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GLOBAL CLIMATE CHANGE - INDIA's MONSOON AND ITS VARIABILITY

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SUMMARY

Globally the Earth's climate is warmer today than at any time during the last 140 years. There is now stronger evidence for a human influence on the global climate, although the precise magnitude of the influence is still uncertain. Global mean surface temperature could rise between 1.4° and 5.8°C in the next 100 years. Globally averaged precipitation is projected to increase, but at the regional scale both increases and decreases are projected. The global warming threat is real and the consequences of the climate change phenomena are many, and serious.

The countries in South Asia will be most vulnerable to the adverse impacts of climate change, including sea level rise. Developing countries in this region have the least capacity to adapt and will be the most adversely affected by climate change. Climate change scenarios for the Indian subcontinent on annual and seasonal mean basis based on analyses performed with data generated in numerical experiments with state-of-the-art atmospheric-oceanic general circulation models under SRES Marker emission scenarios are presented here. The annual mean area-averaged surface warming is projected to be between 3.5° and 5.5°C over the Indian subcontinent by the end of the 21st century. This warming would be more pronounced in winter than during monsoon season. During winter, India may experience between 5 and 25% decline in rainfall. The decline in wintertime rainfall over India is likely to be significant and may lead to droughts during the dry summer months. Only about 10% increase in area-averaged monsoon rainfall is projected over the Indian subcontinent. The year-to-year variability in central India rainfall during the monsoon season is not likely to change significantly in the future. However, the date of the onset of the summer monsoon over central India would become more variable. More intense rainfall spells are also projected in a warmer atmosphere, increasing the probability of extreme rainfall events. The climate change scenarios for Indian subcontinent presented here should not be viewed as a prediction but only as a plausible projection for broader scale impact assessments.

GLOBAL CLIMATE CHANGE: A SOUTH ASIA PERSPECTIVE

For about 1,000 years before the industrial revolution, the amount of greenhouse gases in the atmosphere remained relatively constant. Since then, the concentrations of various greenhouse gases have increased. The amount of carbon dioxide, for example, has increased by more than 30% since pre-industrial times and is still increasing at an unprecedented rate of about 0.4% per year, mainly due to the combustion of fossil fuels and deforestation. The concentrations of other natural radiatively active atmospheric components, such as methane and nitrous oxide, are increasing as well due to agricultural, industrial, and other activities. Chlorofluorocarbons and some other halogen compounds do not occur naturally in the atmosphere but have been introduced by human activities. Beside their depleting effect on the stratospheric ozone layer, they are strong greenhouse gases. All these gases, except tropospheric ozone, have long to very long atmospheric lifetimes and therefore become well mixed throughout the atmosphere. Human, industrial, energy related, and land use activities also increase the amount of aerosol in the atmosphere, in the form of mineral dust, sulfates, nitrates, and soot. The increases in greenhouse gas concentration and aerosol content in the atmosphere result in a change in the radiative forcing and a rise in the Earth's temperature. The Third Assessment Report of the Intergovernmental Panel on Climate Change (Houghton *et al*., 2001) reiterates that human activities have increased the atmospheric concentration of greenhouse gases.

Globally the Earth's climate is warmer today than at any time during the last 140 years. A mean global warming of about 0.8°C has been observed since the late 19th century (Houghton *et al*., 2001). This increase in surface air temperature took place in two distinct phases, the first one between 1910 and 1945, and since 1976. The observations also suggest that the atmospheric abundances of almost all greenhouse gases have now reached their highest values in recorded history. Anthropogenic CO_2 emissions due to human activities are virtually certain to be the dominant factor causing the observed global warming. Recent years have been exceptionally warm, with a larger increase in minimum than in maximum temperatures, possibly related, among others, to an increase of cloud cover. Surface temperature records indicate that the 1990s were the warmest decade of the millennium over the globe. Seven of the 10 warmest years on record have all occurred since 1990, and all 10 of them have come since 1980. The year 1998 was the warmest year ever recorded and 2001 the second warmest. January to June 2002 was the warmest 'first six-month period' of any year since global records began. Concomitant with this temperature increase, sea level has risen by 10-25 cm and there has been a general retreat of glaciers worldwide. The Arctic ice sheet decreased by 10% in area during the 20th century and the temperature of the oceans is rising. There has been an increase in the frequency of heavy rainfall events.

The observed warming has been largest over the mid- and high-latitude continents in winter and spring. Patterns of precipitation have changed in land areas in the Northern Hemisphere. There is more rainfall over land in mid- and high latitudes of the Northern Hemisphere during winter and early spring, but over the tropics and the Northern Hemisphere subtropical belt, particularly over the Mediterranean region during winter, conditions have become drier. There is evidence that El Niño episodes since the mid-1970s have been relatively more frequent than the opposite La Niña episodes. Even with the recent rate of warming, the 1997-1998 El Niño event stands out in both surface and tropospheric temperature as a very unlikely event. Across most of the globe there has been a decrease in the frequency of much below normal seasonal temperatures.

Future projections of human induced global warming are based on the premise that the growth rate of atmospheric greenhouse gases will accelerate in the future. According to most recent estimates (Houghton et al., 2001), the average global surface temperature is projected to increase by between 1.4° and 3°C above 1990 levels by 2100 for low-emission scenarios and between 2.5° and 5.8°C for higher emission scenarios of greenhouse gases and aerosols in the atmosphere (*see* Fig. 1 *for the projected range of emission scenarios*). The projected warming by the end of the 21st century will be sensitive to assumptions concerning future concentrations of greenhouse gases and aerosols. Because there is still considerable uncertainty in current understanding of how the climate system varies naturally and reacts to emissions of greenhouse gases and aerosols, current estimates of the magnitude of future warming should be regarded as tentative and subject to future adjustments (either upward or downward).

Climate change will continue to 'work through' for many decades, because the lead times in climate change are very long. The tropical and developing countries would be more vulnerable to climate change, because of their already more extreme climate, the fragility of the food security of their people, their inadequate and vulnerable infrastructure, population density in marginal lands, and other factors. The greater vulnerability could be in terms of water and food insecurity and more extreme weather conditions. Even small temperature increases in arid and semi-arid tropical regions could well lower agricultural productivity. Water scarcity will dramatically increase vulnerability and threaten food supplies in most tropical countries. In addition, vector-borne diseases such as malaria and dengue fever and water-borne diseases such as cholera could increase. Many developing countries in South Asia will have no choice but to adapt to the anticipated adverse effects of climate change. They will need to ensure that their economic structures and price signals encourage the private sector to take adaptive measures. They also need to consider increased vulnerability and adjust current development paths to substantially decrease future costs.

Climate change is no longer a distant scientific prognosis but is becoming a reality. A recent study (UNEP, 2002) reported that a brown haze layer (believed to be the result of forest fires, the burning of agricultural wastes, dramatic increases in the burning of fossil fuels in vehicles, industries, and power stations, and emissions from inefficient cookers burning wood, cow dung, and other 'biofuels') covering South Asia to a depth of 3 kilometers is disrupting seasonal monsoon weather patterns, damaging agriculture, and risking the lives of hundreds of thousands of people in the region. This blanket of aerosols is believed to reduce the amount of sunlight or solar energy reaching the Earth's surface by as much as 10 to 15%. At the same time, its heat absorbing properties are estimated to be warming the lower parts of the atmosphere considerably. This combination of surface cooling and lower atmosphere heating appears to be altering the Indian monsoon, leading to a sharp fall in rainfall over the northwestern parts and an increase in rainfall along the eastern parts of the Indian subcontinent. The aerosols could also affect rainfall in other ways. Raindrops may be becoming smaller and more numerous, triggering less frequent rainfall and longer lived clouds. One potential consequence is to move precipitation away from populated regions. A 10% reduction in the levels of solar energy reaching the Indian Ocean and adjoining seas in turn could reduce the evaporation of the moisture which controls summer monsoon over Indian subcontinent.

The Earth's climate is expected to change must faster than normal over the coming decades. Since the Indian economy is intrinsically linked with the annual monsoon cycle, a better understanding of the future behaviour of the monsoon and its variability is warranted for disaster mitigation and for developing adaptation strategies to cope with climate variability and climate change. A quantitative assessment of the magnitude of climate change over the Indian subcontinent, with some confidence and accuracy, is also crucial to evaluate the social and economic consequences expected and to formulate appropriate, though flexible, policy options. This paper presents an assessment of the magnitude of climate change over the Indian subcontinent and its implications on the monsoon rainfall and its variability, including plausible changes in extreme weather events. The next section details an account of the background information on the climatology of India in general and the Indian monsoons in particular. The subsequent sections present the observed variability and changes in key climatic elements over the Indian subcontinent and the future scenarios as inferred from state-of-the-art global and regional climate model simulations. The implications of the projected changes on various sectors are also explored herein.

INDIA'S CLIMATE AND THE MONSOONS: KEY FEATURES

India, a country of subcontinental size, is the largest peninsula in the world and is surrounded by seas on the three sides with an extensive coastline of about 6,000 km. Climatologically, India covers the tropical, subtropical, and temperate regimes. The country is divided into almost two equal halves by the Tropic of Cancer. The northern half, cut off from the rest of the continent by the Himalayan range, experiences temperate type of climate, whereas the extreme southern part of the country falls within the tropical latitudes. The inner Himalayas present subpolar conditions, registering extremely low temperatures in winter due to the altitude effect, while the presence of the seas on all three sides brings the south peninsular India under direct maritime influence, with low diurnal temperature differences and a very moderate climate. The interior of the country experiences a continental type of climate, with extreme annual temperature swings. The summer temperatures over this region soar and often go beyond 40^{o}C while the temperature in winter drops radically.

India's unique geographical configuration gives it the peculiar climate regime with four seasons. The winter season of December, January, and February is followed by the summer (pre-monsoon) season extending from March to May. India comes under the sway of the southwest monsoon season from June to September and then goes through post-monsoon season from October to November. The basic driving force behind the monsoons is the thermal contrast between the land and the sea. During the pre-monsoon, as the sun progresses northward, a simultaneous shift in the converging zone of the trade winds of the two hemispheres (ITCZ) occurs to the north of the geographical equator. The southeasterly trades blowing in from the Southern Hemisphere get deflected to the right as they enter the Northern Hemisphere and blow into the subcontinent from the west coast, bringing moisture from the adjoining seas. This marks the advent of the southwest monsoon over the subcontinent. The point of first entry of the southwest monsoon in India is the Kerala coast at the southern tip of west coast of India. These southwesterlies bring rain throughout the country, mainly to south of the monsoon trough (an elongated zone of low pressure). As the southwest monsoon winds blow over peninsular India they collect more moisture from the Bay of Bengal and, on striking the Himalayan range in the north, get deflected westward. These deflected southeasterly trades bring rains to the northern half of the country. As the summer monsoon enters from the southwestern corner of the country, it moves progressively north and by 15 July, it covers the entire Indian subcontinent.

During the monsoon season, the monsoon trough is a persistent feature over the Indian region with its axis located at about 22°N in the east to about 27°N in the west (Rao, 1976). The summer monsoon season over India is punctuated by the intermittent emergence and subsequent decay of well-defined, synoptic-scale, northwestward-moving low pressure systems forming over the Bay of Bengal during the monsoon and moving inland along this monsoon trough. These are accompanied by moist convective clouds and cause intense spells of rainfall over central India. The frequency and intensity of these synoptic-scale systems in a particular year largely determine whether the monsoon rainfall will be excessive, normal, or deficient. These synoptic-scale systems, commonly called monsoon depressions, have a time scale of several days and a length scale of about 500-1000 km and owe their existence to not only the larger and longer lasting components of the monsoon circulation but also the smaller and more transient subsystems. An analysis of seasonal records of daily rainfall at central Indian stations provides many components with time scales ranging from 7 to over 40 days and thus suggests the multiplicity of scales in the monsoon circulation (Bhalme *et al*., 1987; Nanjundiah *et al*., 1992). The monsoon circulation over the Indian subcontinent is also linked with the development of the Tibetan high occurring over the Tibet plateau, the Mascarene high off the coast of Madagascar, and the weakening of the subtropical westerlies over north India with the subsequent onset of the tropical easterly jet stream over the peninsular India.

Toward the end of the September, as the sun begins its journey southward, the monsoon starts withdrawing. This event is heralded by the reinforcement of the subtropical westerlies over north India. The easterly jet disappears rapidly with the recession of the monsoons. As the westerly jet stream re-establishes itself south of the Himalayas, winter rains start along the southeast coast near Tamil Nadu in India. This is known as the northeast or the winter monsoon. During the winter months, rain also occurs over north India because of the southward shift of the polar fronts. Frontal or extratropical cyclones developing over west Asia and the Mediterranean Sea pass through north India during their passage eastward. The presence of the Himalayas weakens these disturbances and the temperature contrast of the air masses is also somewhat reduced because of which the frontal characteristic of these extratropical cyclones is not clearly evident. Since these disturbances have their origin in the west, the rains that result over north India are said to be due to the western disturbances.

Thus, the monsoon can be regarded in general as a manifestation of the seasonal migration of the planetary-scale equatorial trough or tropical convergence zone (TCZ). Regional characteristics, e.g., land-sea thermal contrast, orographic features, vegetation cover, and inland water basins, play an important role in the establishment of the summer monsoon over the Indian subcontinent. The thermal structure of the adjoining oceanic areas – the Arabian Sea, the Bay of Bengal, and the South Indian Ocean – and its temporal variations also have a modulating influence on the monsoon. The onset and the retreat of summer monsoon over the Indian subcontinent are associated with rather abrupt changes in the atmospheric general circulation.

The long-term average annual rainfall for the country as a whole is 116 cm – the highest for a land of comparable size in the world. But this rainfall is highly variable both in time and space. The percentage aerial distribution of annual rainfall over India is given in Table 1. About 75% of the total annual rainfall over India occurs during the summer monsoon season. During winter, there is some rain over the northern parts of India (associated with western disturbances) and over the southern peninsular India (associated with northeast monsoon). The area-averaged, long-term mean summer monsoon rainfall over India (based on data for 1871-2000) is 85 cm, with a standard deviation of ±8.1 cm (coefficient of variation is 9.7%). The maximum rainfall occurs in July and August during the four-month (June to September) southwest monsoon season (Rao, 1976). Significant interannual variations in the dates of onset of monsoon rains and intraseasonal variability in the observed monsoon rainfall are also displayed over the Indian subcontinent.

Table 1: Percentage Areal Distribution of Annual Rainfall over India

Mean Annual Rainfall	Corresponding % Area
0 - 75 cm	30 %
75 - 125 cm	42 %
125 - 200 cm	20 %
> 200 cm	8 %

The summer monsoon rainfall oscillates between active spells with good monsoon rains (above normal) and weak spells or the breaks in the monsoon rains when deficient to scanty (≤20%) rain occurs for a few days at a stretch. Weak and active spells of the summer monsoon are determined by the position of the monsoon trough extending from the northwestern end over the Rajasthan desert to the head of the Bay of Bengal. The monsoon trough oscillates either south or north of this normal position over the Gangetic plains. When the trough is to the south or close to the normal position, active spells result and when it is near the foothills, weak monsoon conditions prevail.

The spatial pattern in observed mean monsoon precipitation is, however, fairly complex. The heaviest rains occur over the hilly states in the northeast and along the mountainous west coast. Orissa, East Madhya Pradesh, West Bengal, and the northeastern states of India, the western coast, and the Ghats receive more than 100 cm of rainfall during the monsoon season. The submontane region extending from north Bihar to Jammu also receives more than 100 cm. The heavy rainfalls in the northeastern states, west coast, the Ghats, and the submontane regions are influenced by the orography. The peninsular India south of 15°N gets less than 50 cm rainfall. There is a sharp gradient in monsoon rainfall from the west coast to the east coast over peninsular India. The lowest rainfall is received in the extreme southeast portion of the peninsula. The west and the northwest regions of the country receive about 50 cm of rain in the season. The rainfall decreases rapidly to less than 10 cm in west Rajasthan. Regions above 50 cm in the season are classified as wet and those less than 50 cm as dry parts of India.

The two monsoon seasons (the southwest monsoon during June to September and the northeast monsoon during November-December) bring forth rains – often in intensities and amounts sufficient to cause serious floods, creating hazardous (and often disastrous) situations. Moreover, cyclonic storms in the pre-monsoon months (April-May) and the post-monsoon months (October-November) cause large-scale inundation, destruction, and death. In fact, floods and cyclones are the two major natural disasters that visit India quite often. The adverse impacts of these two natural disasters cannot be assessed merely in economic terms based on destruction of crops, property, and infrastructure because the toll of human misery in the form of death, disease, injury, loss of employment, psychological trauma, and above all the setback to development is too difficult to evaluate.

OBSERVED CHANGES IN TEMPERATURE AND RAINFALL, INCLUDING EXTREME EVENTS

In India, an analysis of seasonal and annual surface air temperatures, using the data for 1881-2001 for 25 or more stations, shows a significant annual mean warming of 0.68°C per 100 years (Fig. 2). On a decadal basis, increasing trends in annual mean surface air temperatures have been found during three periods (1905-1925, 1932-1956, and 1972 onward). The warming is mainly in the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in most parts of the country except for a significant negative trend over northwest India. A relatively more pronounced trend in maximum daytime temperatures has been found compared to minimum nighttime temperatures. It is difficult to interpret the observed temperature increases over India in terms of cause and effect. Across most of the Indian subcontinent, increases in the frequency of above normal seasonal temperatures have been observed in recent years. Moreover, significant increases in surface air temperatures relative to climatological normal have been observed the year 2002 at most locations in India. These observed increases in surface air temperatures on local scale provide some evidence of the anticipated magnitude of global warming.

The rainfall fluctuations in India have been largely random over a century, with no systematic change detectable on either annual or seasonal scale (Fig. 3). However, the linear trends of monsoon rainfall during 1871-1998 at each of over 300 observing stations spread over India show statistically significant trends in some broad contiguous areas. The increasing trends in the seasonal rainfall have been observed over Punjab, Delhi, Haryana, and Chandigarh, no significant change along the west coast, and the decreasing trends over East Madhya Pradesh and the northeastern states of India during recent years. Intense deforestation activities have taken place along the foothills of Himalayas and in the Assam region, and land use patterns have undergone definite changes over parts of Rajasthan and Punjab (northwest India). Surface cooling with significant increase in rainfall has also been observed in the peripheral regions of the Rajasthan desert and it is believed that the increased area under irrigation is one of the main casual factors. However, all India monsoon rainfall, unlike observations from the Sahel region, shows rather stable long-term characteristics, with extremes being a part of its natural variability.

The frequency of extreme weather events in India — for example, heat waves, droughts, and floods — has increased over the past two decades. For example, the State of Orissa has been reeling under contrasting extreme weather conditions for more than a decade: from heat waves to cyclones and from droughts to floods. Since 1965, calamities are not only becoming more frequent but also striking areas that never have been vulnerable. A heat wave in 1998 killed around 1,500 people in coastal Orissa, a region otherwise known for its moderate temperature. Andhra Pradesh is the fifth-largest state in India, with about 76 million people; it is also regarded as the "rice bowl" of India. In May 2002, more than 1,000 people died during a week-long heat wave in the state when surface air temperatures soared to almost 51^{o}C (temperatures were more than 7% above the monthly average). Severe heat waves also struck Andhra Pradesh in 1996 and 1998. But the heat wave of 9-15 May 2002, caused the highest one-week death toll from thermal stress in Indian history. The death toll due to heat waves during March to May in Rajasthan, Punjab, Gujarat, Orissa and Bihar is also on the rise in recent years.

Drought recurs chronically in west Orissa. However, it is not only the recurrence but also the expanse of the drought that haunts this state. The drought in 2001 engulfed districts like Sundergarh and the Kendrapada, which historically were drought-free. Since the great famine of 1866, 2001 was the first time that drought of such a magnitude hit Orissa. It affected 25 of the state's 30 districts. By February 2001, Orissa's western districts were reeling under a severe water crisis and people started migrating. The worst affected districts like Kalahandi and Balangir reported 60% less rainfall than normal. The situation in nine western districts was severe as it was the second consecutive drought.

By May 2001, 61 starvation deaths had already been reported. The state government put the economic loss due to crop damage at 64.289 billion Indian Rupees. The Orissa drought in 2001 affected the lives of 11 million people.

In 1994, monsoon rainfall was deficient (by between 20% and 43%) in 10 of the 35 meteorological subdivisions of India. Gujarat, West Rajasthan, Tamil Nadu, and Kerala had deficient monsoon rainfall during 1999. Two consecutive droughts in 1999 and 2000 were reported in Pakistan and northwest India, and increased flooding occurred in the high rainfall areas of Bangladesh, Nepal, and the northeastern states of India. In Gujarat, low monsoon rainfall in 1999 and 2000 led to all the reservoirs containing only 50% or less of installed capacity. The drought in 2000 was the worst to hit Gujarat in the past 100 years. Sixteen of its 27 districts and 26 of adjoining Rajasthan's 32 districts were affected. The situation was further aggravated because it followed the 1999 drought. According to official sources, out of 143 dams and other reservoirs in Kutch, Saurashtra, and North Gujarat, 107 had gone dry in the pre-monsoon months of 2001.

The monsoon-driven floods in August 2000, the worst in the southern state of Andhra Pradesh in decades, left thousands homeless, brought misery to millions, and damaged or destroyed large areas of crops. At least 165 people died in the floods. And 24 cm of rain were recorded in Hyderabad, the state capital on 9 August – the highest amount in more than five decades. In coastal Orissa, almost 490,000 ha of fertile lands have been waterlogged, salinated, and sandcasted by cyclones and floods in recent years. The devastating floods in 2001 (15 floods were reported between 8 July and 10 August 2001) induced crop failures worth 150 billion Indian Rupees. The incessant rains for 40 days starting from the first week of July 2001 was largely responsible for the worst ever flood recorded in the last century. The 2001 floods (more devastating than the 1982 floods) were deadly because the Mahanadi, the Brahmani, and the Baitarani rivers, sharing a common delta, flooded simultaneously. These floods inundated 25 of the 30 districts, including hilly areas like Kalahandi and Phulbani, and affected one-third of their 30 million residents. About 2.12 million ha of standing crop were also damaged.

In the year 2002, while drought conditions prevailed in Vidarbha (in the state of Maharashtra) during June and July, heavy downpours in August amounted to 80 cm of rainfall, compared to 95 cm of normal seasonal rainfall. On 2-3 September, 25 cm of rainfall was recorded, which lifted the water level of Sardar Sarovar dam along the Narmada River to 12 m above its full capacity of 95 m, inundating hundreds of villages in the region. The monsoon wreaked havoc in seven districts of Maharashtra from 1 to 3 September 2002, claiming 35 lives and causing massive damage to crops and throwing normal life out of gear. The Gujarat government issued a "high alert" for 15 big and small dams after those three days of incessant rains in the state. Such intense rainfall events have become more frequent in recent years in many parts of India, Nepal, and Bangladesh.

From a mild winter in northern and central India to copious downpours in Assam, Bihar, and other northeastern states during monsoon season, India recorded unusual weather in 2002. During the year, there were droughts in Pakistan and in the north and central parts of India, while Bangladesh, Nepal, and the northeastern states of India suffered severe flooding during monsoon season. Two-thirds of Bangladesh's land area were submerged, ruining millions of hectares of cropland. Incessant monsoon rains across Nepal in July 2002 triggered flash floods and landslides in 20 out of 75 districts. About 100,000 people in 50 villages were directly affected by water logging in eastern and southern Nepal. The northeastern states of India – Assam, Bihar, Meghalaya, Tripura, and Arunachal Pradesh – were the hardest hit by flood waters this year. More than half of Assam State was flooded as heavy rains burst dams and caused rivers to overflow, inundating more than 5,000 villages and destroying hundreds of thousands of houses in July and August 2002. About 2.5 million people fled to take shelter on higher ground. Monsoon rainfall in all of India, as of 31 July 2002, has been estimated to be 24% lower than normal. Erratic monsoon rains in the states of Punjab, Haryana, Gujarat, Madhya Pradesh, Maharashtra, Orissa, Andhra Pradesh, and west Uttar Pradesh in 2002 sparked worries about economic growth, already dragged down by industrial slowdown.

Tropical cyclones are not part of the monsoons *per se* but they do cause devastating floods in the coastal states of India. Severe tropical cyclones generally develop during the pre-monsoon or post-monsoon seasons (generally the cyclone seasons are October-November and March-June). The eastern coast of India along Bengal, Orissa, and Andhra Pradesh is prone to such tropical cyclones. Observational records suggest that, although the sea surface temperature over the Bay of Bengal has risen since 1951, the numbers of monsoon depressions and tropical cyclones forming over the Bay of Bengal and Arabian Sea have declined since 1970. However, the intensity of tropical cyclones in Bay of Bengal seems to have increased in recent past. On 6 November 1996, a deadly cyclone with winds approaching 100 miles per hour and extremely heavy rains (8.8 inches in some areas) devastated India's southeastern coast in the state of Andhra Pradesh. At least 500 thousand homes were destroyed; 1.5 million acres of rice, sugar cane, cotton, and tobacco were flooded (1/3 of the entire agricultural output of Andhra Pradesh); millions of banana plants, lime, and mango trees were uprooted; and countless cattle, sheep, and chickens were killed. Crop and property damage was estimated at about 60 billion Indian Rupees, more than the annual budget of the state government. The tropical cyclone of 29 October 1999 hit the coast of Orissa with wind speed of 135 knots (~260 mph) and heavy rains that caused severe floods. This was the worst cyclone to hit the region in three decades and ranked highest in the damage caused in terms of both life and property. According to the official records, 9,885 people lost their lives; 2,142 people were injured; 370,297 head of cattle perished; and 1,617,000 hectares of paddy field and 33,000 hectares of other crops were damaged. Several villages had been completely wiped out and over a million made homeless with storm surge of height 9 m above astronomical tide level at Paradip, which penetrated 35 km inland. This “super cyclone” was more or less stationary (with slight southward drift) over the region after making landfall, and this led to excessive destruction of the infrastructure.

Almost 67% of the glaciers in the Himalayan mountain ranges have retreated in the past decade. The mean equilibrium line altitude at which snow accumulation is equal to snow ablation for glacier is estimated to be about 50-80 m higher relative to the altitude during the first half of the 19th century (Fushimi, 1999). Available records suggest that Gangotri glacier is retreating by about 28 m per year. Global warming is likely to increase the melting far more rapidly than the accumulation. Glacial melt is expected to increase under changed climate conditions, which would lead to increased summer flows in some river systems for a few decades, followed by a reduction in flow as the glaciers disappear.

The observed trends in the mean sea level along the Indian coast indicate a rising trend of about 1 cm per decade, which is close to that recorded in other parts of the globe. An average rise in the sea level around India of ~2.5 mm per year has been reported since the 1950s (Das and Radhakrishna, 1991). Today, coastal regions in India and Bangladesh are subjected to stronger wind and flood damage because of storm surges associated with more intense tropical storms. Frequent inundation of low-lying areas, drowning of coastal marshes and wetlands, enhanced erosion of beaches, more flooding, and increased salinity of rivers, bays, and aquifers in the coastal regions of India have occurred.

These instances of extreme weather events point to an unusually strong manifestation of a long-term problem – global warming. Many of the developing countries in South Asia could be severely impacted by climate change because of their already extreme climate and since the economy of most countries in this region is largely dependent on agriculture and is already under stress due to current population increase and associated demands for energy, fresh water, and food.

In India, a number of scientists today are engaged in studies to understand important aspects of observed large-scale, long-term changes in average climatic conditions – changes that we increasingly recognize could be induced by the industrial or agricultural/development activities of society. The primary objective of most studies of climatic change is to enhance our ability to predict future climate. Although there have been some notable achievements along these lines in India (as discussed in the next section), our ability to predict the time sequence of future climatic events is still limited. Modelling is a priority activity in climate research in India as elsewhere, and the development and use of models coupling the atmospheric, oceanic, sea ice, and land surface components to understand the variability and predictability of the coupled climate system on time-scales from months to centuries is being given increasing attention in recent years.

CLIMATE CHANGE OVER INDIA: REVIEW OF PAST ASSESSMENTS

The performance of a few atmospheric general circulation models with oceanic mixed layer (developed in the 1980s at leading climate research centers in the world) in simulating the observed climate over the Indian subcontinent and the assessment of the future changes over the region as projected by these models were first examined by Sikka and Pant (1991), who suggested that the expected temperature increase over India due to doubling of CO_2 would be around 2 to 4^{o}C in winter and 1 to 2^{o}C in summer. Similar conclusions were inferred from analysis of data generated in global climate model of NCAR, USA (Lal and Bhaskaran, 1992). Based on inferred surface warming along the Indian coastline at the time of doubling of atmospheric CO_2, it was suggested that an annual mean sea level rise of about 15 to 20 cm was likely along the West Bengal and Bangladesh coast as a result of thermal expansion of sea water. While only a marginal rise of 5 cm in sea level was projected along the Kerala coast, no significant change was suggested along much of the Maharashtra and Gujarat coastline.

The intraseasonal and interannual variability in monsoon rainfall as simulated in CSIRO, UKMO, and ECHAM coupled atmosphere-ocean global climate models (A-O GCMs) was examined in their long time integrations (Chakraborty, 1994; Chakraborty and Lal, 1994; Lal, 1994). The plausible changes in intraseasonal and interannual variability in monsoon rainfall were examined in transient numerical experiments with UKMO and ECHAM A-O GCMs under the *IS92a* radiative forcing scenario of IPCC (Lai *et al.,* 1994b; Bhaskaran *et al.*, 1995). An examination of the frequency distribution of daily monsoon rainfall over India in the model-simulated data suggested that the intensity of extreme rainfall events would be higher in the future as a consequence of increased convective activity during the summer, suggesting thereby the possibility of more frequent flash floods in parts of India, Nepal and Bangladesh (Lal *et al*., 2000).

An extensive intercomparison study on the performance of as many as 17 global climate models in simulating the climatology of the Indian subcontinent for the present-day atmosphere (in equilibrium experiments with atmospheric models coupled to slab ocean models and in transient experiments with fully coupled atmosphere-ocean models) was undertaken in India (Lal *et al.*, 1998a, 1998b). Almost all the models showed higher interseasonal temperature ranges over north-central India compared to observed climatology. However, the UKMO (England), CSIRO (Australia), and CCCma (Canada) global climate models were able to realistically simulate the observed land-to-sea temperature gradient over the Asian monsoon region during the summer. The ECHAM (Germany), UKMO (England), and CCCma (Canada) model simulations demonstrated some skill in simulating the observed monsoon rainfall climatology as well as seasonality in rainfall over India.

The sensitivity of the ECHAM global climate model to horizontal resolution in simulating the observed Indian climatology was also analysed (Lal, 1993; Lal *et al.*, 1997). An in-depth study was conducted to examine the spatial and temporal variability in monsoon rainfall as simulated by A-O GCMs in their long time integrations. The data generated in a high-resolution global climate model simulation were analysed to investigate the appearance, intensification, and movement of synoptic-scale monsoon depressions over the Indian seas. Lal *et al*. (1995b) found no significant change in the number and intensity of monsoon depressions (largely responsible for the observed interannual variability of rainfall in the central plains of India) in the Bay of Bengal in a warmer climate. Considering the need to investigate the response of the monsoon climate to changes in external forcing factors, e.g., greenhouse gases with a view to develop future climate change scenarios, the plausible changes in key climatic elements as simulated in transient numerical experiments with coupled global climate models under the *IS92a* radiative forcing scenario (Houghton et al., 1994) were also estimated (Lal *et al*., 1994a).

The climate change projections for the Indian subcontinent were subsequently updated using the data generated in numerical experiments with combined CO_2 and sulfate aerosol forcings (Lal *et al*., 1995a) and based on an ensemble of results inferred from the four skilled A-O GCMs (Lal and Harasawa, 2001). Three future time periods centered on 2020s (2010-2029), 2050s (2040-2069), and 2080s (2070-2099) were considered for developing scenarios of changes in surface air temperature and precipitation relative to the baseline period of 1961-1990 over the Indian subcontinent. The model simulations with combined greenhouse gas and aerosol forcings suggested that, contrary to earlier modelling results cited above and elsewhere in literature, monsoon rainfall over India was likely to decline in the future.

It may be worthwhile reporting here that an intensification of the Asian summer monsoon and an enhancement of summer monsoon precipitation variability with increased greenhouse gases has been re-confirmed in the IPCC Third Assessment Report (Houghton *et al*., 2001). The effect of sulfate aerosols is to weaken the intensification of the mean precipitation, but the magnitude of the change depends on the size of the forcing. Several studies (Kitoh *et al*., 1997; Lal *et al*., 2000) confirmed earlier results (Kattenberg *et al*., 1996) of an increase in the interannual variability of daily precipitation in the Asian summer monsoon with increased greenhouse gases. The effect of sulfate aerosols on Indian summer monsoon precipitation would be to dampen the strength of the monsoon compared to that seen with greenhouse gases only (Mitchell *et al*., 1995; Lal *et al*., 1995a; Hasselmann *et al*., 1995; Cubasch *et al*., 1996; Roeckner *et al*., 1999). The overall effect of the combined forcing would be at least partly dependent on the land/sea distribution of the aerosol forcing and if the indirect effect were included as well as the direct effect. Table 2 suggests that even though the introduction of aerosol forcing led to a reduced magnitude of surface warming, the projected warming was still considerable and could affect South Asia substantially.

The simulation of present-day climate on regional scales has improved considerably in recent years (Houghton *et al*., 2001), and refinements have been made in coupled global climate models to make them more self-deterministic; *e.g.*, the use of self-determined cloud optical properties to replace the prescribed values (Senior, 1999) or the sensitivities of a coupled system to changes in cloud amount and albedo feedbacks have been explored (Meehl and Washington, 1995). The coupled A-O GCMs are now being used for studies related to the natural variability of the climate system and its response to changes in anthropogenic radiative forcings (Latif, 1998). Also, there has been encouraging progress in simulating the spatial distribution of monsoon rainfall in coupled A-O GCMs on various time scales. In fact, simulation of the Asian monsoon circulation has proved to be a critical test of the ability of A-O GCMs in simulating tropical climate variability (Webster *et al*., 1998).

The IPCC Special Report on Emission Scenarios (SRES) recently proposed a new set of scenarios which covers a wide range of the main demographic, technological, and economic driving forces of future emissions (Nakicenovic *et al*., 1998; Nakicenovic *et al*., 2000). Four 'Marker' scenarios (namely, A1, A2, B1, and B2 scenarios) have been identified, each of which describes a different world evolving through the 21st century and each of which may lead to quite different greenhouse gas emission trajectories. Scenario B1 projects the most conservative future emission of greenhouse gases, and A2 scenario is characteristic of scenarios with higher rates of greenhouse gas emissions in combination with higher sulfur and other aerosol emissions. The A1 scenario family has been further divided into three groups that describe alternative directions of technological change in energy systems. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). The future projections of aerosol loading as envisaged in SRES 'Marker' scenarios are significantly lower compared to the *IS92a* scenario. The

SRES scenarios exclude the effects of climate change and climate policies on society and the economy ('non-intervention'). These new emission scenarios are considered more realistic than the *IS92a* emission scenario used earlier in transient experiments with A-O GCMs. In India, recent efforts have focussed on updates of the earlier projections based on newly performed climate simulations with the radiative forcings given under the SRES 'Marker' scenarios and assessing the impacts of projected climate change scenarios for the Indian subcontinent. The salient findings on the likely changes in monsoon climate and its intraseasonal and interannual variability over the Indian subcontinent as inferred from CCSR/NIES A-O GCM are discussed in the next section. The CCSR/NIES A-O GCM has demonstrated skill in simulating the south to north progression of the monsoons (Lal *et al*., 2001). The model is also able to resolve various scales of summer monsoon circulation and simulate the observed characteristic features of intraseasonal variability over the Indian subcontinent. The simulated periodicities in simulated monsoon rainfall are comparable with observations over the central Indian region.

CLIMATE VARIABILITY AND CHANGE OVER INDIA: UPDATED SCENARIOS

The precise magnitude of future changes in the mean and/or variance of climatological parameters on regional scales due to anthropogenic increases in greenhouse gases is required to evaluate the vulnerability of the region to such changes. We present here the changes in monsoon climate and its intraseasonal and interannual variability over the Indian subcontinent as inferred from CCSR/NIES A-O GCM simulation experiments. The key elements examined here are surface air temperature and precipitation. Some additional elements are also considered, depending upon their importance in specific aspects of variability and change.

(a) Annual and seasonal changes in temperature and rainfall

Three future time periods centered on 2020s (2010-2029), 2050s (2040-2069), and 2080s (2070-2099) were considered for developing scenarios of changes in surface air temperature and precipitation relative to the baseline period of 1961-1990 over the Indian subcontinent. The analysis of data simulated in CCSR/NIES A-O GCM suggests that the area-averaged annual mean surface temperature rise over land regions of the Indian subcontinent by the end of 21st century is projected to be least in the B1 scenario and maximum in the A2 scenario and will range between 3.5^o and 5.5^{o}C (Lal *et al*., 2001). During winter, the area-averaged surface temperature increase over India by 2080s would be at least 4^{o}C, while during the monsoon it may range between 3.0^o and 4.5^{o}C (Table 2). The projected surface warming is more pronounced in the winter than in the monsoon season for each of the four emission scenarios (Fig. 4). The warming in the monsoon season may produce an increase in water vapor and cloud water content, which should enhance the reflectivity of the clouds (a negative feedback) but also contribute to an increase in the longwave emissivity of cloud (a positive feedback especially for the high cloud).

The spatial distribution of annual mean surface warming over the Indian subcontinent by the 2050s as a consequence of increase in anthropogenic radiative forcings (with respect to 1961-1990) as simulated by CCSR/NIES A-O GCM suggests that north India may experience an annual mean surface warming of 3°C or more, depending upon the future trajectory of anthropogenic forcings (Fig. 5). The spatial pattern of temperature change has a large seasonal dependency. The model simulates peak warming of about 3°C over north and central India in winter (Fig. 6). Over much of the southern peninsula, the warming is under 2°C during the winter season. In the monsoon season, the temperature rise over south India is less than 1.5°C (Fig. 7). The increase in surface temperature is more pronounced over north and east India (~2°C) in the monsoon season.

Table 2: Climate change projections* for Indian subcontinent under the four SRES Marker emission scenarios

Time ↓		**Temperature Change** (°C)				**Rainfall Change** (%)			
	Scenarios →	A1	A2	B1	B2	A1	A2	B1	B2
2020s	Annual	1.18	1.00	1.32	1.41	2.29	2.16	4.15	5.97
	Winter	1.19	1.08	1.37	1.54	0.39	-1.95	4.36	3.64
	Monsoon	1.04	0.87	1.12	1.17	1.81	2.37	3.83	5.10
2050s	Annual	2.87	2.63	2.23	2.73	9.34	5.36	6.86	7.18
	Winter	3.18	2.83	2.54	3.00	3.22	-9.22	3.82	3.29
	Monsoon	2.37	2.23	1.81	2.25	10.52	7.18	7.20	8.03
2080s	Annual	5.09	5.55	3.53	4.16	9.90	9.07	7.48	7.62
	Winter	5.88	6.31	4.14	4.78	-19.97	-24.83	-4.50	-10.36
	Monsoon	4.23	4.62	2.91	3.47	14.96	15.18	11.12	10.10

*Based on CCSR/NIES Model Experiments; Area-averaged for land regions only

An increase of about 7 to 10% in area-averaged annual mean precipitation is simulated in the CCSR/NIES A-O GCM over the Indian subcontinent by the 2080s (Table 2). A decline of between 5 and 25% in area-averaged winter precipitation is projected (Fig. 8). In the monsoon season, an increase in area-averaged summer precipitation of only about 10 to 15% over the land regions is likely. The larger increase in surface temperature over land results in the intensification of heat over north India and an increased land-sea pressure gradient, which should strengthen the summer monsoon flow. The enhanced moisture convergence associated with stronger monsoon flow over the region in a warmer atmosphere could result in increased summer monsoon precipitation.

Contrary to previous projections, the new simulation experiments suggest an appreciable change in the spatial pattern of winter as well as summer monsoon precipitation over land regions of the Indian subcontinent. This could be attributed to the inclusion of more realistic estimates of regional aerosol concentrations as well as the indirect radiative forcing due to aerosols. A decrease of between 10 and 20% in winter precipitation over most parts of central India is simulated for the 2050s (Fig. 9). In the monsoon season, the results suggest an increase of up to 30% in seasonal mean precipitation over northwest India by the 2050s (Fig. 10). The western semi-arid margins of the Indian subcontinent could receive higher than normal rainfall in a warmer atmosphere.

Table 3: All India Annual Mean Climate Change in the 21st Century
(as simulated by the state-of-the-art Global Climate Models)

Models → Scenarios ↓	CCCma CGCM2	CSIRO mk2	CSM1.3	ECHAM4	GFDL R15b	MRI	CCSR-NIES	DOE-PCM	HadCM3
Temperature (°C)									
DJF – A2	3.68	4.02	3.06	3.96	3.65	1.82	6.37	3.33	4.52
JJAS – A2	2.74	2.69	1.67	2.41	2.52	0.79	4.58	1.69	3.01
DJF – B2	2.74	3.28	2.20	2.87	2.30	1.50	4.84	2.49	3.33
JJAS – B2	1.56	2.23	1.34	1.68	1.91	0.71	3.41	1.12	2.06
Precipitation (%)									
DJF – A2	1.24	0.71	-5.08	2.67	13.91	1.78	-28.93	-8.46	14.67
JJAS – A2	23.40	19.43	23.12	32.76	6.64	10.54	15.76	14.18	19.46
DJF – B2	0.52	-0.89	-0.03	5.11	-6.24	-3.72	-14.60	-4.83	7.63
JJAS – B2	17.12	13.54	12.94	26.54	5.68	4.16	10.48	11.20	14.38

Data Processing: The original data took the form of a value for each box on a 0.5 degree latitude / longitude grid. The weighted mean of the values from its constituent grid boxes of aggregated changes for India (land region only) was calculated for two seasons (DJF and JJAS). Each grid box was weighted by surface area, using the cosine of the latitude. The data are from nine state-of-the-art A-O GCMs and values are for the changes between 1961-90 and 2070-99 (30-year mean). Two SRES Marker scenarios of anthropogenic emissions of greenhouse gases and sulfur dioxide (A2 and B2) were considered.

The climate change scenarios for the Indian subcontinent on seasonal mean basis based on the analysis performed with data generated in numerical experiments with as many as nine A-O GCMs under two 'Marker' emission scenarios (A2 and B2) have also been developed, and these scenarios are presented here in Table 3. It is clearly evident from Table 3 above that the *inter-model differences are significantly large and more so for the projections of precipitation change, suggesting rather low confidence in the future projections of regional precipitation*. It may, however, be noted that the skill of the CCSR/NIES A-O GCM in simulating the past and present climatological characteristics of the Indian subcontinent has been extensively validated (Lal *et al*., 2001). Moreover, only the CCSR/NIES A-O GCM has considered four aerosol species, namely, sulfate, carbon, dust, and sea salt. While dust and sea salt aerosols are supplied as climatology with seasonal variations, the carbonaceous and sulfate aerosols follow the SRES 'Marker' scenarios. The aerosol scattering is explicitly represented to account for their direct effects. The indirect effects of aerosol on the effective radius of cloud droplets and on precipitation efficiency are treated through a relationship between cloud droplet and aerosol number concentrations. Hence, a reasonable degree of confidence can be placed on the future projections inferred from the CCSR/NIES A-O GCM for broader scale impact assessments.

(b) <u>Intraseasonal and interannual variability in monsoon rainfall</u>

The interannual fluctuations in summer monsoon rainfall over India are sufficiently large to cause devastating floods or serious drought. Also, there are fluctuations between active spells with well-distributed monsoon rainfall and weak spells or breaks with hardly any large-scale rainfall on a time scale of one to two weeks. The major difference between strong and weak monsoon seasons is in the duration and intensity of the dry spells, suggesting that interannual variation between good and poor monsoons is a manifestation of the variation in duration and intensity of active spells of rainfall.

Likely changes in intraseasonal and interannual variability in summer monsoon activity over the central plains of India have been explored over the Indian subcontinent in response to changes in anthropogenic forcings in each of the four SRES 'Marker' scenarios. The standard deviation of future projections of area-averaged monsoon rainfall centered on the 2050s is not found to be significantly different in each of the four scenarios relative to that simulated for the present-day atmosphere. This implies that the year to year variability in central India rainfall during the monsoon season may not change significantly in the future. More intense rainfall spells are, however, simulated over the land regions under all four scenarios (relative to that simulated for the present-day atmosphere), thus increasing the probability of extreme rainfall events and hence flash floods in parts of India in a warmer atmosphere.

There are no appreciable shifts in rainfall maxima during July-August (located at about 20^{o}N) in the temporal variation of simulated monthly mean precipitation over the Indian subcontinent in any of the four 'Marker' scenarios. The northward advancement of monsoon rains over India with the progression of the season therefore seems quite robust. A detailed analysis of the daily rainfall data suggests that, under the A1 and A2 scenarios, while the model still simulates the first spell of intense rainfall appearing over south India (10^{o}N) during the first week of June on an average, the spread of simulated onset date at 10^{o}N extends from 24 May to 11 June during the 30 year period centered on the 2050s compared to between 29 May and 8 June of the present-day atmosphere. This implies the possibility of enhanced variability in the date of onset of summer monsoon over central India in a warmer atmosphere.

To ascertain the dominant time scales of monsoon circulation in the model and to examine the likelihood of changes in frequency of monsoon depressions in a warmer atmosphere, which could contribute to enhanced precipitation over the Indo-Gangetic plains, spectral energy computations have been performed on the detrended time series of simulated daily rainfall for each of the 30 consecutive years of the four SRES forcing simulations. For central India, the simulated daily rainfall exhibits statistically significant spectral peaks at periodicities not substantially different from those in simulated and observed present-day rainfall (Lal *et al*., 2001). This suggests that no appreciable changes are likely in the number of monsoon depressions moving across the central plains of India in a warmer atmosphere.

(c) Extreme weather events, including tropical cyclones

A warmer surface air temperature should increase the probability of extreme warm days and decrease the probability of extreme cold days. This result has appeared consistently in a number of recent different climate model configurations (Dai *et al*., 2001; Yonetani and Gordon, 2000). There is a possibility of a decrease in diurnal temperature range (DTR) since the night-time temperature minima warm faster than the day-time maxima in many locations (*e.g*., Lal *et al*., 1996; Zwiers and Kharin, 1998). Some of these changes in DTR also have been observed over a number of locations in India (Karl *et al*., 1991; Kumar *et al*., 1994). An additional effect is that increased temperature variance adds to the probability of extreme high temperature events over and above simply what could be expected from increases in the mean alone. In general, the pattern of change in return values for 20-year extreme temperature events from an equilibrium simulation for doubled CO_2 with a global atmospheric model coupled to a non-dynamic slab ocean showed larger increases over the Indian subcontinent. These findings from a slab ocean configuration without ocean currents were confirmed in a subsequent study with the fully coupled ocean version of the global climate model (Kharin and Zwiers, 2000). An increase in the 20-year return values of daily maximum temperature is possible over central India, where there is a possibility of decrease in soil moisture content. Large extreme temperature increases are also likely over the drier regions of India.

The ENSO is associated with some of the most pronounced year-to-year variability in climate features in many parts of Asia. Since 1995, several global climate models indicate that as global temperatures increase due to increasing greenhouse gases, the Pacific climate will tend to more resemble an El Niño-like state (Meehl and Washington, 1996; Knutson and Manabe, 1998; Mitchell *et al*., 1995; Timmermann *et al*., 1999; Boer *et al*., 1999). Collins (1999) finds an increased frequency of ENSO events and a shift in their seasonal cycle in a warmer atmosphere, so that the maximum occurs between August and October rather than around January as currently observed. Meehl and Washington (1996) suggest that future seasonal precipitation extremes associated with a given ENSO event are likely to be more intense in the tropical Indian Ocean region; anomalously wet areas could become wetter and anomalously dry areas could become drier during future ENSO events. In India, drought disasters are reported to be more frequent during years following ENSO warm events than in normal years. At least half of the severe failures (note that during 1998 El Niño, the Indian monsoon was reported to be normal) of the Indian summer monsoon since 1871 have occurred during El Niño years (Webster *et al*., 1998). The enhanced anomalous warming of the eastern equatorial Pacific Ocean in the future and associated change in Indian summer monsoon variability have implications for increasing the likelihood of drought and flood during the monsoon season.

A number of studies have considered likely changes in tropical cyclones (Lighthill *et al*., 1994; Knutson *et al*., 1998; Henderson-Sellers *et al*., 1998; Royer *et al*., 1998; Krishnamurti *et al*., 1998). Some suggest an increase in tropical storm intensities with CO_2-induced warming, though there is no conclusive evidence to suggest that cyclone frequencies or their preferred locations may change in the future. An increase in sea surface temperature will be accompanied by a corresponding increase in cyclone intensity. The relationship between cyclone intensity (maximum sustained wind speed) and sea surface temperature is well discussed in literature (Emanuel, 1987; 1999). A possible increase in cyclone intensity of 10-20% for a rise in sea surface temperature of 2 to 4^{o}C relative to the threshold temperature of 28^{o}C is very likely in Indian seas. Thus, while there is no evidence that tropical cyclone frequency may change, the available data strongly suggest that an increase in its intensity is most probable.

Storm surges are generated by the winds and the atmospheric pressure changes associated with cyclones. At low latitude, land-locked locations such as the Bay of Bengal, tropical cyclones are the major cause of storm surges. Any increase in sea surface temperature is likely to cause greater convective activity, leading to an increase in wind speed. The stress exerted on water by wind is proportional to the square of the wind velocity. Amplification in storm surge heights should result from the occurrence of stronger winds and low pressures associated with tropical storms. Thus, an increase in sea surface temperature due to climate change should lead to higher storm surges and an enhanced risk of coastal disasters along the east coast of India. There is a need for much more work in this area to provide robust results. Because of the difficulties of spatial resolution in A-O GCMs, there is virtually no information available at present to indicate possible future changes of thunderstorms and tornadoes.

(d) Uncertainties in regional climate projections

There are several levels of uncertainty in the generation of regional climate change information. The first level is associated with emission scenarios of greenhouse gases and aerosols that are strongly related to the socioeconomics of the countries in the region and could be strongly dependent on development pathways followed by individual nations. The conversion of emissions of greenhouse gases and aerosols into resulting concentrations with which global climate models are forced introduces additional uncertainty. The second level of uncertainty is related to the simulation of the transient climate response by coupled A-O GCMs for a given emission scenario.

On the modeling aspects, uncertainties are associated with imperfect knowledge and/or representation of physical processes, limitations due to the numerical approximation of the model's equations, simplifications and assumptions in the models and/or approaches, internal model variability, and inter-model or inter-method differences in the simulation of climate response to given forcing. The minimum scale at which climate change information can be reliable, which is determined by the model resolution, is still about several hundred kilometers. By definition, coupled A-O GCMs cannot provide direct information at scales smaller than their resolution; neither can they capture the effect of forcing acting at sub-grid scales. Second, past analyses have indicated that even at their smallest resolvable scales, which still fall under our definition of regional scale, coupled A-O GCMs have substantial problems in reproducing present-day climate characteristics. It is also important to point out that regional climate observations are also sometimes characterized by a high level of uncertainty, especially in regions characterized by complex topographical features.

Finally, the natural variability of the climate system adds a further level of uncertainty in the evaluation of a climate change simulation. In view of these constraints, the climate change scenarios presented here should not be viewed as a prediction but only as a plausible projection for broader scale impact assessments. To increase our skill in simulating the monsoon rainfall and its intra-seasonal variability over the Indian subcontinent, it is of foremost importance that we improve our understanding of the basic differences in parameterization techniques of physical processes adopted in the A-O GCMs and their effects on the simulation of regional precipitation. A model's sensitivity to the treatment of the interaction between monsoon clouds and radiative processes appears to be a key factor.

The degree of confidence that could be placed on the regional climate projections in terms of temporal and spatial changes would depend on the simulation skill of the space and time evolution of large scale monsoon circulation features in A-O GCMs. There are significant gaps in the available database in remote mountainous regions of the globe, as a result of which many basic questions concerning the altitudinal variation of water balance components and energy budget components, for example, cannot be properly validated in global climate models. Such questions are of great importance if climate model results are to be interpreted properly within areas of complex terrain, *e.g.*, the Himalayan region, where knowledge of climate-hydrology-ecology interrelations deserves priority attention.

Current efforts on climate variability and climate change studies increasingly rely upon diurnal, seasonal, latitudinal, and vertical patterns of temperature trends to provide evidence for anthropogenic signatures. Such approaches require increasingly detailed understanding of the spatial variability of all forcing mechanisms and their connections to global, hemispheric, and regional responses. Since the anthropogenic aerosol burden in the troposphere would have large spatial and temporal variations in the atmosphere, its future impact on regional scale would be in striking contrast to impacts from anthropogenic greenhouse gases. Considerable uncertainty still prevails about the indirect effect of aerosols on tropospheric clouds, which could strongly modulate the climate. We are still unclear about the implications of localized radiative forcing on deep convection in tropical Asia and on Hadley circulation (Lal *et al.*, 2000). It has also been suggested that aerosols produced by tropical biomass burning could lead to additional negative radiative forcing. The radiative forcing due to tropospheric ozone increases as a consequence of biomass burning has been found to be of same magnitude but opposite in sign to that due to the direct effect of biomass burning aerosols (Portmann *et al*., 1997). However, the geographical extent of increases in tropospheric ozone is considerably larger than that of aerosols. The precise magnitude as well as the role of these spatially localized potential forcings must be known before a confident prediction of regional changes in monsoon climate and its variability can be made.

HIGH RESOLUTION CLIMATE CHANGE SCENARIOS – ONGOING STUDIES

Regional climate is often influenced by forcings and circulations that occur at smaller scales (*e.g.*, Giorgi and Mearns, 1991; 1999). As a result, A-O GCMs cannot explicitly capture the fine-scale structure that characterizes climatic variables in many regions of the world and that is needed for impact assessment studies. Recent nested regional climate modeling (RCM) efforts account for sub-GCM grid scale forcings (*e.g.*, complex topographical features and land cover inhomogeneity) in a physically based manner and provide high resolution information on regional climate change. In India, research has shown that the simulation of the spatial patterns of precipitation and temperature over complex terrain such as those around western Ghats and the Himalayas is generally improved with the increasing resolution obtained with this technique (Lal *et al*., 1998c). The increased spatial resolution in RCMs allows realistic simulations of synoptic systems such as monsoon depressions, western disturbances, mesoscale convective systems, and extreme weather systems (*e.g*., tropical storms). The RCM simulations can also be more effectively used to infer daily precipitation frequency and intensity distributions, surface wind speed variability, storm inter-arrival times, and monsoon onset and breaks.

Two 20 year long climate simulations with a limited-area RCM nested into an A-O GCM were recently performed, one for the present-day climate (1971-1990 period) conditions (for comparing the results with observed climatologies) and the other for the period 2041-2060 assuming a 1% compound increase of CO_2. Both the driving AGCM and RCM had identical dynamical and physical processes in that they were part of the United Kingdom Meteorological Office Unified Model (UM). The atmospheric component of the UM was configured as a regional climate model for long-term high resolution simulation experiments over the Indian subcontinent such that the RCM differed from the driving AGCM only in horizontal resolution and hence the time step of integration. Before performing long-term integrations, a series of numerical experiments were carried out to decide the optimum domain size over the Indian subcontinent. The RCM was carefully validated against observations of historical climate (using boundary conditions from analyses of observations for given historical periods) before proceeding to the nesting within the GCM. An assessment of biases induced by the GCM forcing fields and the added value of the nested RCM was also carried out to evaluate the level of realism of the driving GCM and nested RCM change signals.

Analysis of the model-generated data suggested that both the range of annual cycle of area-averaged surface temperature over the Indian subcontinent and the spatial distribution of seasonal surface temperatures were more realistically simulated in the RCM than in the driving GCM (Lal *et al*., 1998c). The same was also true for the surface and upper air winds over the region. This is largely attributed to the fact that the RCM was able to better resolve the mesoscale and synoptic scale forcings that have a strong influence on local climate. The unrealistic near-surface temperatures over the Himalayas simulated in the GCM were better resolved in the RCM. The spatial patterns of monsoon rainfall produced by the RCM were also in better agreement with those of observations compared to those of the GCM. There was also some evidence that the RCM reproduced better precipitation extremes. The RCM produced the steep gradient in monsoon rainfall from west coast towards the east (a rain shadow effect in the lee of the western Ghats) more realistically (Fig. 11). The striking observed variations in monsoon rainfall in the hilly and mountain ranges of northeast India were also reproduced by the

RCM. While the GCM failed to capture the interannual variability in the low frequency intraseasonal oscillations, these were simulated reasonably well in the RCM, suggesting thereby that the interannual variability of monsoon associated with regional dynamics can be better simulated in models with higher horizontal resolution. While the large-scale patterns of surface characteristics in the nested and driving simulated climate changes were found to be similar, the mesoscale details of the simulated changes were significantly different.

Attempts have been made to generate climate change scenarios at local scales using the data from climate change experiments following rigorous mathematical/statistical procedures. Some of the key characteristics of monsoon rainfall at selected stations over India as simulated by the RCM nested in the GCM for the present-day atmosphere (1990s) and for the middle of 21st century (2050s) due to changes in anthropogenic radiative forcing are discussed here. For Bangalore (south India), a marginal decline in total rainfall during monsoon is simulated for 2050s relative to present-day conditions, with fewer wet days during the season and a decline in rainfall intensity and reduced contribution of upper 10% quantile of daily rainfall to the total seasonal rainfall as inferred from the trends obtained in an analysis of 20 year mean data (Fig. 12a). Over Delhi (north India), the results suggest a reduction in total monsoon rainfall with fewer wet days during the season, a marginal decline in rainfall intensity, and an increased contribution of the upper 10% quantile of daily rainfall to the total seasonal rainfall (Fig. 12b). For the Jorhat (northeast India), an increase in total monsoon rainfall but fewer wet days during the season and higher rainfall intensity with an increased contribution of the upper 10% quantile of daily rainfall to the total seasonal rainfall is simulated (Fig. 12c). The model simulates an increase in total monsoon rainfall with more wet days during the season and more intense daily rainfall but a lesser contribution of the upper 10% quantile of daily rainfall to the total seasonal rainfall over Srinagar in the Himalayan region (Fig. 12d). For Udaipur (northwest India), a decrease in total monsoon rainfall but fewer wet days during the season and more intense daily rainfall with a higher contribution of the upper 10% quantile of daily rainfall to the total seasonal rainfall is simulated (Fig. 12e). Additional data analyses for climate change scenario development at the station level, aimed at providing advice on the range of possible climate change impacts for possible adaptive options, are currently in progress.

ADVANCING OUR UNDERSTANDING ON CLIMATE CHANGE

The climate change scenarios presented here should not be viewed as a *prediction* but only as a *plausible projection*. To increase our skill in simulating the monsoon rainfall and its intra-seasonal variability over the Indian subcontinent, it is of foremost importance that we improve our understanding of the basic differences in parameterization techniques of the physical processes adopted in the climate models and their effects on the simulation of regional precipitation. The model's sensitivity to the treatment of interactions between aerosols, monsoon clouds, and radiative processes appears to be a key factor for accurate prediction of monsoon climate.

Reducing the wide range of uncertainty inherent in model projections of global and regional climate change will require major advances in our scientific understanding on the subject in the years to come. A number of fundamental scientific questions relate to the buildup of greenhouse gases in the atmosphere and the behaviour of the climate system. The key issues that need to be addressed include (a) *the future usage of fossil fuels*, (b) *the future emissions of methane*, (c) *the fraction of the future fossil-fuel carbon that will remain in the atmosphere and provide radiative forcing versus exchange with the oceans or net exchange with the land biosphere*, (d) *details of the regional and local climate change given an overall level of global climate change*, (e) *the nature and causes of the natural variability of climate and its interactions with forced changes*, and (f) *the direct and indirect effects of the changing distributions of aerosols*. An effective strategy for advancing the understanding of adverse impacts of climate change in India will require strengthening the academic and research institutions to make an all-out effort to conduct innovative research at the regional or sectoral level that also promotes analysis of the response of human and natural systems to multiple stresses. Research enterprises dealing with climate change and the interactions of human society with the environment must also be enhanced.

Climate is not static and assumptions made about the future based on the climate of the past may be inappropriate. Assumptions about the probability, frequency, and severity of extreme events should be carefully re-evaluated. Climate changes will be imposed on top of current and future non-climate stresses. Certain threshold events may become more probable and non-linear changes and surprises should be anticipated, even if they cannot be predicted with a high degree of confidence. The time lags between identifying the nature of the problems, understanding them, prescribing remedies, and implementing them are long. Waiting for relative certainty about the nature of climate change before taking actions to reduce climate change related risks might prove far more costly. There is also a need for a major coordinated research effort focusing on the science and technology that underpin adaptation strategies related to climate change.

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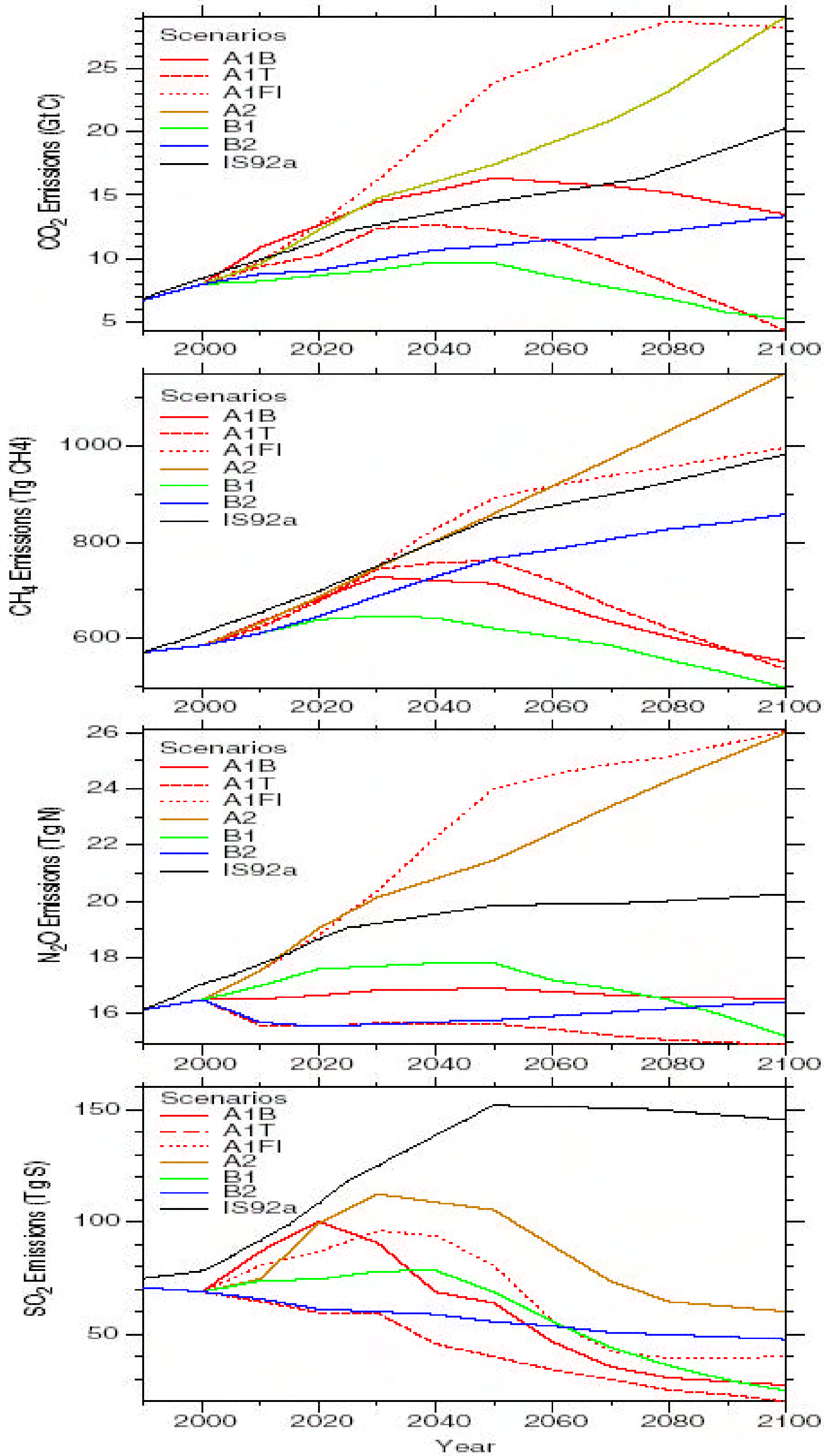

Fig. 1: A comparison of trend in emissions of greenhouse gases and sulfur dioxide under the four SRES Marker scenarios with those under IS92a scenario in the 21st Century

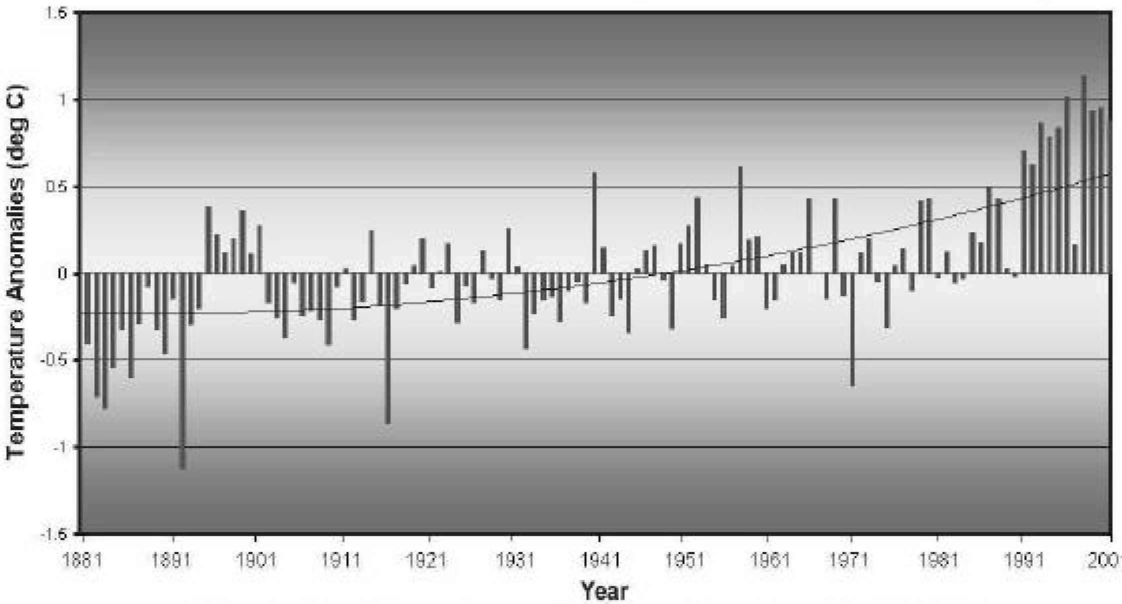

Fig. 2: All India Mean Surface Air Temperature Anomaly (1881-2001)

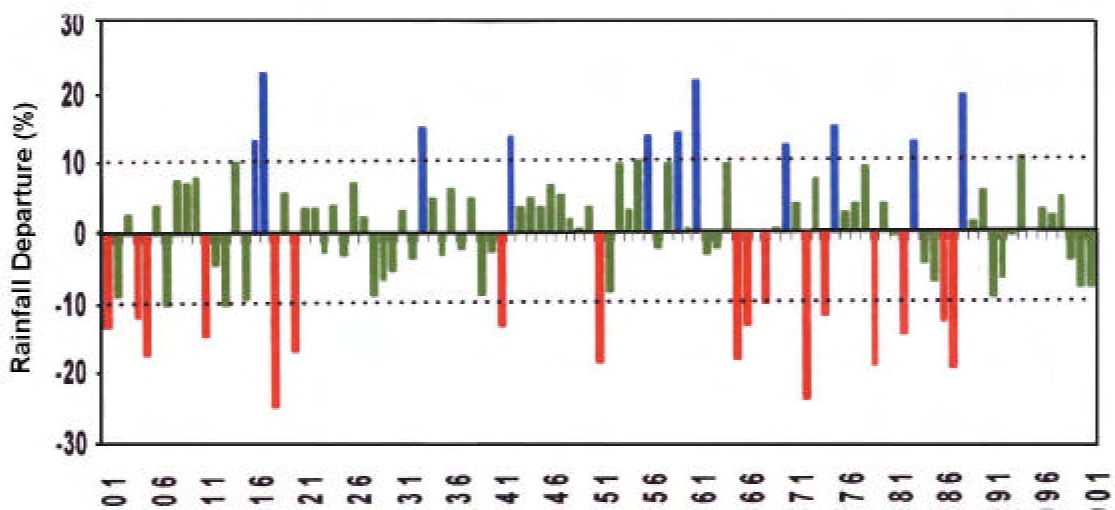

Fig. 3: All India Monsoon Rainfall (1901-2001)

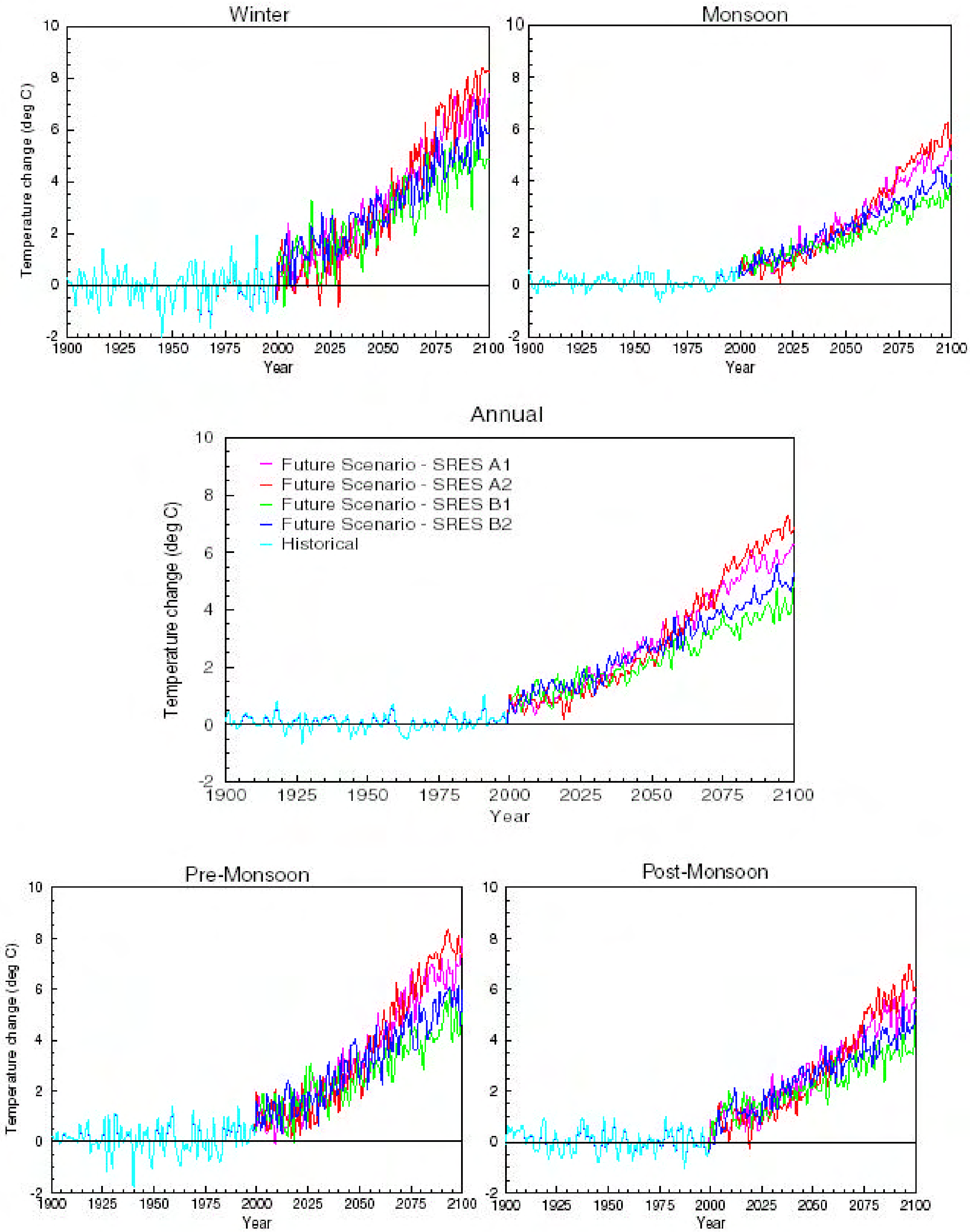

Fig. 4: Trends in area-averaged (land points only) annual and seasonal mean surface air temperature change (deg C) for the past century under observed radiative forcing and for the 21st century under the four SRES Marker emission scenarios as simulated by the CCSR/NIES A-O GCM over the Indian subcontinent

Annual mean surface air temperature change (deg C)

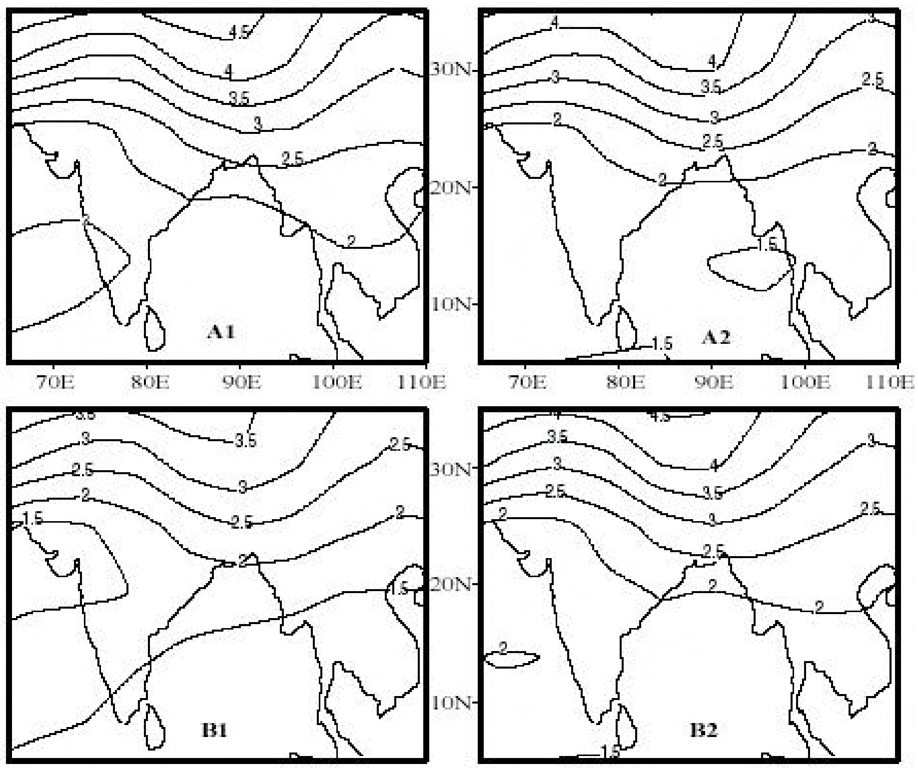

Fig. 5: Spatial distribution of annual mean surface air temperature change (deg C) over Indian subcontinent in 2050s with respect to present-day under the four SRES emission scenarios

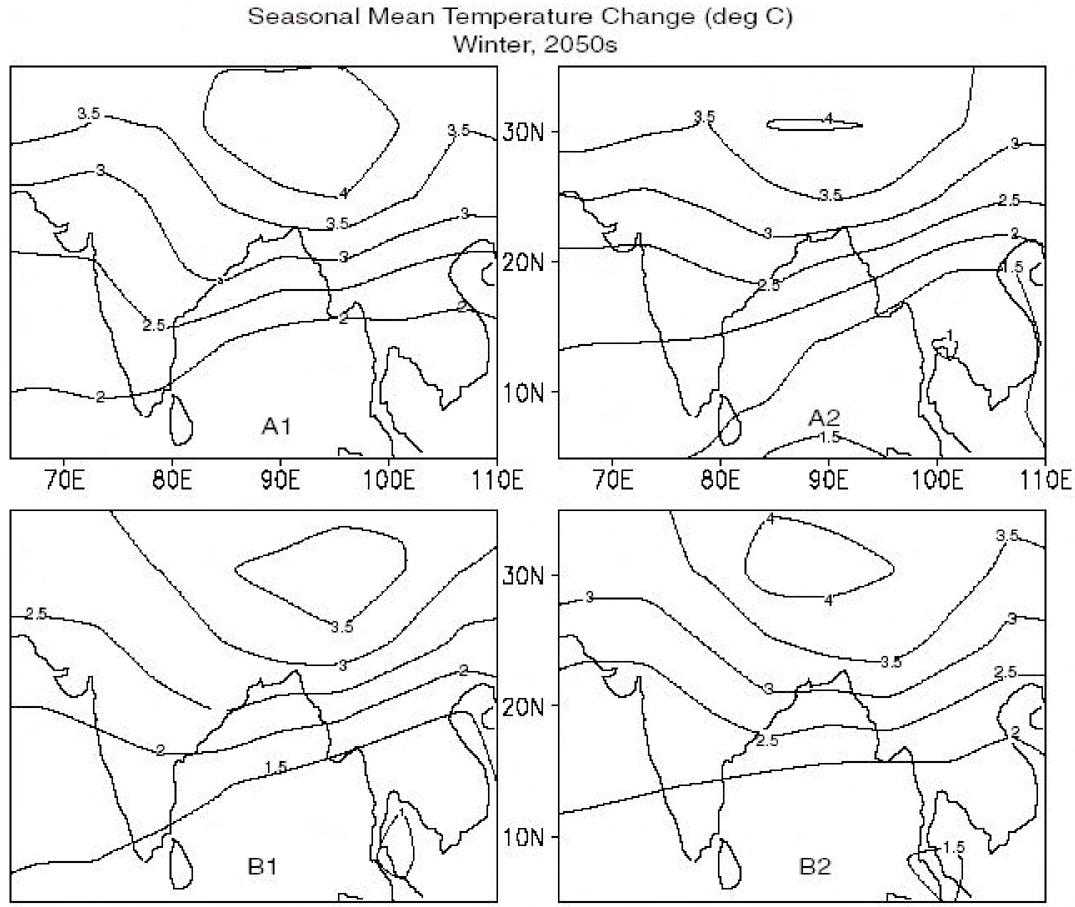

Fig. 6: Spatial distribution of surface air temperature change (deg C) during winter over the Indian subcontinent in 2050s with respect to present-day under the four SRES emission scenarios

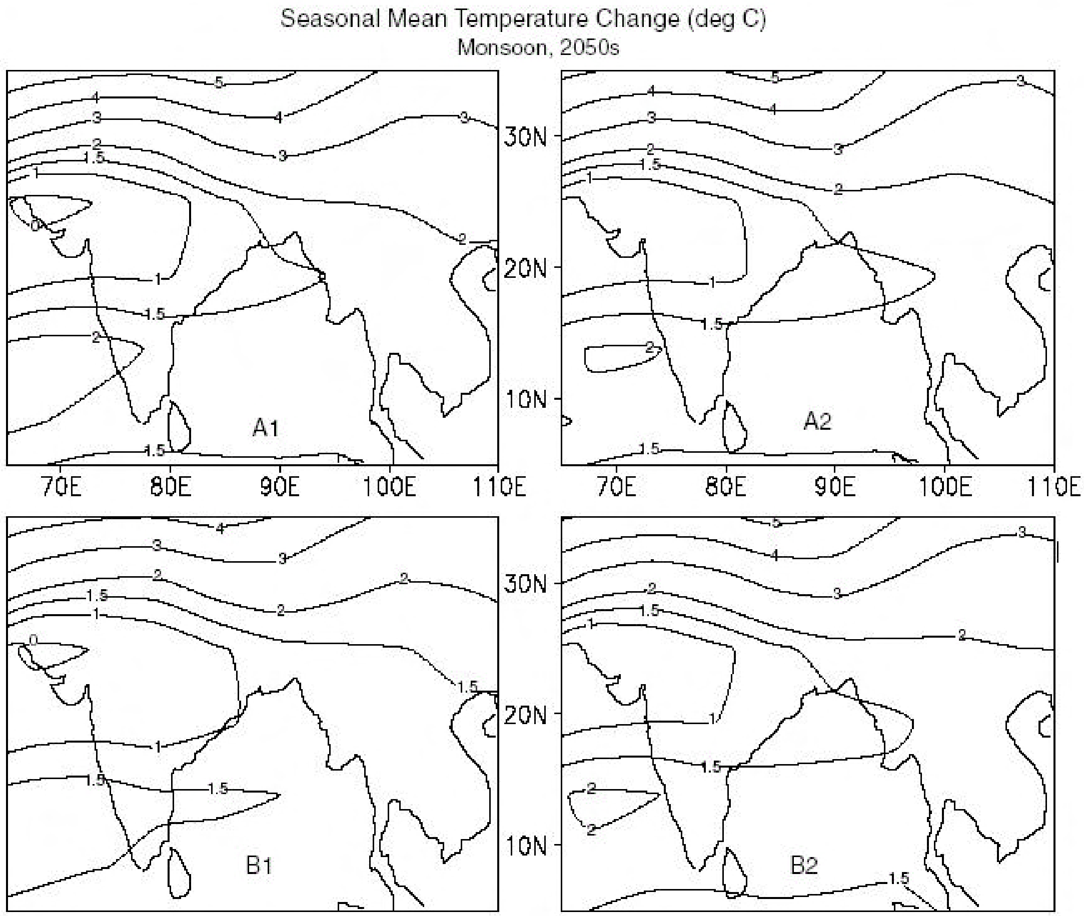

Fig. 7: Spatial distribution of surface air temperature change (deg C) during monsoon over the Indian subcontinent in 2050s with respect to present-day under the four SRES emission scenarios

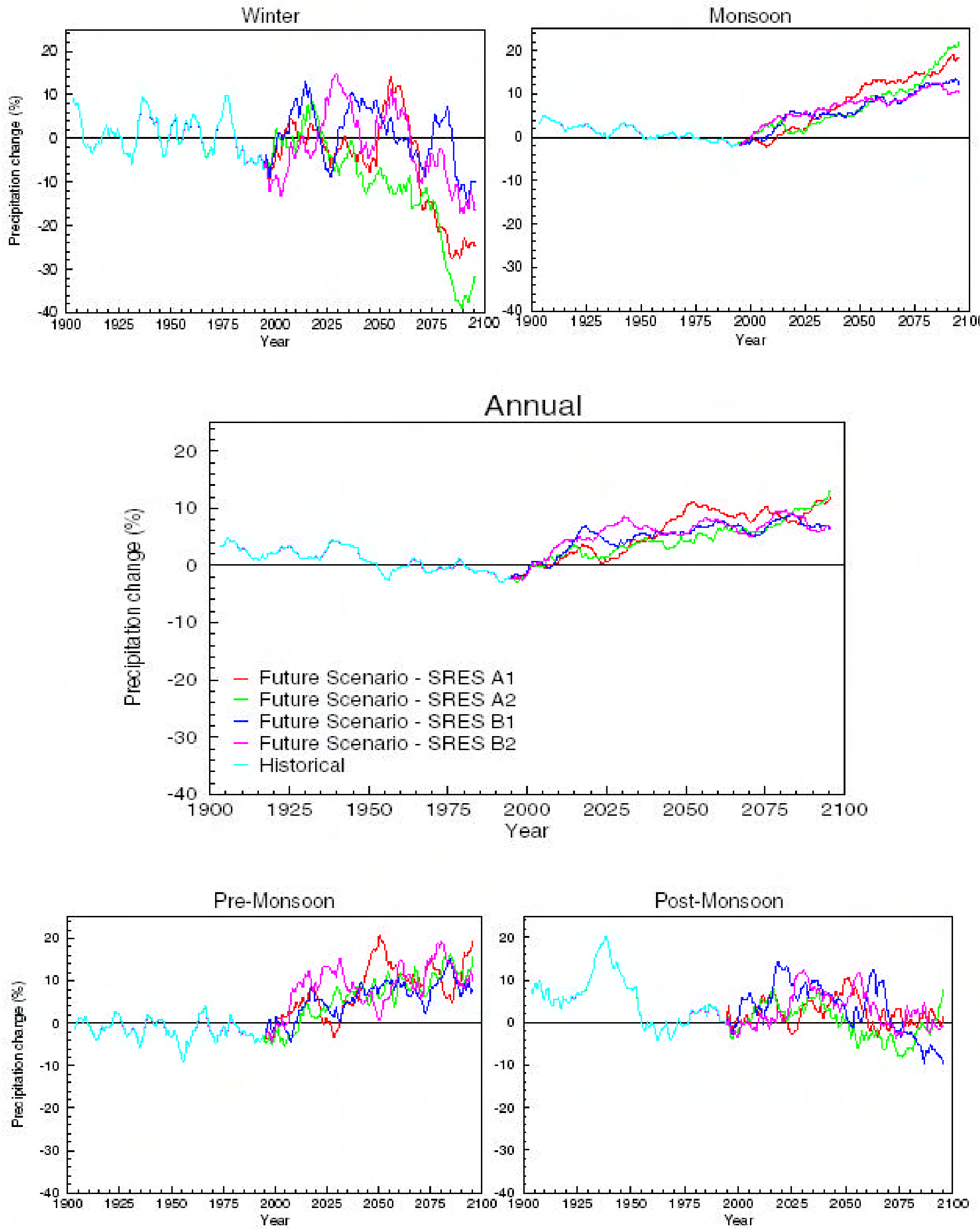

Fig. 8: Trends in area-averaged (land points only) annual and seasonal mean rainfall change (in percent) for the past century under observed radiative forcing and for the 21st century under the four SRES Marker emission scenarios as simulated by the CCSR/NIES A-O GCM over the Indian subcontinent

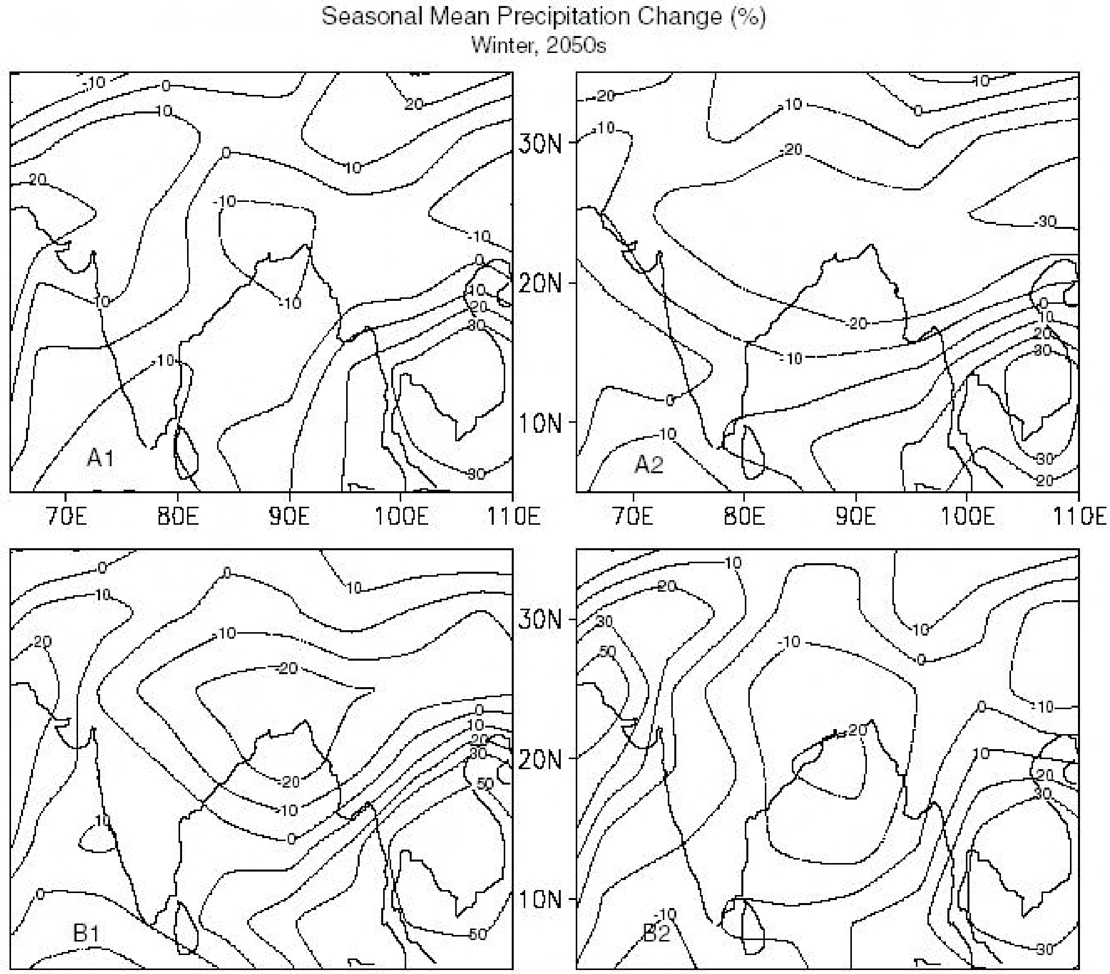

Fig. 9: Spatial distribution of precipitation change during winter over Indian subcontinent in 2050s with respect to present-day under the four SRES emission scenarios

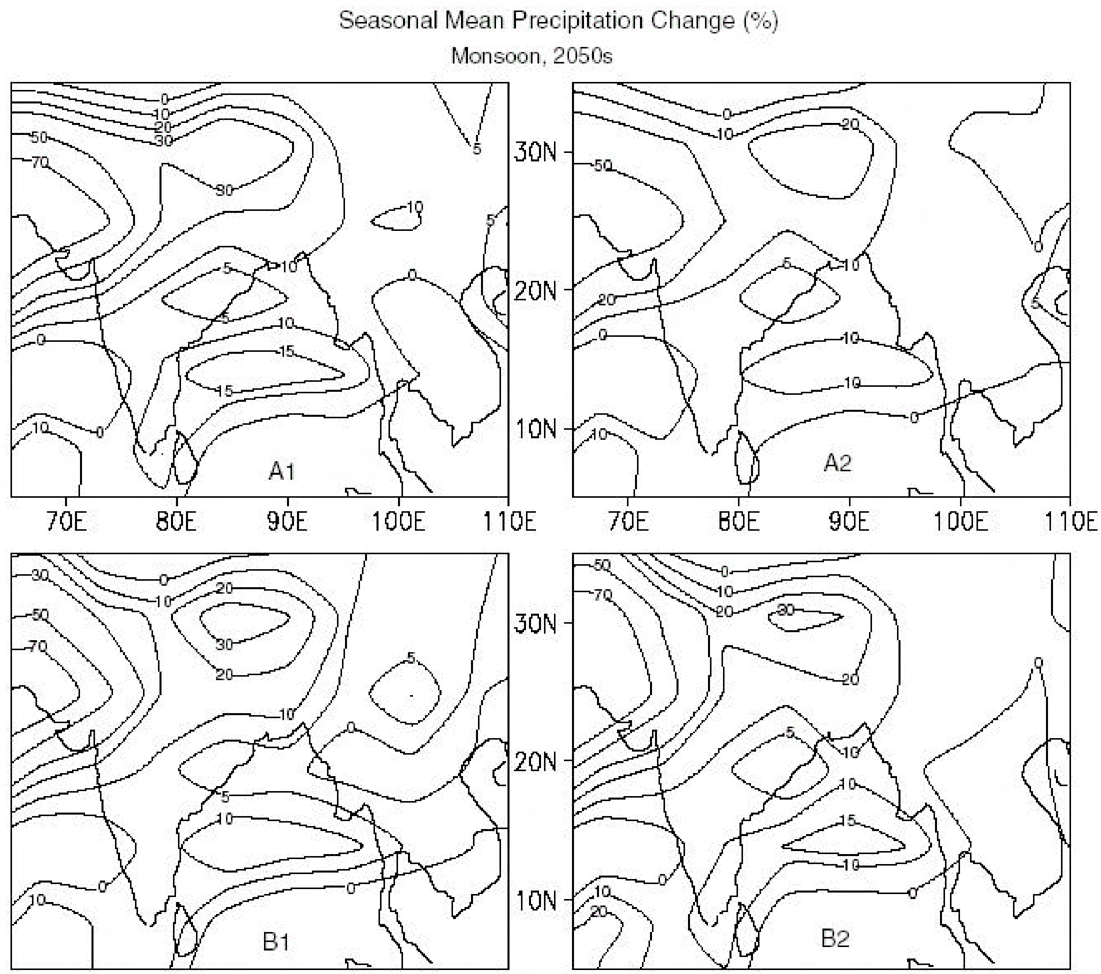

Fig. 10: Spatial distribution of precipitation change during monsoon season over Indian subcontinent in 2050s with respect to present-day under the four SRES emission scenarios

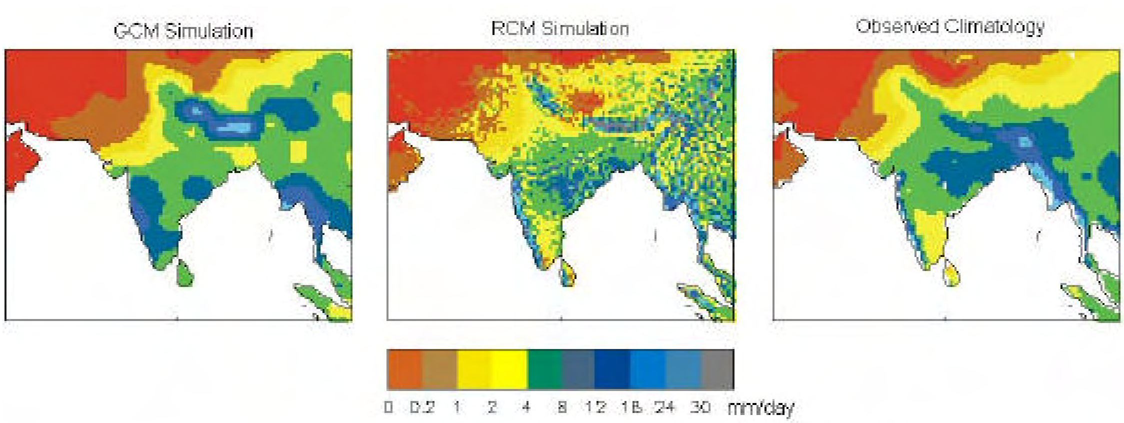

Fig. 11: A comparison of observed spatial distribution of monsoon rainfall over Indian subcontinent with those simulated by GCM and RCM

BANGALORE

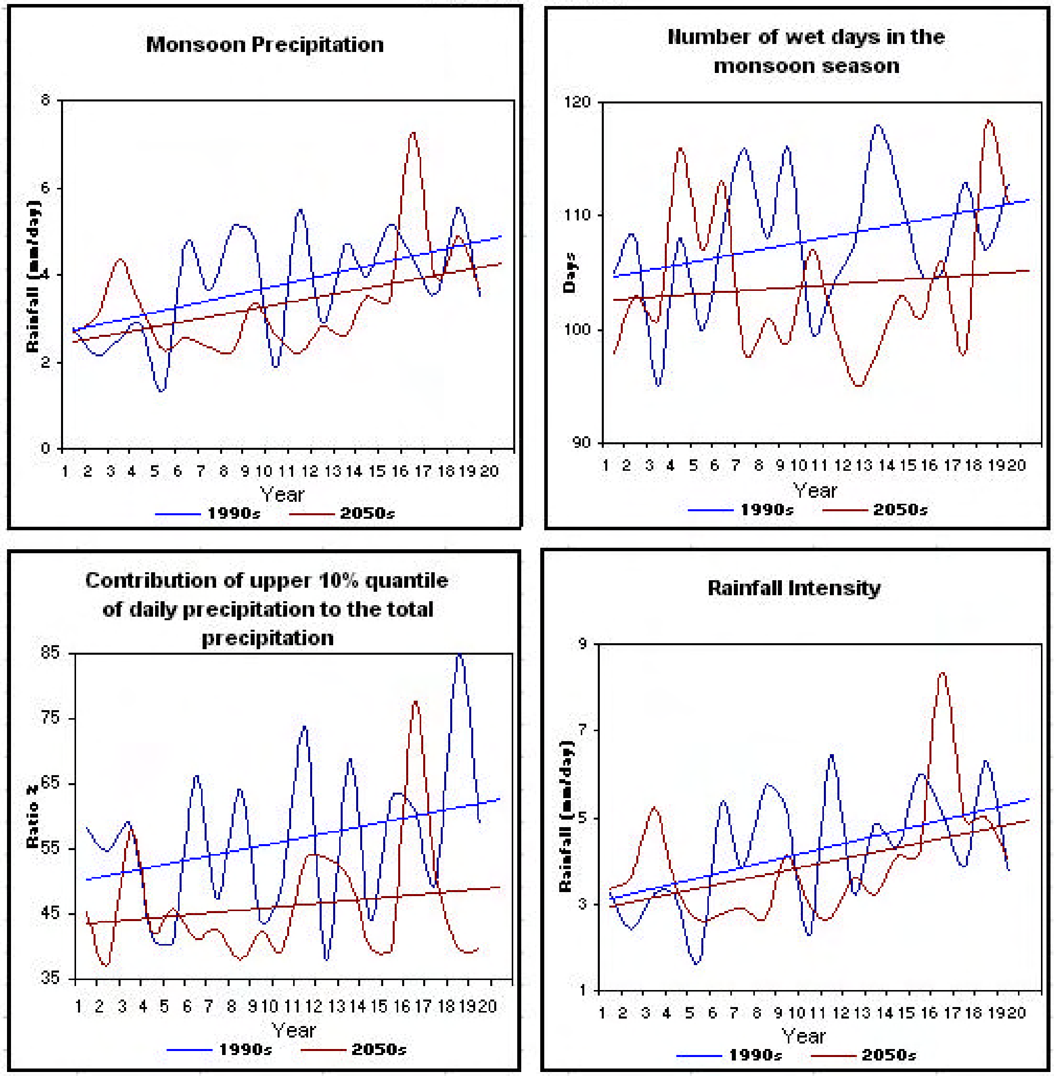

Fig. 12 a: Key characteristics of summer monsoon rainfall over Bangalore as simulated by the RCM nested in the GCM for the present day (1990s) and for the mid-Century (2050s) due to anthropogenic radiative forcings

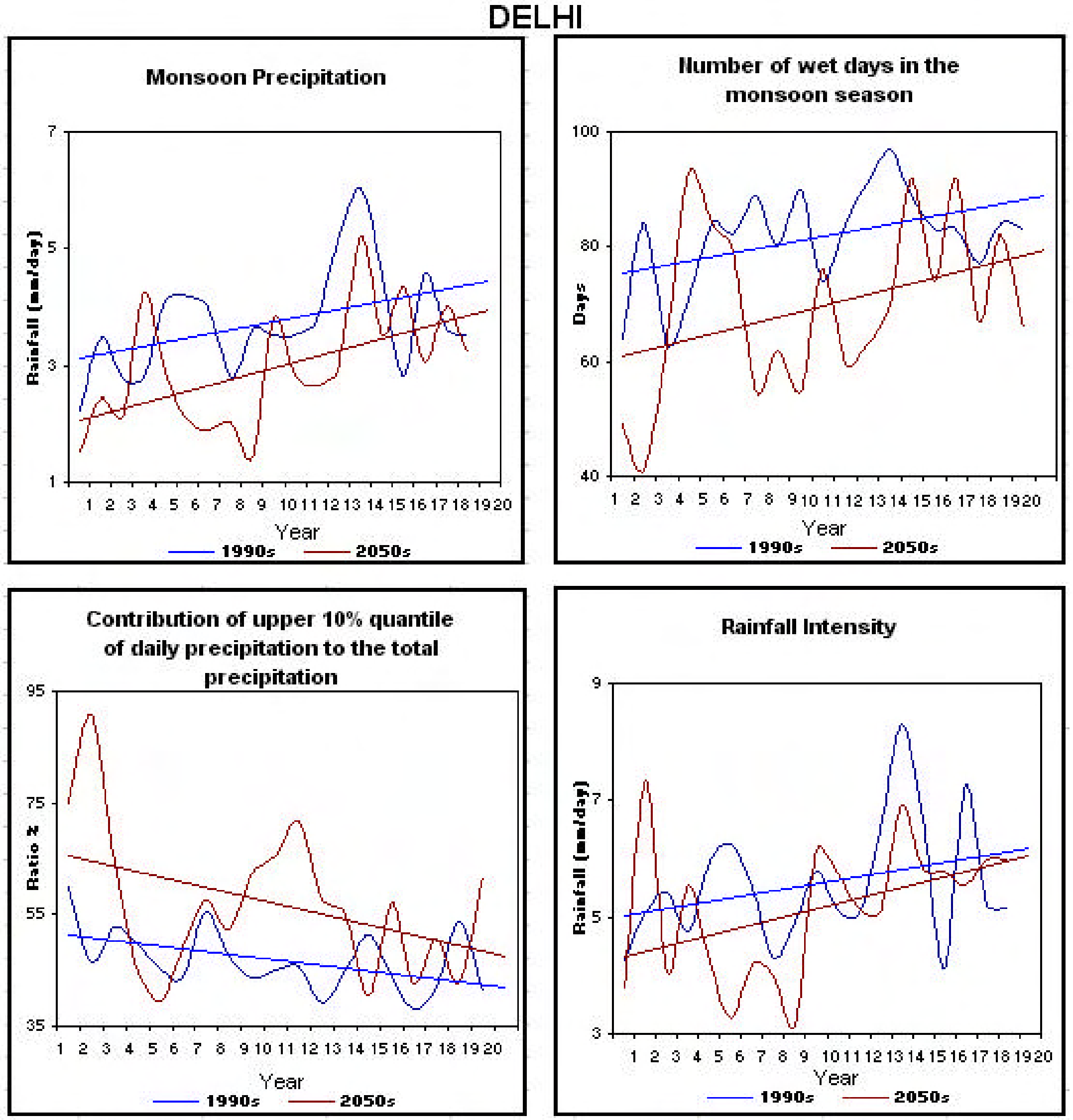

Fig. 12b: Key characteristics of summer monsoon rainfall over Delhi as simulated by the RCM nested in the GCM for the present day (1990s) and for the mid-Century (2050s) due to anthropogenic radiative forcings

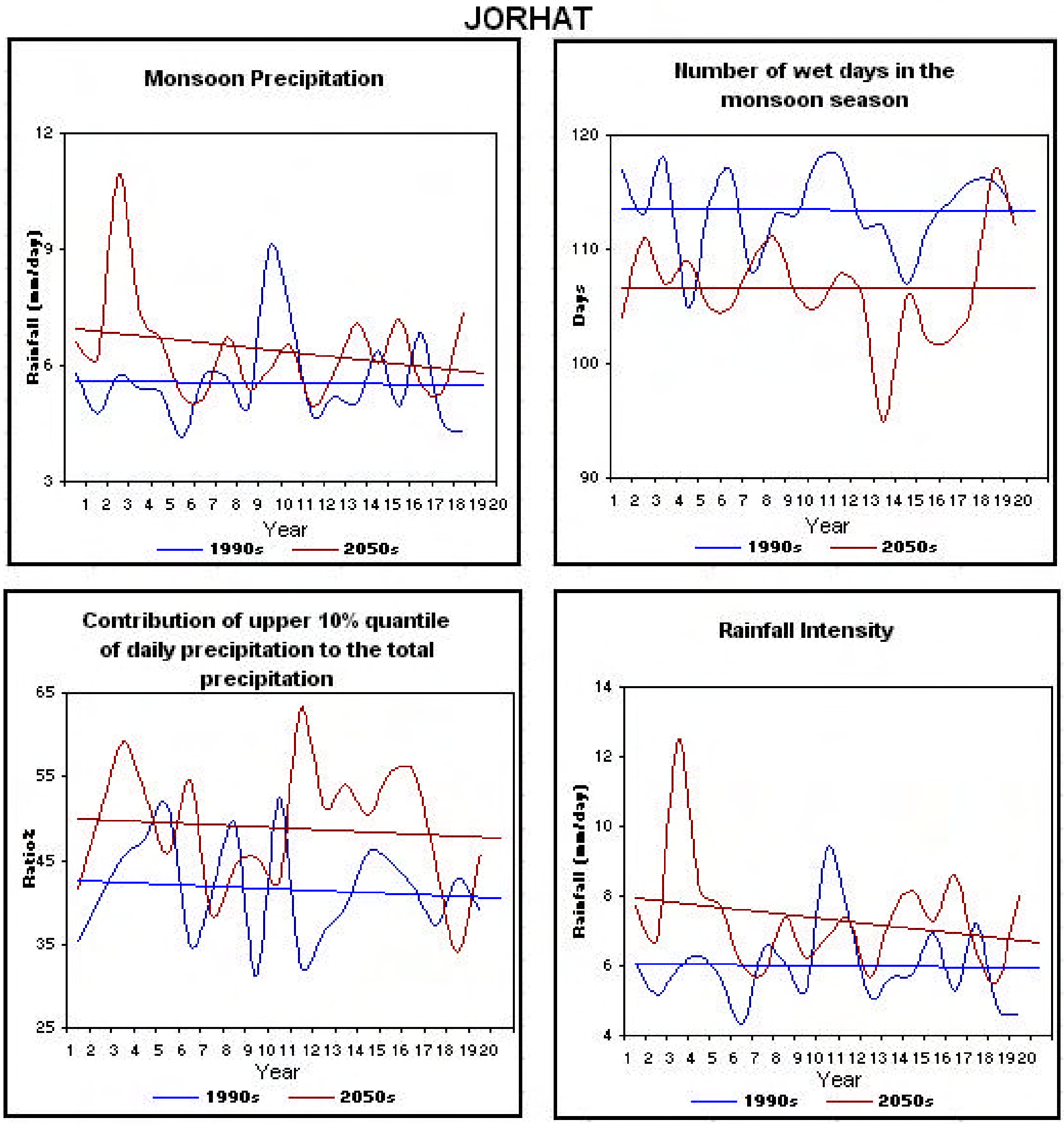

Fig. 12c: Key characteristics of summer monsoon rainfall over Jorhat as simulated by the RCM nested in the GCM for the present day (1990s) and for the mid-Century (2050s) due to anthropogenic radiative forcings

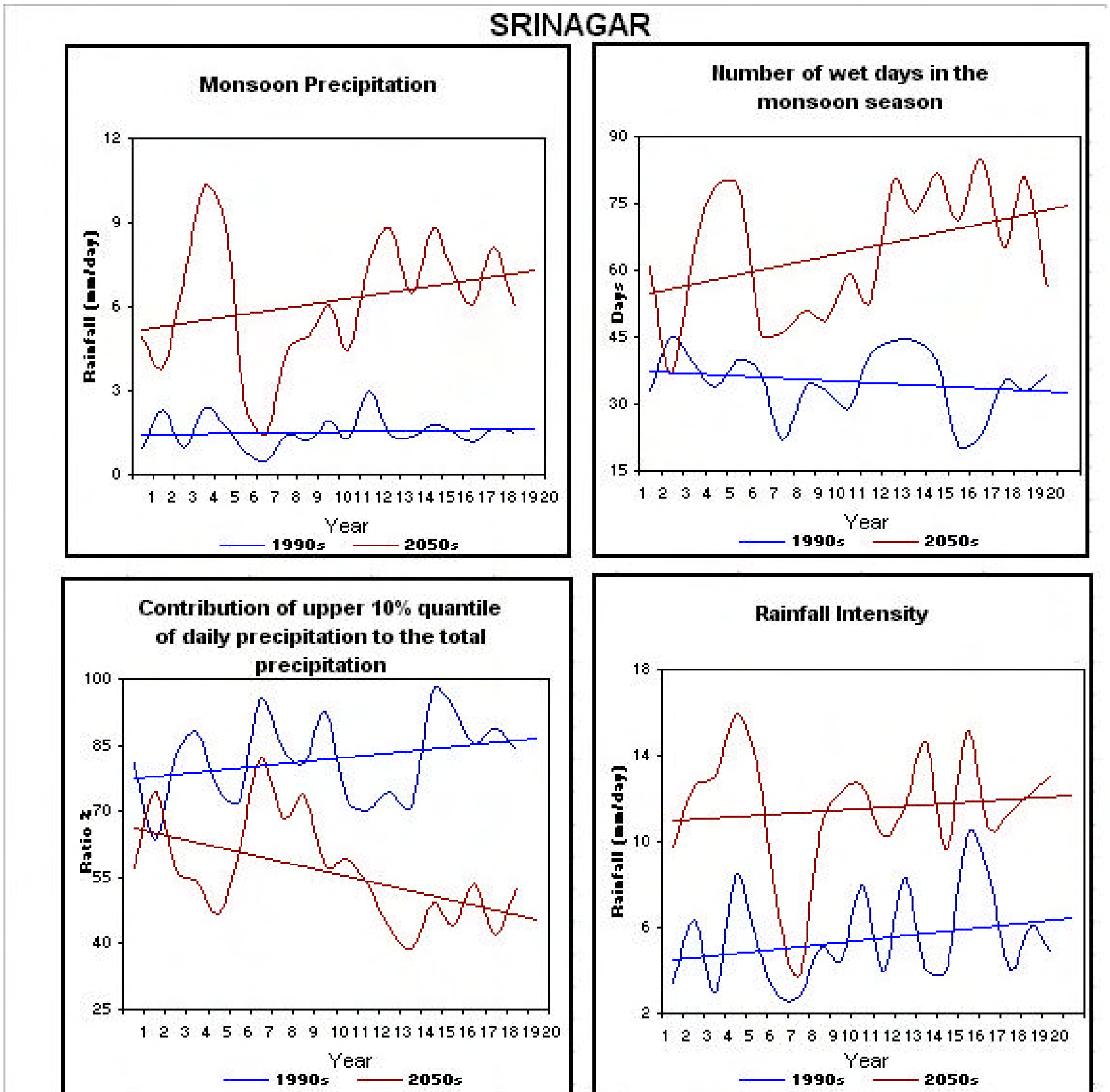

Fig. 12 d: Key characteristics of summer monsoon rainfall over Srinagar as simulated by the RCM nested in the GCM for the present day (1990s) and for the mid-Century (2050s) due to anthropogenic radiative forcings

UDAIPUR

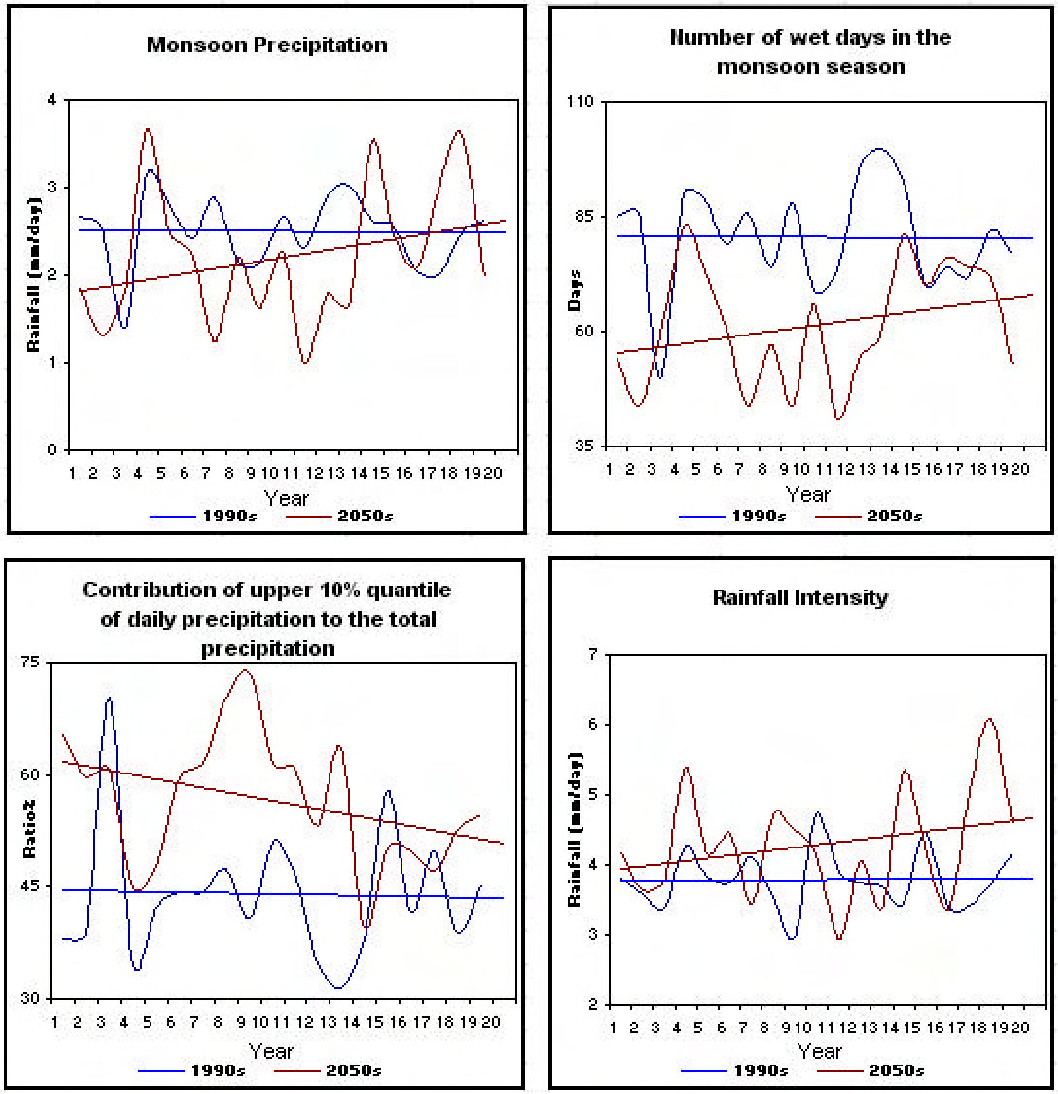

Fig. 12 e: Key characteristics of summer monsoon rainfall over Udaipur as simulated by the RCM nested in the GCM for the present day (1990s) and for the mid-Century (2050s) due to anthropogenic radiative forcings