between both the models can also be observed in *figure 8 (e & f)*, in northern regions, which might be the response of evapotranspiration in RCA GUESS. The cold bias that was observed during winter months and which was pronounced in south and central regions might be a response of overestimation cloud cover. However, cloud cover is considered as one of the indeterminate variable, which is quite hard to simulate and predict. It is also difficult to make observations of cloud cover on the field. Therefore, deviations present between modeled and observed data are sometime also a result of inaccurate observation of cloud cover.

5.1.4 Leaf Area Index

Leaf Area Index is measurement of the proportion of leaf cover relative to the land surface area. Higher LAI represent higher vegetation cover or the land biomass over the region. RCA GUESS results show fair correspondence with satellite vegetation observation made by Forest Survey of India (FSI). As per the satellite observation, northeastern regions, some areas of central and southwestern regions are covered with dense vegetation and the results from RCA GUESS has also reproduced similar pattern (refer *figure 1 & 16*).

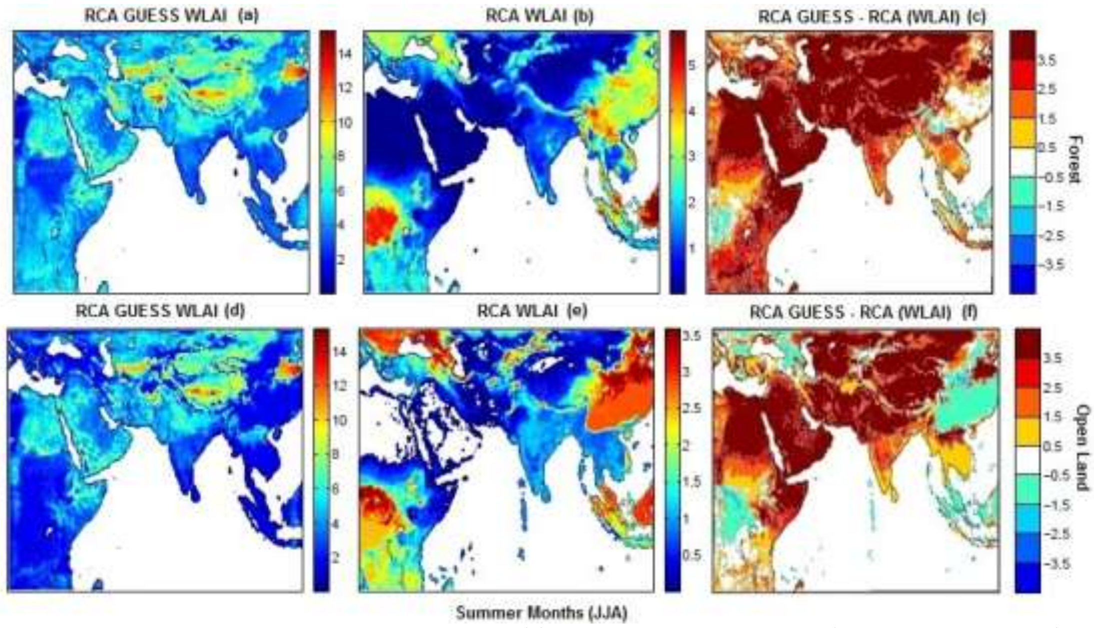

Figure 9: Averaged Jan. 1989 to Dec. 2005 weighted LAI of forest area where a) is the result from RCA GUESS,b) is from RCA, c) is the difference between RCA GUESS and RCA; LAI of open land where d) is the result from RCA GUESS e) is from RCA, f) is the difference between RCA GUESS and RCA

Figure 9 depicts the weighted LAI of forest and open land for summer months in RCA and RCA GUESS simulations. It can be seen that there is a substantial difference between LAI of RCA and RCA GUESS results. RCA GUESS depicts higher LAI over entire country for both forest area and open land (*figure 9 c & f).* The maximum difference presents over northern India in order of 3.5 or more. Similar pattern of differences in LAI can be visible in winter months with higher LAI over northern regions but marginally less extensive (*figure 10*).

It is interesting to note that higher LAI in RCA GUESS explains some of the positive bias present in summer months (which was more extensive and intense in RCA) (*figure 4*). On the other hand, higher LAI also explains the amplification of negative bias in winter months over central and southern regions (*figure 5*). However, some inconsistencies in both the model results are due to simplification of vegetation pattern. Vegetation composition is quite diverse and heterogeneous in India with extensive agricultural lands spread across the entire country. Therefore, depicting the overall vegetation under few categories certainly limits the reproduction of similar climate pattern.

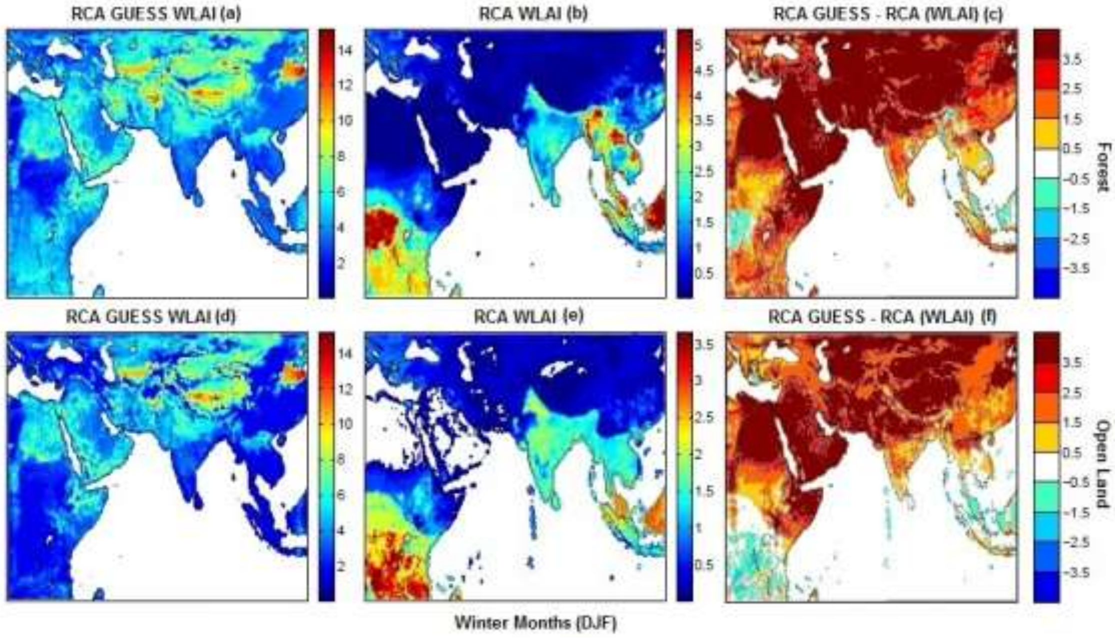

Figure 10: Averaged Jan. 1989 to Dec. 2005 LAI of deciduous for winter months where a) is the result from RCA GUESS, b) is from RCA, c) is the difference between RCA GUESS and RCA; LAI of coniferous forests where d) is the result from RCA GUESS e) is from RCA, f) is the difference between RCA GUESS and RCA

5.1.5 Sensible and Latent Heat Fluxes

This part presents the direction of partitioning of available energy in the form of sensible and latent heat fluxes during summer and winter months. This part will also confirm what we have discussed in the previous section. The signs in figure *11(c & f)* are reversed so the difference between RCA GUESS and RCA as positive numbers implies that the fluxes are greater in RCA and negative numbers represent higher fluxes in RCA GUESS.

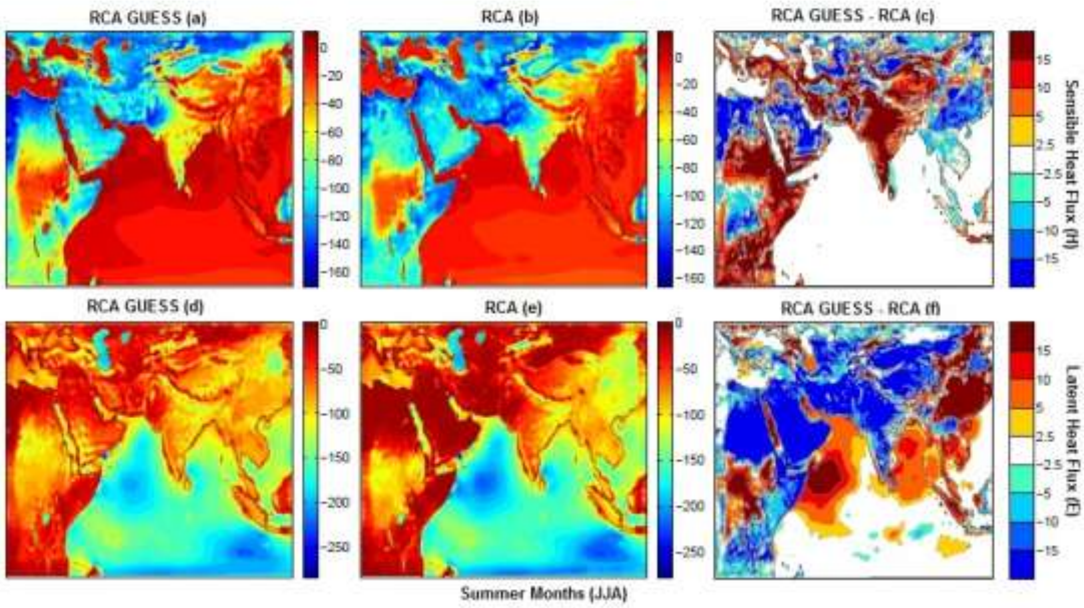

Figure 11: Average Sensible Heat Fluxes from Jan. 1989 to Dec. 2005 for summer months where a) is the result from RCA GUESS, b) is from RCA, c) is the difference between RCA GUESS and RCA; Latent Heat Fluxes in summers where d) is result from RCA GUESS e) is from RCA, f) is the difference between RCA GUESS and RCA

Figure 11 (c & f) shows that latent heat fluxes are higher in RCA GUESS and sensible heat fluxes are consequently lower. These are the effect of the greater LAI predicted by RCA GUESS, since a greater LAI implies more evapotranspiration. This result also explains dampening effect observed during summertime temperature in RCA GUESS. The warming predicted was dampened by the higher latent heat fluxes from the vegetation and ground in RCA GUESS but this phenomenon should have been more pronounced because of higher rainfall which is not properly represented in the model. This inconsistency might have led to a positive bias in RCA GUESS for summer months. However, RCA results showed negative bias over entire country which was more pronounced in some areas. The main reason of this inconstancy might be a result of deficiency in RCA in predicting wintertime climate, which was further exaggerated in RCA GUESS due to higher latent heat fluxes (*figure 12 f*).

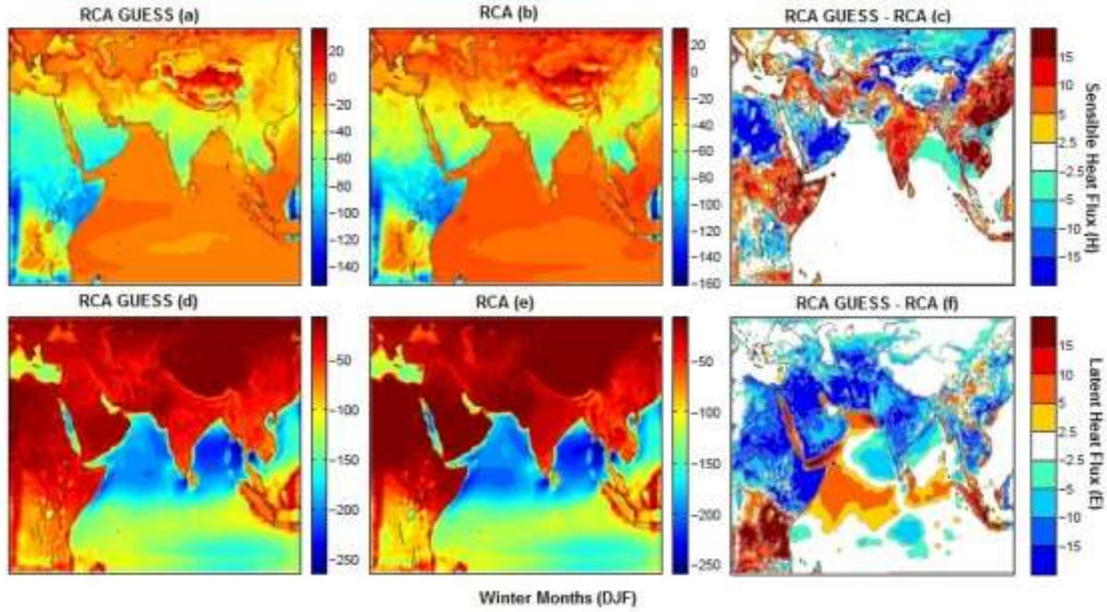

Figure 12: Average Sensible Heat Fluxes from Jan. 1989 to Dec. 2005 for winter months where a) is the result from RCA GUESS, b) is from RCA, c) is the difference between RCA GUESS and RCA; Latent Heat Fluxes in winter months where d) is result from RCA GUESS e) is from RCA, f) is the difference between RCA GUESS and RCA

5.1.6 Surface Albdeo

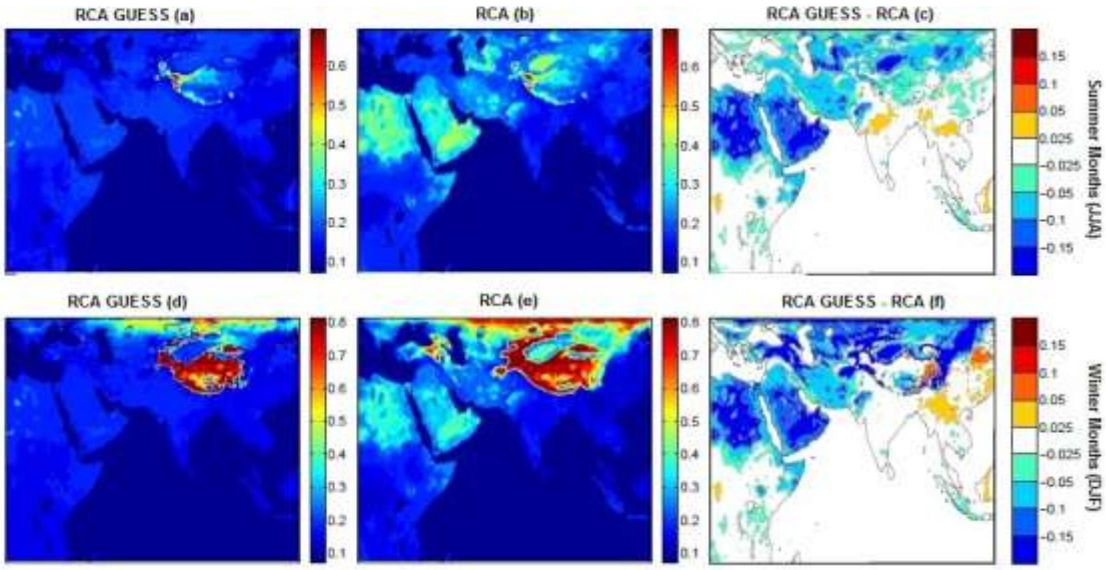

Figure 13: Surface Albedo Jan. 1989 to Dec. 2005 in summer months a) is the result from RCA GUESS, b) is from RCA, c) is the difference between RCA GUESS and RCA; in winter months where d) is the result from RCA GUESS e) is from RCA, f) is the difference between RCA GUESS and RCA

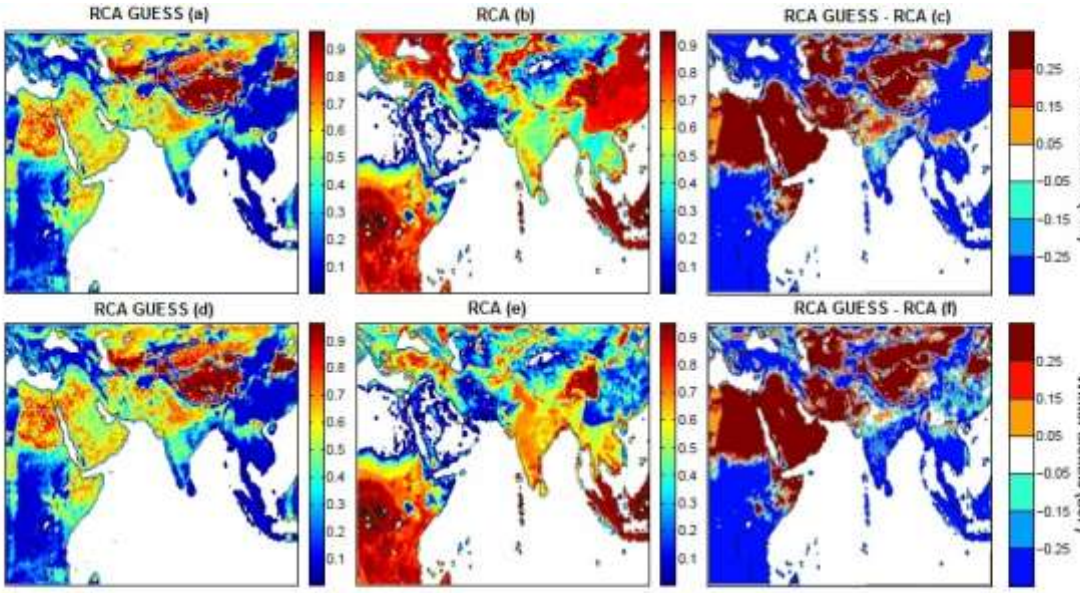

Figure 14: Vegetation open land Jan. 1989 to Dec. 2005 in summer months a) is the result from RCA GUESS, b) is from RCA, c) is the difference between RCA GUESS and RCA; in winter months where d) is the result from RCA GUESS e) is from RCA, f) is the difference between RCA GUESS and RCA

From the above *figure (13)*, it can be observed that there was a very mild effect of albedo change on the northwestern climate of India. The amplification of surface temperature due to albedo feedbacks was found between 0.025 to 0.05°C in summers over some parts of central India while a dampening effect was found between 0.05 to 0.15 °C over northwestern region in summer as well as in winter. It can be seen from the *figure (14)* that RCA GUESS is predicting more open land vegetation over northwest region, which might have initiated this feedback and affected the surface temperature. In reality, the northwestern region is characterized by extensive desert land with very high albedo. Therefore, it can be seen that RCA GUESS quite realistically reproduced the actual land cover. However, the influence of albedo feedback is not as strong as hydrological feedbacks on surface temperature and would not lead to any dramatic shift in surface temperature.

5.2 Predicting Future Climate over India using RCA

In this section, the simulations of future climate by RCA will be discussed. The difference between the future climate (2034 to 2049) and present climate (1989 to 2008) is presented below.

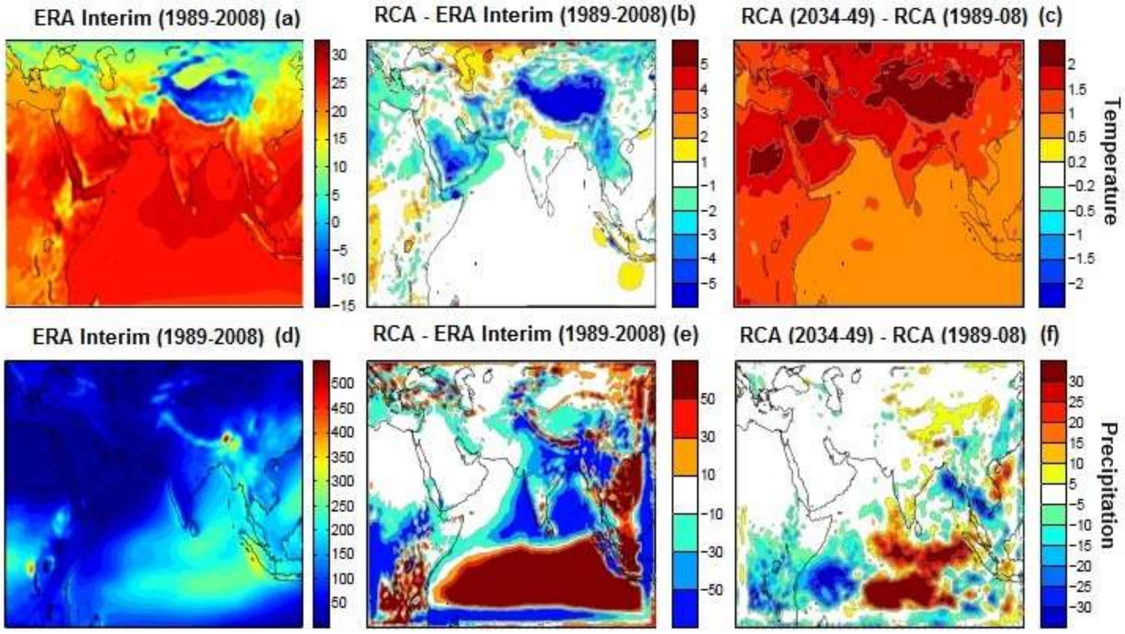

Figure 15: a) Average temperature a) ERA Interim (1989.2008), b) difference between RCA and ERA Interim (1989-2008), c) difference between RCA (2034-2049) – RCA (1989-2008); average precipitation d) ERA Interim (1989.2008), e) difference between RCA and ERA Interim (1989-2008), f) difference between RCA (2034-2049) – RCA (1989-2008).

Figure 15 (a & b) clearly shows that RCA simulates surface temperature quite realistically when compared to observation datasets. The biases observed in the last section, were basically limited to summer and winter months but generally RCA is giving reasonable result with some small deviations. The one major difference between previous results and these results is that the former simulations were forced by ERA Interim on the lateral boundary but this simulation used boundary conditions from ECHAM5. *Figure 15 (c)* shows that there will be 1.5 to 2^{o}C warming over northern, western and some parts of central and northeastern regions while other parts of India will experience warming in range of 1-1.5^{o}C. In case of average precipitation pattern, a negative bias can be observed over entire country in simulated results (*figure 15 d & e*) therefore, this point needs to be kept in mind while interpreting the future scenarios. *Figure 15 (f)* shows no major shift in future precipitation but some shifts are evident in small patches over northeastern region and other parts of the country.

6.0 Discussion

6.1 Validation of RCA and RCA GUESS

Validating RCA GUESS and RCA simulations against observational datasets is crucial before applying these models to a large domain such as India. Currently, model validation process has been receiving a lot of attention from the scientific community. Many scientific groups are studying regions that are beyond their fixed domain. Earlier, mostly all models were developed focusing on Europe, North America or to their fixed domain. Now, researchers are trying to run these models over different bioclimatic regions, where not many studies have been performed as a result of which limitations in these models can be identified and corrected (Randall 2007 and Sörensson *et al.* 2009b). Till date, no study is found that has used regional earth system model especially RCA GUESS over India nor RCA is ever applied over that domain. Therefore, this limits the understanding why these models are showing deviation from the actual observed state. This section will not only answer the reasons of deviations in RCA GUESS and RCA simulations when applied over India but also helps in identifying the possible areas where improvement needs to be done.

It is clear from the results (refer *figure 4 and 5*) that RCA GUESS is performing fairly well in simulating the summer temperature (JJA). However, strong warm bias is observed over northern part of India particularly in Himalayan region when compared with ERA Interim dataset. The overestimation of temperature is also evident over similar regions when compared with more robust observation dataset i.e. CRU. On the other hand, RCA depicts a strong positive bias over entire country particularly in northern regions. In case of wintertime temperature, both models did not give satisfactory results. The negative bias was noticed over entire country in RCA GUESS results and in some places, the negative bias was amplified by high LAI and also due to overestimation of cloud cover (*figure 6, 7, 8, 9 & 10*). Simulations of RCA are also showing similar pattern of deviations. As mentioned before, for comparison, no study was found where validation of regional earth system model was done over India with which the results can be compared.

Nevertheless, contrastingly, the study by Smith *et al.* 2010, found significant cold bias of 1^{o}C in summer using RCA GUESS over Europe when compared to CRU and ERA 40 observation datasets. The overestimation of wintertime temperature was also observed over northeastern part of Europe and underestimation was noticed in Mediterranean and North African regions. As compare to other parts of Europe, Mediterranean and North African regions are considered warm areas. The study observed negative bias over these regions in winter. The negative bias was more pronounced over Northern Africa that was quite similar to the bias observed over India in winter. The study stated that cold bias observed over these regions during winter season is due to the presence of high number of cold days. It was mentioned by the author that the deviations present in RCA GUESS is very similar to the bias observed and documented by Samuelsson *et al.* 2011 for RCA.

According to Samuelsson *et al.* 2011, the reasons of cold bias observed over these areas in Europe are not very clear but it was speculated that this error might be a response of overestimation of intensity and frequency of anti-cyclonic conditions in winter. The wintertime anti cyclonic circulation happens due to dry and clear sky that leads to a strong long wave cooling. The results also showed positive bias over Northern Africa in summer but the reasons of this deviation was not discussed. On the other hand, Sörensson *et al.* 2009b mentioned that the local biases present in the RCA could be corrected to a certain extent for tropical countries (up to around 10^{o}C) when actual land surface data is used. It is reported that by including land use data in the model, the simulations give more realistic results for tropical countries. In another study, Sörensson *et al.* 2009a found a negative bias over eastern-central Brazil in winter (DJF) and summer (MAM) months using new version of RCA i.e. RCA3-Ecoclimap (RCAE). The reason of this negative bias was attributed to the erroneous representation of convergence zones. According to the study, the model bias was amplified by taking boundary conditions from ECHAM5.

Since we can't compare apples and oranges, similarly two different model outputs can't be compared. This is because every model has its unique and different parameterizations as well as assumptions that might influence the final results. However, when the studies are less and outputs are indicating similar kind of bias than some conclusion can be drawn. There is another study, which also compared simulated and observed temperature (the difference between ECHAM4 AOGCM and ERA 40) over India for the period 1979 to 1993. According to this study, the warm bias over certain areas is due to the unrealistic drying of soil during dry season in the summer months which in turn reduces the evaporation. This decrease in evaporation rate from the ground further leads to a reduction in local precipitation. Therefore, this could be seen as one of the reason of strong positive bias that was observed over Northern part of India in summers (May 2003). It is reported that these biases can be corrected by improving the parameterization of soil processes and vertical fluxes in planetary boundary layer. It is also noted that the underestimation of ground water holding capacity is the main problem. In the model structure, the soil store less water and also evaporates at very high rate in dry seasons. This high rate of vertical fluxes present in the model further makes the land surface area deprived of water, which leads to a warm bias.

In case of total precipitation, RCA and RCA GUESS simulations didn't give satisfactory results when compared to the observation datasets for summer (refer *figure 6*). While for winter months, the results were quite reasonable (refer *figure 7*). But it is the summer months (JJA), when India receives most of the rainfall; therefore, a strong underestimation of precipitation in these months certainly affects surface temperature of proceeding months as well as overall climate. It is assumed that both models have been struggling to simulate Indian Summer Monsoon, which in a way is also contributing to unexplainable bias in summer and winter months. The above argument is corroborated by *figure 8* where underestimation of cloud cover over entire country can be clearly visible. This underestimation of cloud cover not only affected the precipitation pattern in the country but also increased the SW energy distribution that led to a warm bias in summer months. In similar way, overestimation of cloud cover might have contributed in negative bias for winter months, which was further amplified by higher latent heat fluxes due to high LAI (*figure 9, 10, 11 & 12*). The problem of correctly representing the Indian Summer Monsoon is not only associated with these models. In some previous studies, other regional climate models when applied over India also struggled in simulating Indian Summer Monsoon. For more detail, refer Martin 1999, Dash 2006 and Mukhopadhyay 2010.

Smith *et al.* 2010, however, found overestimation of precipitation over central and northern regions of Europe in summers. This overestimation of precipitation in summers believed to be inherited from RCA to RCA GUESS. In our study also, it can be observed from *figure 6 and 7* that error in precipitation estimation of RCA might be inherited to RCA GUESS.

Sörensson 2009a and 2009c discussed that RCAE reasonably predicted the precipitation over South America for all seasons but deviation was observed in tropical regions during summer and autumn. The reasons of these deviations are not very clear and can be attributed to model deficiency. In another study, Menendez *et al.* 2010 assessed the performance of four different regional models including RCA over South America. The study pointed out that all RCMs were struggling in predicting the rainfall pattern of tropical countries of South America.

RCA and RCA GUESS simulation showed reasonable overall agreement with CRU and ERA interim datasets but strong positive bias over Himalayan belt, Western Ghats and Northeastern regions were found in summer. This shows that model is not performing well over mountainous areas. RCA GUESS also experienced similar difficulty over mountainous regions of European Continent. As per Simth *et al.* 2010, RCA GUESS was also not giving reasonable precipitation for European Mountainous regions such as Alps, Scandes and Scottish Highland due to its varied topography that make difficult to predict orographic rainfall. Higher precipitation over mountainous regions was also observed by Samuelsson *et al.* 2010 in Europe when compared RCA results to ERA40 and CRU. According to the study, cloud cover is overestimated over mountainous regions by RCA as compare to satellite observation or field measurements, which led to strong positive and negative biases. This happens due to inaccurate estimation of vertical velocity by numerical models for mountainous region due to their complex terrain that lead to strong deviations in precipitation pattern. The other reason for not reproducing the precipitation pattern over mountainous regions is the problem in Kain-Fritsch convection scheme, which gives deviations in summer precipitation. Sörensoon *et al.* 2009a observed similar overestimation of precipitation in RCAE over Andes Mountain. This study also reported that the complex and steep topography of the Andes Mountain is the main reason for the biases and it was also associated to the less data used for CRU compilation.

From the above discussion, it can be seen that not only RCA but some other regional circulation models also showed some sort of deviation from observed temperature and precipitation for tropical countries. This raises certain doubts on the credibility of future predictions made by these models over those regions. It is, therefore, recommended that instead of using present version of RCA as a regional model for the tropical countries any better regional climate model can be used or improvement can be done in the present version so that it gives more realistic results for tropical countries. In one of the previous study, RCA was modified keeping in mind the complexity and behavior of tropical climate, for instance, for better representation of South American climate, Sörensson *et al.* 2009a used new version of RCA i.e. RCA3-Ecoclimap (RCAE). This version was especially modified to improve the performance of RCA for tropical and sub-tropical climates. In this model, the land surface description is more accurate than the previous version of model. In order to obtain more realistic land description, model utilized ECOCLIMAP database (Champeaux *et al.* 2005). The most relevant factors, which are useful for tropical countries climate in this database, are LAI and soil depth. Apart from this, modifications were also done in convection scheme, raindrop formation from liquid water and some other atmospheric physics processes for tropical and sub tropical countries. However, the modified version of the model also struggled in reproducing accurately some variables, as discussed earlier.

It is also important to recognize that these observation datasets (ERA Interim and CRU) don't give accurate measurements of studied variables. These variables were interpolated across the country. For some regions very dense station observations are present while observations were scarce in other regions (New *et al.* 1999, Sörensson *et al.* 2009a and Simth *et al.* 2010). In case of ERA 40, the observations get smoothed over mountainous region due to its coarse grid resolution. CRU observations also underestimate precipitation over mountainous area due to sampling error of rain gauges. The error increased in regions when snow is major fraction of overall precipitation and also amplified during the strong wind conditions. Lind and Kjellstrom and Lind 2009 discussed that RCA could not reproduce similar precipitation pattern of Baltic Sea drainage basin when compared to CRU dataset. They found 20% overestimation of precipitation, which was significantly reduced to 5% when more accurate datasets of Rubel and Hantel 2001 was used. The under-sampling problem of rain gauge can increase in mountainous region because the rain gauges are not evenly spread which further lead to inaccuracy in precipitation estimation for the regions that fall between interpolated stations. This under-sampling problem is also noticed over Alps by Frei *et al.* 2003, which varies based on different seasons and regions. Therefore, these points need to be kept in mind before interpreting reasons of deviations.

6.2 Estimation of vegetation-climate feedbacks

Since both models are showing considerable uncertainty in predicting the climate variables for studied period. Therefore, it is very hard to deduce the actual impact of climate on vegetation pattern and vice versa. Though RCA GUESS depicts higher LAI than RCA, the underestimation of Indian Summer Monsoon suggests that LAI would have to be much greater (*figure 9 & 10*). During Indian summer monsoon period, plenty of water is available on ground, which promotes vegetation growth and agricultural production in entire country (Sarkar and Kafatos 2004). Therefore, before quantifying the impact of vegetation feedbacks, inconsistencies in the models need to be corrected. However, growth of plants are not only linked with availability of water but other factors such as humidity, moisture, soil moisture, length of monsoon period, adequate temperature also play critical role (Sarma and Sivaram 2010). But according to Lee *et al.* 2009, for the period 1982-2003, the surface temperature in July was significantly reduced in India as a result of vegetation growth and increased irrigation activities. The result clearly shows that there was significant growth of vegetation during the studied months, which might not be properly represented in RCA GUESS. Higher LAI due to correct representation of Indian summer monsoon over northern region might also help in explaining some of the warm bias in RCA GUESS. This study also highlighted the importance of including the irrigation pattern in the present model structure.

If the climate simulated over India would be similar in magnitude for the feedback and non-feedback simulations than it would be reasonable to question the role of vegetation. However, the results indicated that vegetation matters since they show comparably significant shifts in temperature, precipitation as well as in cloud cover, depending on the vegetation cover. It is also important to keep in mind that incorrect estimation of temperature and precipitation pattern will evolve new climate state that is very different from the actual observation. For instance, during winter season strong negative bias was amplified as result of presence of vegetation (refer *figure 5*). Therefore, a proper representation of regional climate is not only useful but a careful selection and representation of vegetation pattern is equally important.

Lashof 1997 reported that overall climate in tropics will be influenced by the evapotranspiration feedback than albedo feedback. In our results, it can be observed that albedo change has very marginal affect on the average surface temperature over central and northwestern region. This marginal change in the surface temperature would be suppressed by strong effect of hydrological feedback (*figure 13& 14*).

Chaturvedi *et al.* 2010 reported that major shift will be seen over upper Himalayan regions, northern and central parts of Western Ghats in future. Therefore, it is assumed that dense vegetation cover in these regions will strongly amplify or dampen surface temperature. Most of the uncertainty lies in predicting the climate of Himalayan region; therefore, no speculation can be made based on present results. However, some other findings suggested that the treeline might shift to high elevation as surface temperature increases (Eriksson *et al.* 2009) which in turn decrease the surface albedo of snow covered upper Himalayan region and accelerate the melting process. Kumar *et al.* 2006 mentioned that northeastern region would receive high rainfall in future. This precipitation increase together with high temperature certainly amplifies the evapo-transpiration rate and which might dampen the warming to certain extent. However, over central part of India, which is mainly covered by dry deciduous forests, warming of 2^{o}C and reduction in the rainfall over those areas may certainly increase water stress conditions, which in turn amplify the surface temperature.

It is also important to consider that above predictions of vegetation change only take into account the natural variations in the vegetation pattern. The land use change due to human influence and livestock pressure might evolve a new climate state. There are some other assumptions and limitations that exist in RCA and LPJ GUESS, which is discussed in later part of the report. Improving or including those processes and mechanisms, which is relevant for tropical countries, will certainly reduce the uncertainty in the model results to certain extent.

6.3 Future Climate over India using RCA

According to RCA results (*refer figure 15*), it appears that India would experience overall warming of 1^{o}C under A_1B scenario by 2050. The results indicated that the increase in surface temperature would be more pronounced over northern, western and central regions. The temperature of these regions will rise as much as 1.5 to 2^{o}C. On the other hand, no significant shift was found in average precipitation. However, based on PRECIS (a regional climate model developed by Hadley Center) results for the period 2071-2100, India will experience warming of around 2.9^{o}C under SRES-B_2 scenario while the increase of average surface temperature is predicted around 4.2^{o}C under A_2 scenario. The study also reported that the warming will be more pronounced over northern part of the country. As far as precipitation pattern is concerned, the rainfall will increase almost over entire country by 2071-2100 except in some places such as Punjab, Rajasthan and Tamil Nadu. It is also predicted that northeastern regions will become wetter while western states turn into drier areas. The study highlighted that the average rainfall would increase by 220 mm in B_2 while 300 mm in A_2 (Kumar *et al.* 2006). In another study using AOGCM, it is predicted that temperature will fluctuate seasonally from 2.7°C in summer (JJA) to 3.6°C in winter (DJF) at the end of the century in A_1B scenario. This study also reported that the warming will be more intense over northern regions of India (Christensen *et al.* 2007). Kumar *et al.* 2002 and 2003 noted that the winter would become warmer in India by the end of this century. This finding was also supported by Kumar *et al.* 2006. Krishna Kumar *et al.* 2003 predicted that average temperature will increase in the range of 2 to 4°C by mid of the century. This study is also done using PRECIS under IPCC IS92a scenario. It is important to keep in mind while comparing the results with findings of other studies that these predictions are made for the end of the 21st Century while in our study the predictions are made until mid of the 21st century. Our predictions are quite comparable with only one study (Krishna Kumar *et al.* 2003), which simulated the average surface temperature for mid of the 21st century but that study was done using AOGCM with different emission scenario. It is also important to note that emission scenarios used in other studies are also different. In our study, SRES A_1B scenario is used while Kumar *et al.* 2003 used A_2 and B_2 scenarios. The A_2 emission scenario is quite near to A_1B emission scenario while B_2 is balanced scenario. Instead of these significant differences, our study gives reasonable prediction of average surface temperature. Though average temperature was simulated quite reasonably but confidence in precipitation predictions is very bleak. Most of the studies indicated major shift in precipitation pattern over India. This major shift in precipitation is not properly captured by present study. Apart from that, limitation also lies in the fact that all of these results did not take into account the vegetation dynamics. Therefore, there is a need for a study which uses earth system model to simulate the future climate over India. However, one thing is quite certain, irrespective of the models used, India will definitely become warmer. This shift in temperature and precipitation will surely poses serious challenges to various sectors within the country.

7.0 Limitations in the model and study

Mostly, all modelling research studies, experience some kind of limitations because of the time constraint or resource availability or due to limited understanding of some complex system that in turn forces to generalize important processes and mechanisms or sometime the understanding of the system is too coarse that important processes are not properly included in the model. This study also experienced some limitations and incorporating these constraints might enhance the confidence in the simulation results.

- RCA GUESS provides information on potential natural vegetation but if the simulated results would be improved with current land use and management data then the strength on the simulated results can be improved. By comparing the simulated potential vegetation with current land management data, the places with false representation of potential natural vegetation can be corrected. For example, places such as India that hosts different bio-climatic conditions due to which vegetation changes quite rapidly after some distance, the simulated vegetation bound to experience false representation of potential vegetation and having the current land management data might provide more realistic results.

- Around 70% of the population is directly or indirectly dependent on the forest and forest resources in India. Nearly, 60 million tribal population, living inside the forests or in surrounding areas with their domestic animals, which also pose immense pressure on forests. These tribal people acquire fuel, food and fooder to meet their daily needs from the forests (Ravindranath *et al.* 2008). In North-eastern part of India, tribal famers practice shifting cultivation where they slash and burn certain portion of the forest land and utilize it for farming purpose which in turn modifies the vegetated areas. Therefore, it is important to include human impact on vegetation distribution particularly on those states where significant number of tribal population is dependent on forests for their livelihood.

- The livestocks population density is very high in India as compare to other countries. This also builds a considerable pressure on Indian forest resources, which remain open throughout the year for grazing purpose (Ravindranath *et al.* 2008). Indian forests have been suffering from overgrazing problem due to these animals, which in turn affects the physical and structural property of vegetation as well as carbon balance of that region. This further lead to modification of regional climate pattern. However, in the present model set up, the impact of the herbivorous population on the vegetation is not properly represented.

- India's Economy is also dependent on its agriculture. In 2009, agriculture sector contributed 16.1% to country's Gross Domestic Product (GDP)[9]. Different crops are grown based on climatic and soil conditions across the country. It is predicted that current cropping pattern might get alter as a result of changing climatic condition. Therefore, including PFTs that characterize

[9] http://en.wikipedia.org/wiki/Economy_of_India

different crops phenology and processes (apart from C_3 and C_4 PFTs), which represent the modification in cropping pattern due to climate change, may certainly strengthen the confidence on the simulated results and understanding of the regional climate behavior.

- Human impact other than agriculture should also be included in the present model output to realistically predict the regional climate pattern. For example, large-scale irrigation that might influence crop growth and hydrological balance as well as nutrient dynamic as a result of application of fertilizers to improve the crop production was not included into the model structure.

- As far as RCA is concerned, there are some inconsistencies present in the calculation of the surface resistances that also needs to be resolved and should be incorporated in RCA GUESS.

- Optimally, the two simulations should have been initiated with identical land cover and allowed to proceed over atleast a few decades. This will allow us to extract how climate evolves through time in response to with and without transient vegetation changes. However, this would require a number of pre and post processing steps on large amounts of data, which for this particularly study was regarded as too time consuming.

- The simulations were carried out for very small period and it is believed that to realistically quantify the feedbacks affect on climate, longer simulations are required. In shorter simulations, the bias present in RCA is actually inherited to RCA GUESS and it is also showing strong bias.

- Another limitation lies in the spinup requirements of the climate versus vegetation. While the climate of RCA requires a few years of spinup, LPJ-GUESS requires centuries of spinup to reach to the equilibrium in vegetation structure and carbon pools. Here I have utilized the standard approach for spinup in LPJ GUESS, which implies the use of CRU climate. This could lead to strange behavior both in terms of climate and vegetation as we shift from CRU to RCA climate after spinup. In other words, my results can be viewed as a "first guess" of the climate affected by vegetation over India. One way of dealing with the contrast between CRU and RCA would be to perform a second spinup with the first guess climate.

- As mentioned before, this field is relatively new and unexplored particularly the Asian region; therefore, not many studies are present from which the results can be compared. The results generated from the study needs to be compared and confirmed by other studies. So, that the limitations in the present model can be evident.

8.0 Conclusion

8.1 Key Findings

RCA is not giving satisfactory results when applied over India. A strong warm bias in summer and cold bias in winter was observed in RCA simulations for the studied period. However, RCA GUESS reproduced reasonable summer climate but showed strong cold bias in winter months. It is believed that the most of the bias that was observed in RCA GUESS was inherited from RCA. Therefore, it is imperative to first make the relevant modifications before carrying out the longer simulations over India with RCA GUESS. The longer simulation done using RCA showed reasonable predictions of average surface temperature but the precipitation results were not comparable to other studies. Results showed that vegetation Indian Climate is quite sensitive to vegetation change and it will certainly play important role in influencing the regional climate in future, therefore, the proper representation of vegetation as well as regional climate is out most important. But, both the models need significant improvement in their model structure to correctly represent the climate and vegetation pattern of tropical region. The study also concluded that India temperature will increase around 1 degree Celsius. In some places such as northern, western and central regions, the warming will be more pronounced. The major drawback of the study was since both models struggled in simulating the present climate, the actual impact of biophysical feedback on Indian Climate could not be quantified.

8.2 Future Research

- Improvement should be done in RCA keeping in mind the complex nature of Indian Summer Monsoon that influence not only the vegetation pattern but and affect crop production
- Other relevant processes need to be incorporated such as effects of large scale irrigation that influence crop production, grazing pressure, fertilizers etc.
- Human induced changes that are not limited to agriculture would also be interesting to examine
- Also, it is interesting to look at the role of vegetation feedback on climate after doing the appropriate modifications

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Annexure: I

Copy files from GIMLE to SIMBA:

In order to copy files from GIMLE to SIMBA, scp command should be used. Given below an example which copies 24 files of era40_anpp_X.out:

- Log in to SIMBA
- Go to **user** directory under **/home/name** then to a **work** directory under **/scratch/name**
- Go to the working directory (cd /scratch/name)
- Copy the files by typing:

scp sm_id@gimle.nsc.liu.se:/nobackup/rossby14/sm_id/INDIA/spinup/era40_anpp* .

- It's important to note that at the end of the command, the dot (.) is mandatory.

- After inserting the scp command, the SIMBA asks password of GIMLE.

- When user enter the password of GIMLE the copying of files gets started and if everything goes fine, all the 24 files of era40_anpp.out under scratch/name on SIMBA.

- It is recommended that files should be moved in small limit rather than copying all your data from GIMLE to SIMBA. This is due to limited space on SIMBA.

Post-processing on SIMBA:

In order to access the post-processing tools, the user need to add the following lines at the end of the .bashrc file in the home directory:

export PATH=/home/anna/util/rtslice:$PATH
export PATH=/home/anna/util/rtseries:$PATH

(system files beginning with '.' like .bashrc are hidden by default - you can see them with ls -a)

In the beginning, the user needs to restart the command by typing: bash

You can extract relevant data e.g. for specific years with some useful tools on simba. The following workflow is good as a starting point:

rtslice . era40 anpp 358 387
Calculates average anpp from year 358 to 387 and outputs to era40_anpp_open.txt (open land) and era40_anpp_for.txt (forest)

gmap era40_anpp_for.txt –i Total –pixsize 0.8 0.8

If you wish .jpg instead of the default output format .ps you can add this specification according to:
gmap era40_anpp_for.txt –i Total –pixsize 0.8 0.8 –o mymap.jpg (see additional options by typing gmap –h)

Another useful tool is **rtseries** that creates timeseries of your data. If you run this command you can bring the resulting file(s) into Excel and create graphs over how e.g. anpp changes over time.

rtseries . era40 anpp

Annexure: II

Useful Commands on GIMLE and SIMBA, LINUX based platforms

Commands	Explanation	
<UpArrow>	Access previously used command in history of the system	
<DownArrow>	Access next command in history	
<tab>	Expand the filename	
cd <dir>	Go to the dicrectory <dir>	
cd.	Current dierectory	
cd..	Directory above	
ls	List directory contents	
ls –l	List directory contents with more detail	
cp <file1> <file2>	Make a copy of <file1> called <file2>	
cp <file> <dir>	Make a copy of <file> and put it in directory <dir>	
cp –r <file> <dir>	Copy recursively	
Scp	Secure file transfer between UNIX machines	
mv <file1> <file2>	Rename (move) <file1> to <file2>	
mv <file> <dir>	Move <file> to <dir>	
rm <file>	Remove <file>	
mkdir <dir>	Create directory <dir>	
more<file>	Show contents of <file>, <space> for next page, q to quit	
less<file>	Like more command but <pageup> snf <pagedown> to navigate	
tail <file>	Show last few lines of <file>	
Pwd	Show current directory	
Vi<file>	A text editor with the following commands:	
	x:	Delete on character
	i:	Insert text
	<esc>	Stop inserting
	a:	Append text
	<esc>	Stop appending
	Dd	Delete current line
	/<text><esc>	Search for text
	N	Repeat last command
	U	Undo last command
	:w	Write contents
	:q	Exit vi command
	:q	Quit or exit vi without saving

Annexure: III

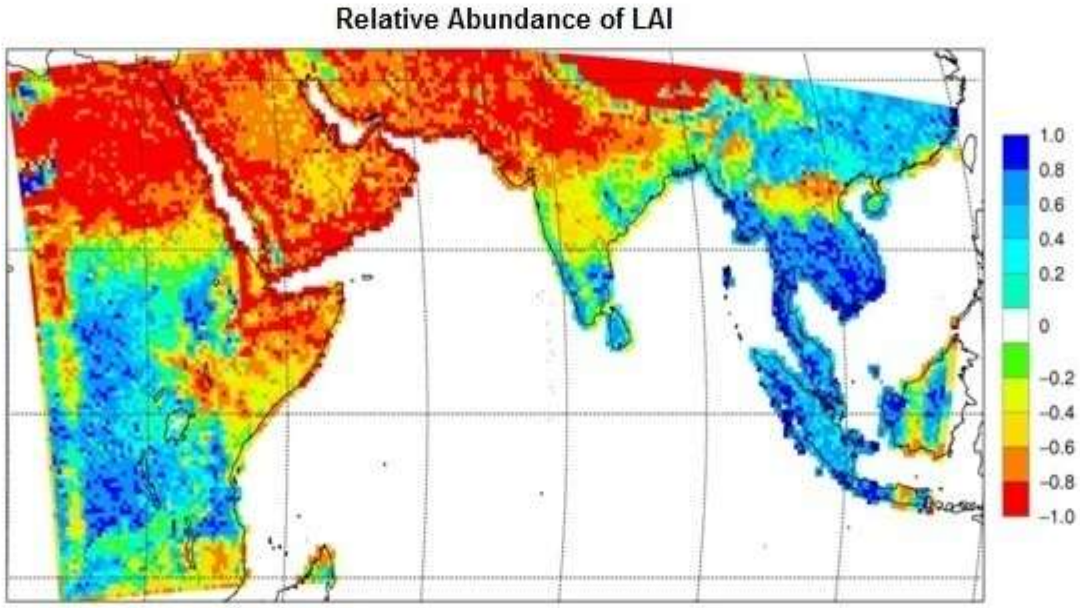

Figure 16: Relative Abundance of LAI

Global PFTs (Plant Functional Types)[10]	
BNE	Boreal needleleaved evergreen tree
BNS	Boreal needleleaved summergreen tree
BBS	Boreal broadleaved summergreen tree
TeBS	Temperate (shade-tolerant) broadleaved summergreen tree
IBS	Boreal/temperate shade-intolerant broadleaved summergreen tree
TeBE	Temperate broadleaved evergreen tree
TeNE	Temperate needleleaved evergreen tree
MNE	Mediterranean needleleaved evergreen tree
TrBE	Tropical broadleaved evergreen tree
TrBR	Tropical broadleaved raingreen tree
C3G	Cool (C_3) grass
C4G	Warm (C_4) grass

Table 1: Global PFTs in RCA GUESS

[10] http://www.nateko.lu.se/lpj-guess/education/html/furtherinfo.html#pft

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The reports are available at the Geo-Library, Department of Physical Geography, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden.

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