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Global warming and monsoon climate

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सार - उपलब्ध युग्मित वायुमंडल महासागर भूमंडलीय जलवाय निदर्शों (ए.-ओ. जी.सी.एम) के संचसात्मक प्रयोगों से प्राप्त ऑकड़ों का उपयोग करके पृथ्वी के वायुमंडल में ग्रीनहाउस गैसों (जी.एच.जी.)और सल्फेट एरोसॉल में होने वाली क्षणिक वृद्धि के एशियाई ग्रीष्मकालीन मानसून पर पड़ने वाले प्रभाव की इस शोध पत्र में जाँच की गई है। इस क्षेत्र में धरातल के निकट के मासिक औसत तापमान और वर्षा की प्रेक्षित प्रवृत्तियों तथा मॉडल अनुकारित प्रवृत्तियों की तुलना करने से यह पता चला कि ए.-ओ.जी.सी.एम के प्रेक्षण क्षेत्रीय जलवायु-विज्ञान के अनुरूप हैं। भारतीय उपमहाद्वीप में जी.एच.जी. प्रेरित उष्णन को प्रभावहीन बनाने में सल्फेट एरोसॉल के संभावित योगदान की इस शोध पत्र में चर्चा की गई है। यद्यपि ग्रीष्मकालीन मानसून ऋतु के दौरान भारतीय उपमहाद्वीप में अनुकरित कुल मौसमी वर्षा को अधिकांश ए.-ओ.जी.सी.एम में कम महत्व दिया गया है तथापि जिस क्षेत्र का अध्ययन किया गया उस में अनुकारित मानसून वर्षा की वर्षवार परिवर्तनशीलता को प्रेक्षित जलवायु विज्ञान के बिल्कुल अनुरूप पाया गया है।

ABSTRACT. The response of the Asian summer monsoon to transient increases of greenhouse gases (GHGs) and sulfate aerosols in the Earth's atmosphere is examined using the data generated in numerical experiments with available coupled atmosphere-ocean global climate models (A-O GCMs). A comparison of observed and model-simulated trends in monthly mean near-surface temperature and rainfall over the region provides evidence of skill of the A-O GCMs in simulating the regional climatology. The potential role of the sulfate aerosols in obscuring the GHG- induced warming over the Indian subcontinent is discussed. Even though the simulated total seasonal rainfall over the Indian subcontinent during summer monsoon season is underestimated in most of the A-O GCMs, the year to year variability in simulated monsoon rainfall over the study region is found to be in fair agreement with the observed climatology.

Key words – Global climate models, Greenhouse gases, Sulfate aerosols, Indian monsoon, Regional climate change.

1. Introduction

The recent state-of- the-art Global Climate Models, while by no means perfect, are sufficiently close to reality to inspire some confidence in their ability to predict the broad features of the climate change due to enhanced radiative forcings. The size of the surface warming during the past century as simulated by these Global Climate Models is consistent with the observational records. There has also been a broad agreement among the Global Climate Models in the simulated large scale patterns of change and in their temporal evolution.

The recent long-term climate simulations with interactively coupled Atmosphere-Ocean General Circulation Models (A-O GCMs) hold much promise in our ability to predict the time- dependent global as well as regional climatic response to future increases in radiative forcings due to anthropogenic greenhouse gases and aerosols. However, as the anthropogenically- induced sulfate aerosol burden have large spatial and temporal variations in the atmosphere, its impact on regional scales could be in striking contrast to the impact from greenhouse gases for which the concentration changes, in most cases, are likely to be uniform throughout the globe. The spatially localized radiative forcing due to anthropogenic aerosols are largely confined to northern hemisphere and tend to yield a steepening of the normalized meridional temperature gradient in that hemisphere. They also yield distinct precipitation responses in the tropical region in general and over the Asian monsoon region in particular. Since the projected anthropogenic sulfate aerosol loadings prescribed for the future are substantial over the south Asian region, its impact on Asian summer monsoon needs to be critically examined.

2. Indian summer monsoon

The Indian summer monsoon constitutes the most spectacular manifestation of regional anomalies in the general circulation of the atmosphere resulting from land-sea thermal contrasts and orographic features. Regional peculiarities assume a dominant role with respect to the monsoonal features over India and its neighbourhood. The thermal structure of the adjoining sea areas - the Arabian Sea, the Bay of Bengal and the south Indian Ocean - and its temporal variations appear to have a modulating influence on the monsoon circulation. The all India monsoon rainfall has shown stable long-term characteristics with extremes being a part of its natural variability. About 70% of the annual rainfall over the Indian subcontinent occurs during the monsoon season (June- September). During the active monsoon period, a series of low pressure vortices form over north Bay of Bengal and move northwestward along the monsoon trough. These low pressure vortices are responsible for much of the rain over the central plains of India.

In spite of the basic stability and assuredness, the monsoon rainfall is highly variable in time and space both on inter-annual and intra-seasonal scales. In particular, the monsoon is found to exhibit variability of an epochal nature in terms of epochs of overall positive or negative anomaly of rainfall on a timescale of about 30 years. Studies of the variability of the monsoon on inter- decadal scale also support the existence of the alternating epochs with positive and negative rainfall anomalies averaged over the epochal span of about three decades each. The Indian summer monsoon is presently in a positive epoch from the year 1988 onwards and it has already given India eleven near normal monsoons in a row. Observations, however, do suggest a general decrease in precipitation in the recent decades over some parts of India (e.g., Orissa, East Madhya Pradesh). An increase in seasonal rainfall in some regions have also been reported recently (e.g., Punjab, West Uttar Pradesh).

3. Indian summer monsoon as simulated by coupled A-O GCMs

Notwithstanding the great strides made in objective modelling of climate and climate change through A-O GCMs, there are still some uncertainties associated with model projections especially for climate change on regional scales. Lal *et al.* (1995) examined the combined effect of increasing anthropogenic greenhouse gases and sulfate aerosols on the monsoon climate of the Indian subcontinent in a set of numerical experiments performed with European Community HAMburg (ECHAM3) coupled global climate model and suggested that model-simulated past trends in surface warming can be reconciled to a large extent with the observed warming trends when the cooling effect of aerosols on climate is accounted for. The model results had a reasonable degree of correspondence with observations as regards the spatial distribution of mean sea level pressure, surface air temperature, winds and precipitation over the Indian subcontinent. There was some resemblance in the spatial distribution patterns as well as the total area-averaged summer monsoon rainfall in the model simulation. The observed steep gradient in monsoon rainfall from west coast towards the east (a rain-shadow effect on lee side of the Western Ghats) was, however, not precisely simulated due to coarser resolution of the model. The model-simulated average monsoon rainfall over land area was 73 cms against the observed climatological rainfall of 85 cms. The interannual variability in simulated monsoon rainfall over the Indian subcontinent for the past century was in fair agreement with the observed climatology. The model also faithfully reproduced the observed seasonality in rainfall over the region. An examination of area-averaged daily rainfall over the Indian subcontinent revealed that the simulated onset of summer monsoon rains over India had a close correspondence with the observed climatology.

Many new numerical experiments have been conducted with A-O GCMs considering transient responses and accounting for both the effects of green-house gases and aerosols. The Data Distribution Centre (DDC) set up by IPCC at two internet sites (CRU, Norwich and DKRZ, Hamburg) has compiled the outputs generated in transient experiments with a set of seven recent A-O GCMs that both reflect the state-of-the-art of model experiments and provide a representative range of results from different GCMs. These experiments are historically forced (warm start) integrations, use an IS92a type forcing scenario with and without aerosol forcings and extend to middle of 21st century and beyond (Table 1). Each of the seven GCMs have undergone through AMIP and CMIP intercomparison exercises.The data sets from numerical experiments from these GCMs, lodged in the public domain, have been used to generate plausible scenarios of climate change over the Indian subcontinent which are presented here.

In order to develop confident climate change scenarios on regional scales, it is first necessary to examine if the models are able to simulate the dynamics of present-day regional climate. The multi-century control integrations of A-O GCMs unforced by anthropogenic changes in atmospheric composition offer an excellent opportunity to examine the skill of individual models in simulating the present-day climate and its variability on regional scales. A model validation exercise carried out by us has indicated that four of the seven A-O GCMs, the data sets from numerical experiments of which are currently included at DDC, have reasonable skill in simulating the broad features of present-day climate over the Indian subcontinent (Fig. 1). The time period of 30 years (1961-90) in baseline

TABLE 1

Summary of control, GHG and GHG+Aerosol forcings experiments with coupled A-O GCMs

	ECHAM4	HadCM2	CSIRO	CCCma	GFDL	NCAR	CCSR
AGCM	2.8°x2.8° L19	2.5°x 3.75° L19	3.2°x5.6° L9	3.7°x3.7° L10	4.5°x7.5° L9	4.5°x7.5° L9	5.6°x5.6° L20
OGCM	2.8°x2.8° L11	2.5°x 3.75° L20	3.2°x5.6° L21	1.8°x1.8° L29	4.5°x 3.75° L12	1°x1° L20	2.8°x2.8° L17
Features	prognostic CLW*, geostrophic ocean	prognostic CLW, isopycnal ocean diffusion			no diurnal cycle, isopycnal ocean diffusion	no diurnal cycle	
Flux correction	monthly mean heat, fresh water, stress	monthly mean heat, fresh water	heat, fresh water, momentum	heat, fresh water	monthly mean heat, fresh water	none	heat, fresh water
Control CO_2	354 ppmv	323 ppmv	330 ppmv	295 ppmv	300 ppmv	330 ppmv	345 ppmv
Transient CO_2	1.0% yr^{-1} (compound)	1.0% yr^{-1} (compound)	0.9% yr^{-1}	1.0% yr^{-1}	1.0% yr^{-1} (compound)	1.0% yr^{-1} (linear)	1.0% yr^{-1}
Greenhouse Gases	CO_2 :	CO_2 :	CO_2 :	CO_2 :	CO_2 :	CO_2 :	CO_2 :
	Historic 1860-1989	Historic 1860-1989	Historic 1881-1989	Historic 1900-1989	IS92a : 1958-2057	Historic 1901-1989	Historic 1890-1989
	IS92a : 1990-2099	IS92a : 1990-2099	IS92a : 1990-2100	IS92a : 1990-2100		IS92a : 1990-2036	IS92a : 1990-2099
Greenhouse gases + Sulphate Aerosols	CO_2 :	CO_2 :	CO_2 :	CO_2 :	CO_2 :	CO_2 :	CO_2 :
	Historic 1860-1989	Historic 1860-1989	Historic 1881-1989	Historic 1900-1989	Historic 1766-1989	Historic 1901-1989	Historic 1890-1989
	IS92a : 1990-2049	IS92a : 1990-2099	IS92a : 1990-2049	IS92a : 1990-2100	IS92a : 1990-2065	IS92a : 1990-2036	IS92a : 1990-2099
	SO_4 :	SO_4 :	SO_4 :	SO_4 :	SO_4 :	SO_4 :	SO_4 :
	Historic 1860-1989	Historic 1860-1989	Historic 1860-1989	Historic 1860-1989	Historic 1766-1989	Historic 1901-1989	Historic 1890-1989
	IS92a : 1990-2049	IS92a : 1990-2099	IS92a : 1990-2100	IS92a : 1990-2100	IS92a : 1990-2065	IS92a : 1990-2036	IS92a : 1990-2099
Simulation length (yr)	Control : 240	Control : 240	Control : 219	Control : 200	Control : 1000	Control : 136	Control : 210
	Greenhouse : 240	Greenhouse : 240	Greenhouse : 219	Greenhouse : 200	Greenhouse : 100	Greenhouse : 136	Greenhouse : 210
	Greenhouse+ A : 240	Greenhouse+ A : 240	Greenhouse+ A : 219	Greenhouse+ A : 200	Greenhouse+ A : 300	Greenhouse+ A : 136	Greenhouse+ A : 210
Warming (°C) at CO_2 doubling	1.3	1.7	2.0	2.7	2.3	2.3 (est.)	2.4
2 x CO_2 sensitivity (°C)	2.6	2.5	4.3	3.5	3.7	4.6	3.5

* cloud liquid water

climatology has been used for the purpose of these model validation exercises and for generating climate change scenarios for Indian subcontinent. Two future time periods centered around2050s (2040-2069) and 2080s (2070-2099) have been considered here for developing scenarios of changes in surface air temperature and precipitation.

The four A-O GCMs that have demonstrated reasonable skill in simulating the present- day area-averaged monthly mean climatology in terms of surface air temperature, diurnal temperature range and rainfall are, HadCM2 model (UK), ECHAM4 model (Germany), CSIRO model (Australia) and CCSR model (Japan). The climate change scenarios based on an ensemble of results as inferred from these models are most likely to be trustworthy. The model projections discussed here are the scenarios due to greenhouse gas-induced positive radiative forcings and also those which take into account the negative radiative forcing of sulfate aerosols (direct effects).

4. Global mean climate change scenarios

In terms of the future climates, each of the seven state-of-the-art global climate models project an increase in temperature with the increases in greenhouse gas concentrations. The warming is more pronounced over the land regions than over the oceans and during winter than during summer. Maximum warming is simulated to be in winter and in late autumn at high northern latitudes associated with reduced sea ice and snow cover. Seasonal variations of projected warming is minimum at low latitudes. Associated with rise in surface air temperatures, a reduction in diurnal temperature range is projected over land in most seasons and most regions. Though, there is little consistency among climate models regarding the variability of daily temperature, a significant increase in mean temperature is accompanied by a marked decrease in the frequency of extremely low temperatures, and a similar increase in the frequency of extremely high temperatures. In general, all global climate models simulate an enhanced global mean hydrological cycle and an increase in average rainfall which is often associated with increase in daily rainfall intensity leading to more frequent heavier rainfall events in many regions. Precipitation is projected to increase at high latitudes in winter.

5. Climate change projections for the Indian subcontinent

(a) *Surface air temperature*

The model projections for the Indian subcontinent based on an ensemble of results as inferred from the four

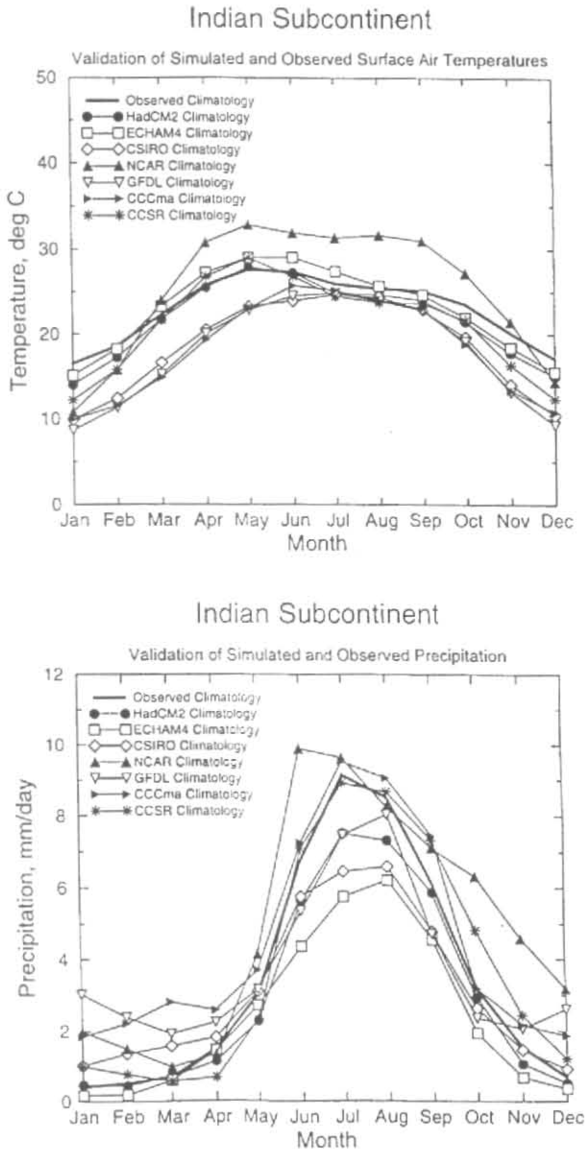

Fig. 1. Annual cycle of monthly mean surface air temperature and rainfall climatology averaged over the Indian subcontinent as observed and as simulated in the seven state-of-the-art coupled atmosphere-ocean global climate models

skilled A-O GCMs suggest the area-averaged annual mean surface temperature rise due to increases in greenhouse gases over the Indian subcontinent is likely to be about 2.7°C (standard deviation is ±0.4°C) and 3.8°C (standard deviation is ±0.7°C) during the decades 2050s and 2080s respectively. The projected warming in the presence of sulfate aerosols would be restricted to 1.9°C (standard deviation is ±0.2°C) and 2.9°C (standard deviation is ±0.4°C) during the decades 2050s and 2080s respectively. The spatial distributions of annual mean surface air temperature change as simulated by the skilled

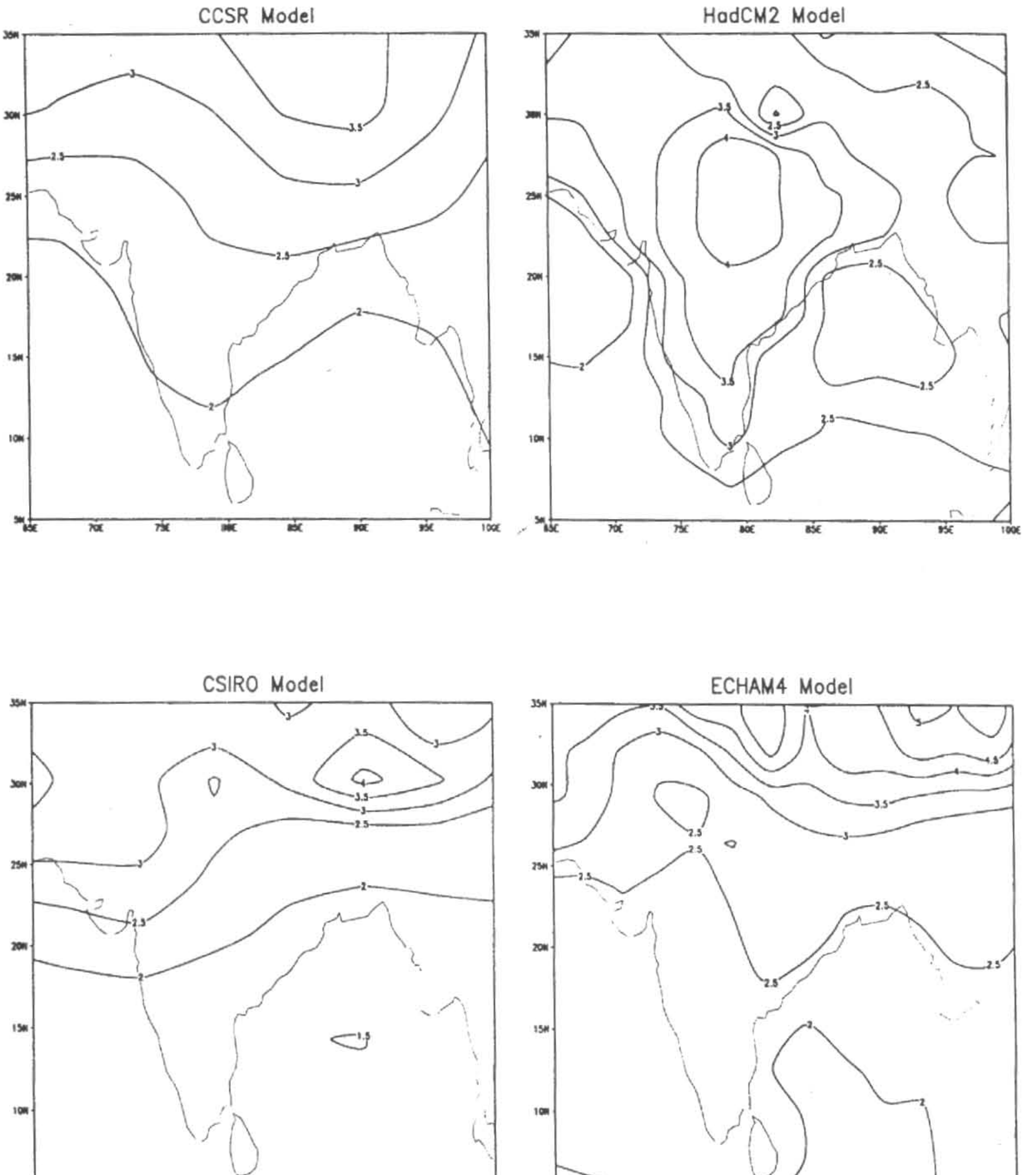

Fig. 2. Spatial distribution of annual mean surface air temperature change (°C) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2050s under the influence of greenhouse gas only forcings

A-O GCMs are depicted in Figs. 2 (GHG Only) and 3 (GHG+Aerosols) for the decade 2050s and in Figs. 4 (GHG Only) and 5 (GHG+Aerosols) for the decade 2080s. On seasonal basis, the projected surface warming

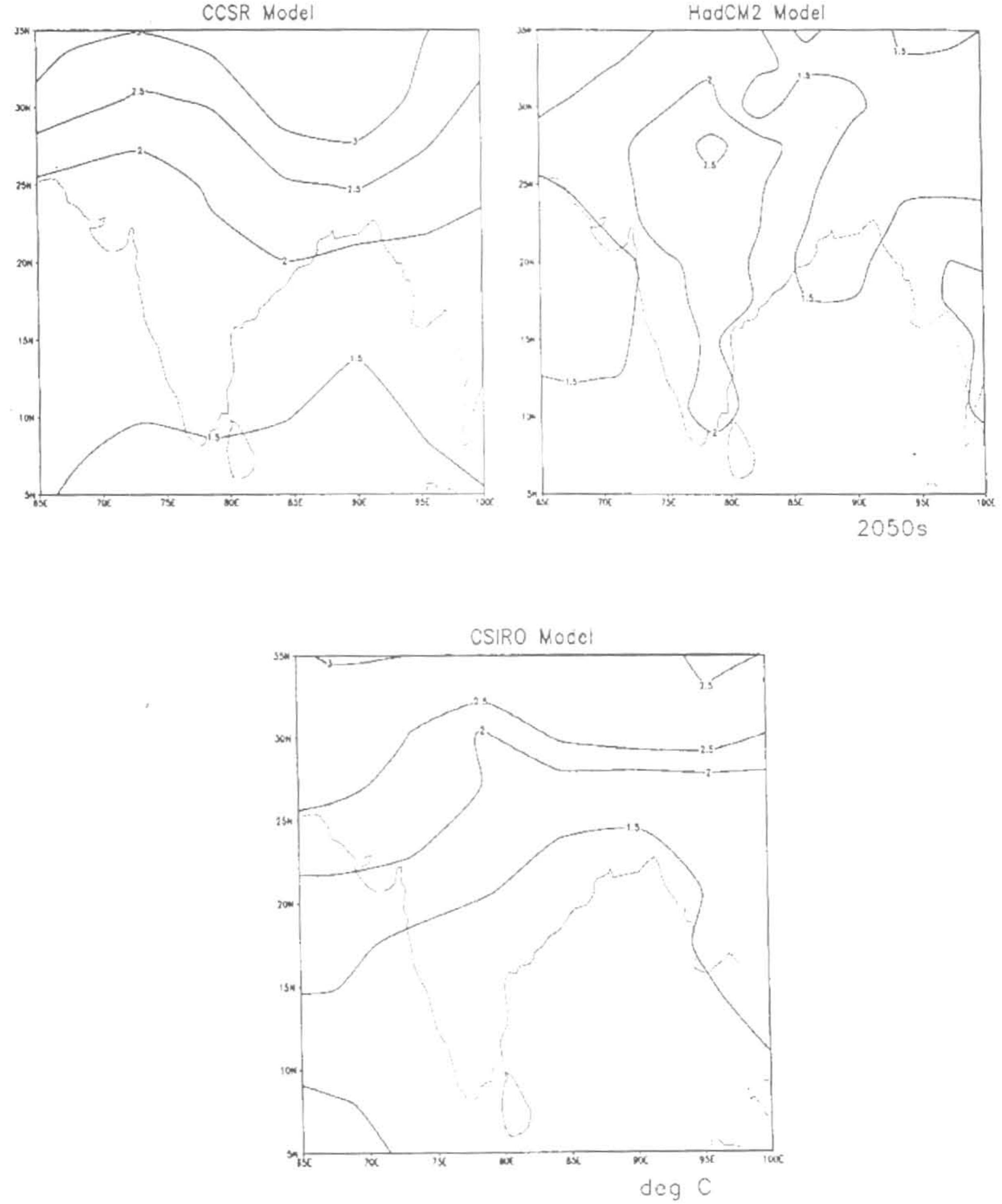

Fig.3. Spatial distribution of annual mean surface air temperature change (°C) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2050s under the combined influence of greenhouse gas and aerosol forcings

is more in winter than in summer (Table 2). This seasonal feature is found to be consistent in each of the four model simulations for both the time periods selected and for greenhouse gas only as well as combined greenhouse gas

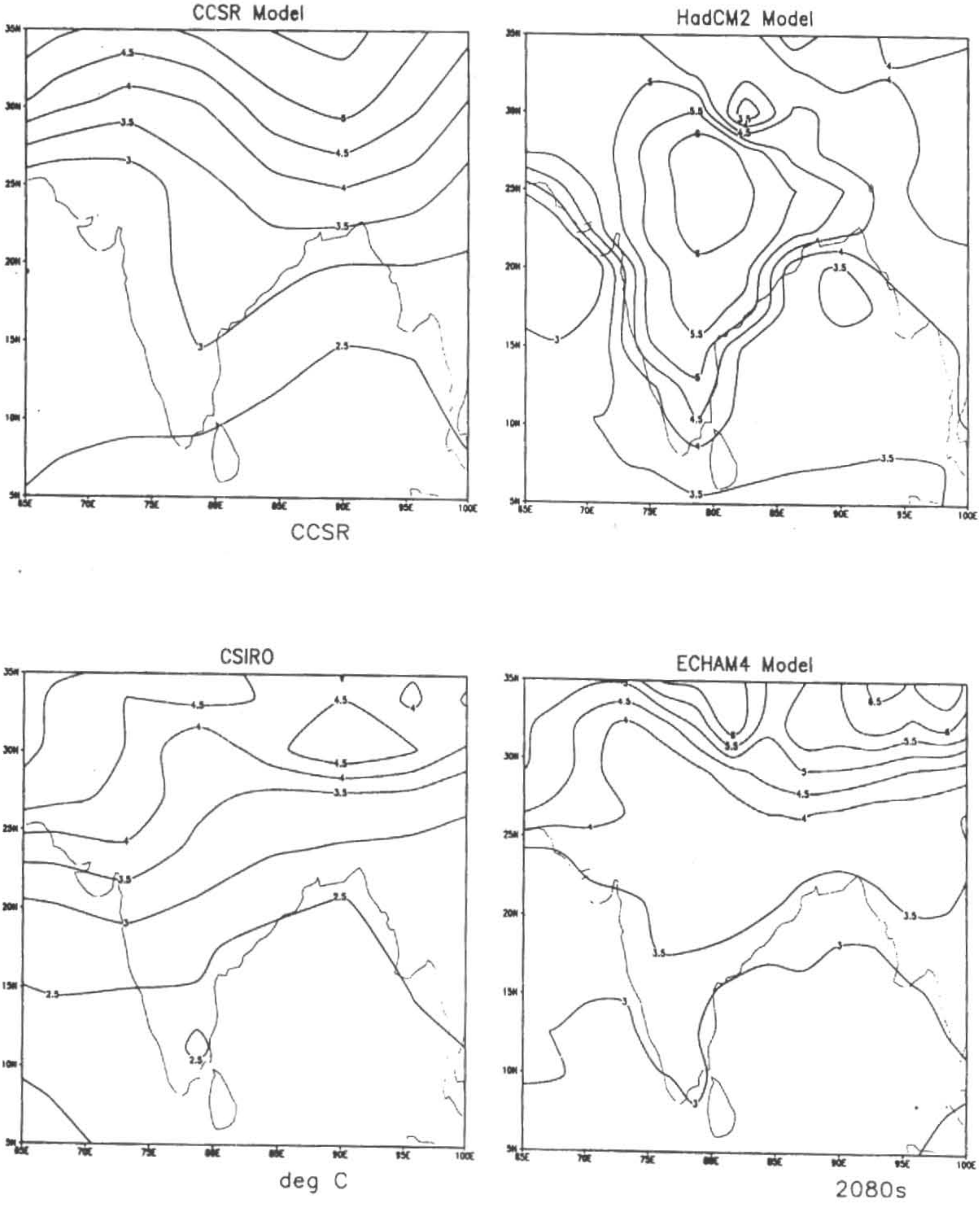

Fig. 4. Spatial distribution of annual mean surface air temperature change (°C) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2080s under the influence of greenhouse gas only forcing

plus sulfate aerosol forcings. The projected area-averaged GHG-induced warming during the decade 2050s is 3.2°C in winter and 2.2°C during summer monsoon. During the decade 2080s, the projected area-averaged GHG-induced

TABLE 2

Area - averaged surface temperature and precipitation change over Indian Subcontinent as inferred from four A-O GCMs

Period	Temperature (deg C)				Rainfall (mm/day)			
	2050s		2080s		2050s		2080s	
	GHG	GHG+A	GHG	GHG+A	GHG	GHG+A	GHG	GHG+A
Annual	2.688 (±0.412)*	1.925 (±0.202)	3.836 (±0.759)	2.986 (±0.421)	6.773 (±8.912)	-2.360 (±7.098)	11.002 (±12.361)	-0.132 (±15.228)
Winter (DJF)	3.254 (±0.363)	2.088 (±0.852)	4.525 (±0.497)	3.248 (±0.529)	-2.090 (±26.39)	-14.840 (±18.99)	5.260 (±34.43)	-11.180 (±21.18)
Summer (JJA)	2.192 (±0.882)	1.813 (±0.575)	3.199 (±1.426)	2.671 (±1.494)	6.590 (±8.40)	0.140 (±7.12)	7.860 (±12.64)	-2.460 (±16.74)
Monsoon (JJAS)	2.194 (±0.786)	1.759 (±0.498)	3.172 (±1.297)	2.633 (±1.331)	0.407 (±0.533)	0.020 (±0.523)	0.541 (±0.821)	0.135 (±1.117)

* Mean ± SD of the four skilled models

warming is 4.5°C in winter and 3.2°C during summer monsoon. Under the combined influence of greenhouse gases and sulfate aerosols, the projected area-averaged warming is restricted to 2.1°C in winter and 1.8°C in summer during the decade 2050s and 3.2°C in winter and 2.7°C in summer during the decade 2080s. It is evident from above that as a result of the cooling effect of sulfate aerosols, the future increase in surface temperature over the region tends to become less severe on annual as well as seasonal mean basis under the combined influence of greenhouse gases and sulfate aerosols.

One important aspect of the observed temperature change over the globe during the past century relates to its asymmetry during the day and night. Observed warming in surface air temperatures over several regions of the globe have been reported to be associated with increase in minimum temperatures (accompanied by increasing cloudiness) and decrease in diurnal temperature range. Any future changes in the diurnal temperature range (DTR) is important in respect of its crucial role in agricultural productivity. GCM simulations with increasing concentrations of CO_2 in the atmosphere also suggest relatively more pronounced increases in minimum temperature than in maximum temperature and hence a decrease in diurnal temperature range. On an annual mean basis, models suggest a decline in area-averaged DTR of about both on seasonal as well as annual mean basis. During winter, a decline in DTR of about 1°C and 2°C respectively is possible over the Indian subcontinent during the decades 2050s and 2080s. During summer, the decline in DTR is only marginal with some regions even showing an increase. The HadCM2 model is an exception in that it suggests a pronounced increase in DTR over the entire Indian subcontinent during summer. In general, the decline in DTR is only slightly moderated in the presence of sulfate aerosols. The projected changes in DTR could have significant impact on the patterns of agricultural productivity over the region.

(b) *Precipitation*

While the increasing trends in surface air temperature are projected even under the combined effects of greenhouse gases and sulfate aerosols albeit at a slower rate, this is not true in the case of changes in rainfall. The area-averaged increase in annual mean precipitation over the Indian subcontinent due to increases in greenhouse gases is projected to be 7% (standard deviation is ±9%) and 11% (standard deviation is ±12%) respectively during the decades 2050s and 2080s. In the presence of sulfate aerosols, however, a decline in area-averaged annual mean rainfall by 2% and 1% during the decades 2050s and 2080s respectively is projected. The decline in annual total rainfall simulated by HadCM2 model is most pronounced (10% and 16% respectively during the decades 2050s and 2080s). The spatial distributions of projected changes in annual mean rainfall over the Indian subcontinent are depicted in Fig.6 (GHG Only) and Fig.7 (GHG+Aerosols) for the decade 2050s and in Fig. 8 (GHG Only) and Fig. 9 (GHG+Aerosols) for the decade 2080s.

Over the Indian subcontinent as a whole, no significant changes in winter precipitation are projected in each of the four GCMs due to GHG-induced radiative

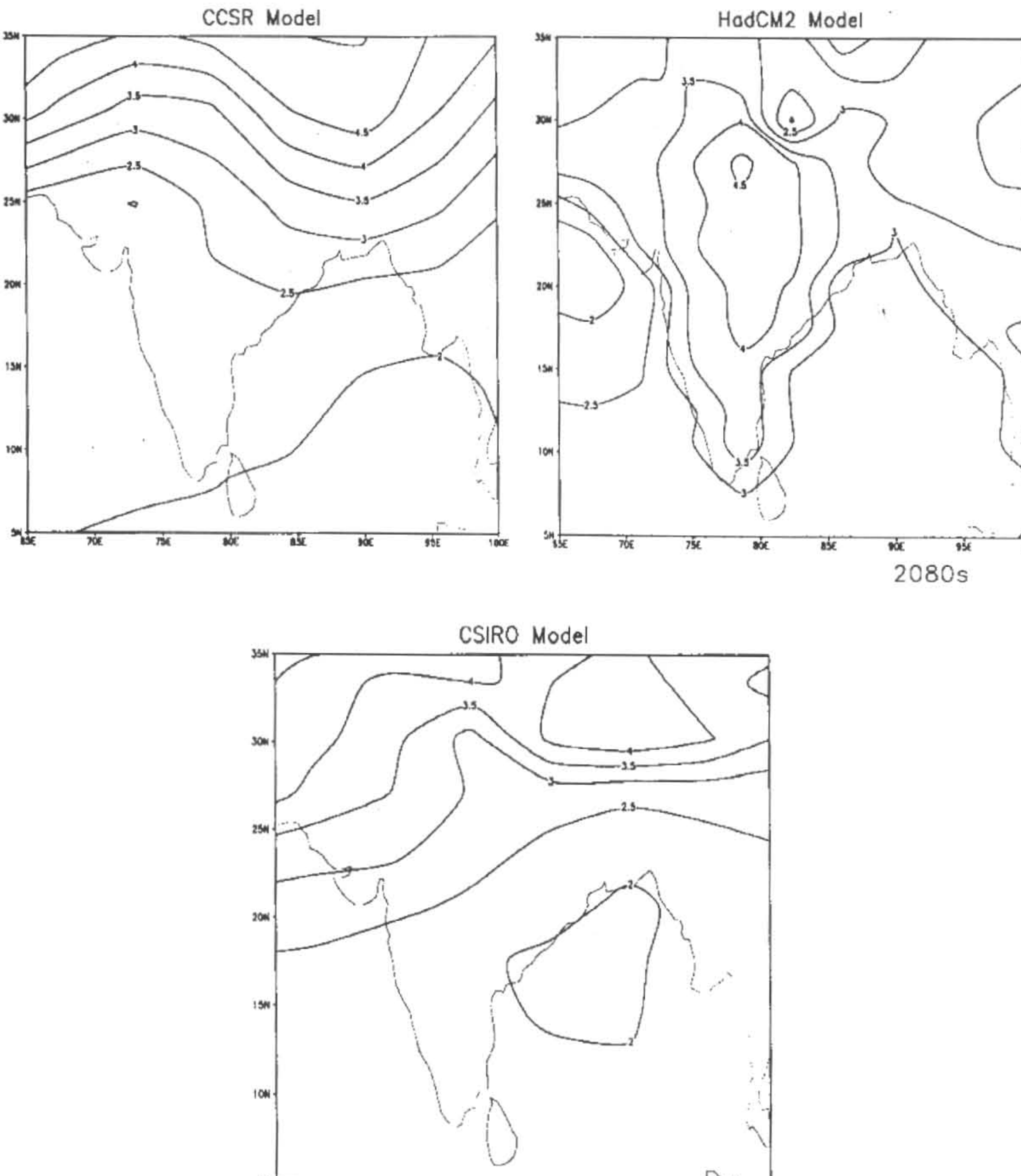

Fig. 5. Spatial distribution of annual mean surface air temperature change (°C) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2080s under the combined influence of greenhouse gas and aerosol forcing

forcings. During summer monsoon, the models suggest about 6% and 8% increases in precipitation on an average over the Indian subcontinent during the decades 2050s and 2080s respectively. The monsoon activity is projected to

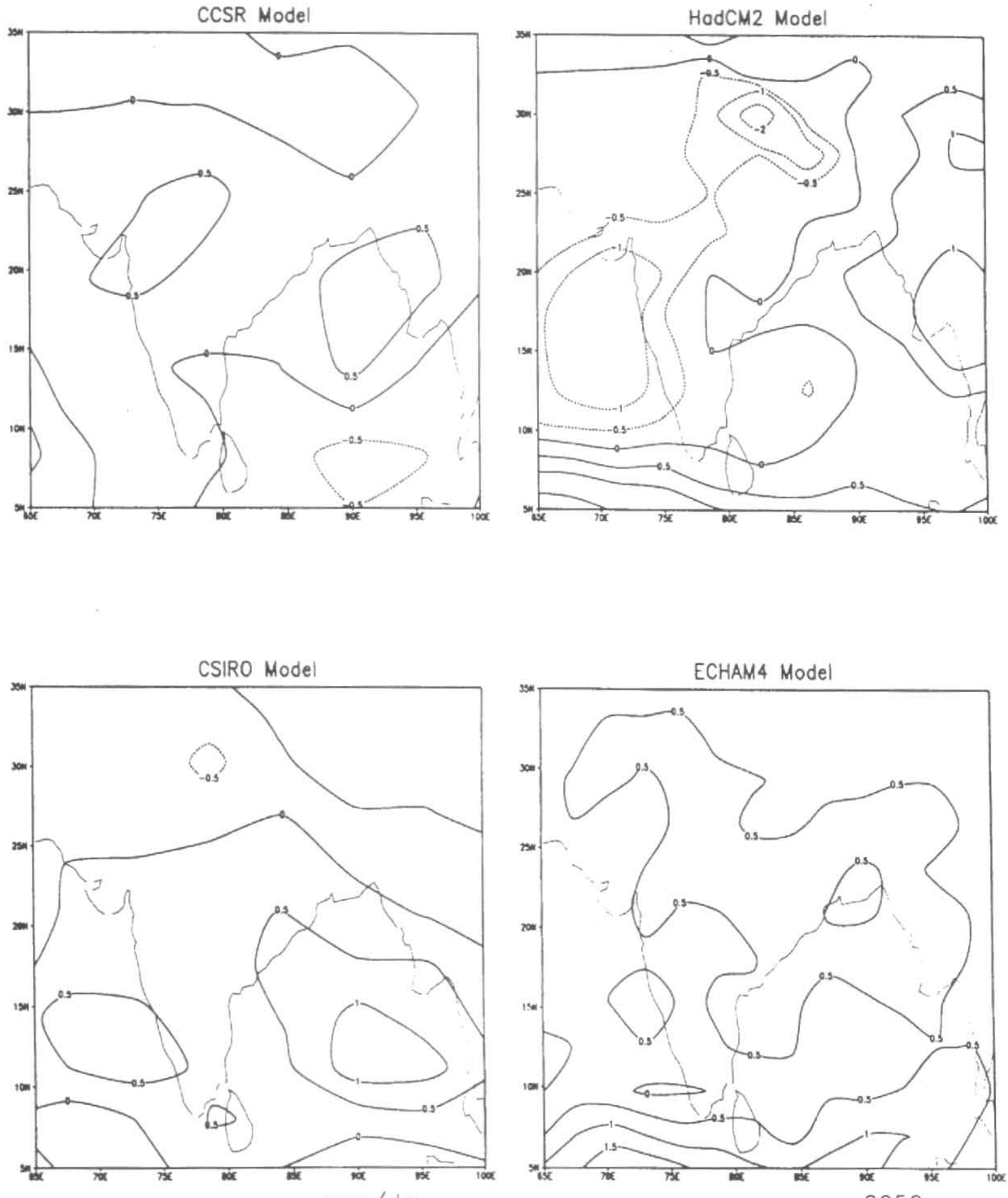

Fig. 6. Spatial distribution of likely changes in annual mean rainfall (mm day^{-1}) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2050s under the influence of greenhouse gas only forcing

be more vigorous under the influence of greenhouse gas forcings. Under the combined influence of greenhouse gases and sulfate aerosols, a decline in both winter (~12%) and summer (~2%) precipitation over the Indian

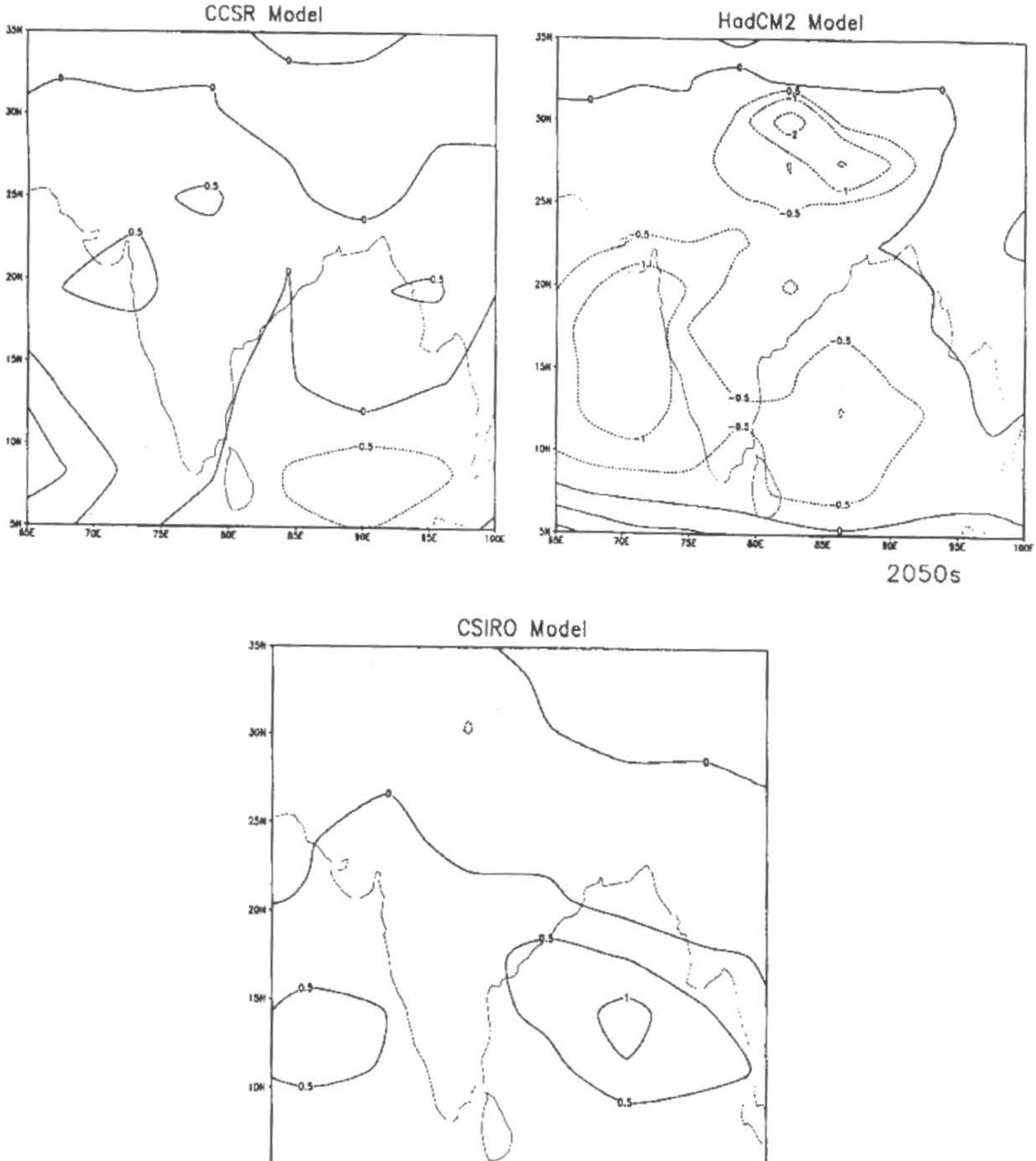

Fig. 7. Spatial distribution of likely changes in annual mean rainfall (mm day^{-1}) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2050s under the combined influence of greenhouse gas and aerosol forcing

subcontinent is projected. The spatial distribution of changes in monsoon rainfall over the region simulated in HadCM2 model for the decade 2050s with respect to 1980s suggests that the decrease in rainfall over the

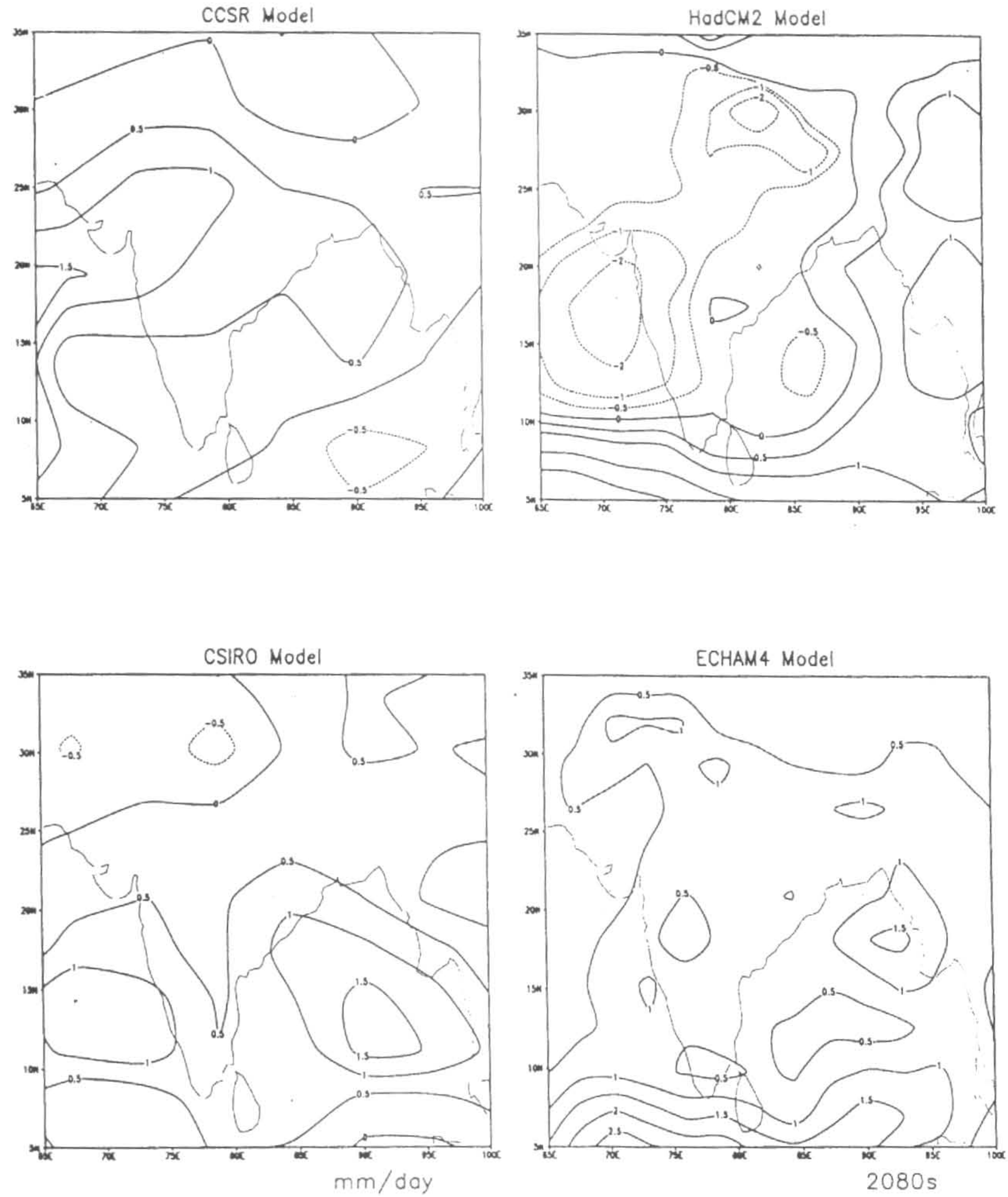

Fig. 8. Spatial distribution of likely changes in annual mean rainfall (mm day^{-1}) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2080s under the influence of greenhouse gas only forcing

central plains of the Indian subcontinent could be larger than 1.0 mm day^{-1}. The projected decline in summer monsoon rainfall over the region was found to be more pronounced (larger than 2.5 mm day^{-1}) in the decade 2080s; these changes are marginally above the range of interannual variability observed over the region for the present-day atmosphere. Since almost 70% of the total annual rainfall over India takes place during summer monsoon and is very crucial for Indian agriculture, perhaps the decline in summer rainfall here could have serious implications. The intensity of extreme rainfall events are projected to be higher suggesting thereby the possibility of more frequent flash floods in parts of India and Bangladesh.

(c) *Soil moisture and surface runoff*

In addition to precipitation, projections of soil moisture and surface runoff are of direct relevance for considering the potential impact of climate change on water resource availability and ecosystem. None-the-less, the regional soil moisture and surface runoff scenarios are most difficult to predict in global climate models in view of the current limitations of these models in accurate treatment of interactions occurring between air, land, oceans and biota.The recent experiments with A-O GCMs, however, suggest the possibility of large changes in soil moisture during the monsoon season over the land regions of the Indian subcontinent. In the case of greenhouse gas forcings only, the length of dry season is generally expected to decline over central India, but increase in parts of southern India. Soil moisture is projected to increase marginally by 15-25% over parts of southern and central India. This increase is confined to the monsoon months of June through September. During the rest of the year, there is either no change in soil moisture, or a marginal decline possibly due to the increase in temperature leading to enhanced evapotranspiration.

Under the combined influence of greenhouse gases and sulfate aerosols, however, Indian summer monsoon circulation is projected to be rather weak resulting in a decline in rainfall and hence soil moisture. Enhanced drying (reduced soil wetness) over the central plains of the Indian subcontinent is likely on an annual mean basis and more prominently during the monsoon season for the future. About 15% decrease in area-averaged soil moisture over the Indian subcontinent is projected during June-August. This can provide a positive feedback between higher surface temperatures and decreased cloud cover. The saturation vapour pressure of water increases non-linearly with temperature, so that at higher temperatures, proportionately more of the increase in radiative heating of the surface is used to increase surface evaporation. But when the land surface becomes sufficiently dry to restrict evaporation, further drying reduces evaporation and hence evaporative cooling. The reduction in evaporation may also produce a decrease in low cloud amount (through reduction in boundary layer convergence) and associated rainfall which would further contribute to a decrease in soil moisture. The decline in rainfall over the Indian subcontinent, as projected for the future under the combined influence of greenhouse gases and anthropogenic aerosols, would also tend to decrease the surface runoff.

Relatively small climate changes can cause large water resource problems in many areas, especially arid and semi-arid regions such as northwest India. If water availability decreases in this region, it could have significant implications for agriculture, for water storage and distribution and for generation of hydroelectric power. For example, under the assumed scenario of a 1°C to 2°C temperature increase, coupled with a 10% reduction in precipitation, 40 to 70% reduction in annual runoff could occur. With still largely unregulated river systems, India is particularly vulnerable to hydrometeorological changes. In India, change in drought risk represents potentially the most serious impact of climate change on agriculture.

(d) *Interannual variability in simulated monsoon rainfall*

In order to understand the nature of year to year variability in simulated monsoon rainfall and likely changes in the future, the area-averaged seasonal (June to september, land points only) rainfall for 30 year period have been calculated from data generated by four skilled A-O GCMs in control experiment (years 1961-90), greenhouse gas forcing and greenhouse gas plus aerosol forcing experiments (years 2036-65). It is observed that while the simulated monsoon rainfall is 97.8 cm (maximum) in CCSR model, it is only 63.9 cm (least of the four models) in the ECHAM4 model (Fig. 10). The observed climatological mean monsoon rainfall over India is reported to be 85 cm with a standard deviation of ±8 cm. The standard deviation in simulated rainfall during the 30 year baseline period is also underestimated by the A-O GCMs. In the case of greenhouse gas forcing experiment, each of the four models suggest an enhancement in total amount of seasonal rainfall and its interannual variability (while there is no appreciable change in HadCM2 model, maximum increase is obtained in ECHAM4 model). In the combined greenhouse gas and aerosol forcing experiment, while the CSIRO and the HadCM2 models suggest a decline in total seasonal precipitation relative to control experiment, total simulated rainfall in the ECHAM4 and the CCSR models are more than that simulated in control experiment but lower than that simulated in greenhouse gas forcing only

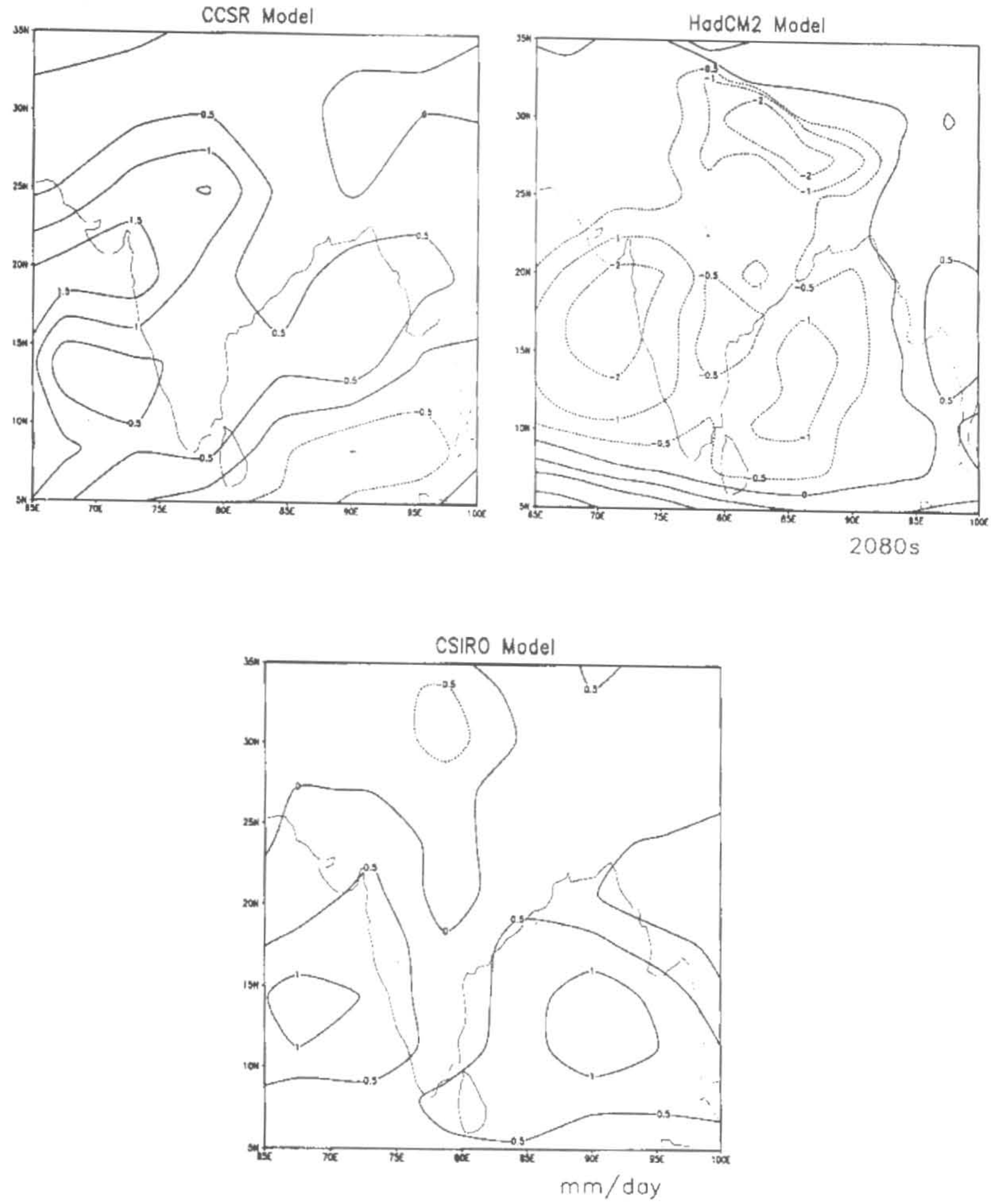

Fig. 9. Spatial distributions of likely changes in annual mean rainfall (mm day^{-1}) over the Indian subcontinent as simulated by the skilled A-O GCMs in the decade 2080s under the combined influence of greenhouse gas and aerosol forcing

experiment (Figs. 10 & 11). Each of the four A-O GCMs, however, suggest enhanced interannual variability in simulated monsoon rainfall in the combined greenhouse gas and aerosol forcing experiment. In view of above, we may infer that the projected changes in summer monsoon rainfall in the future could be marginally above the range

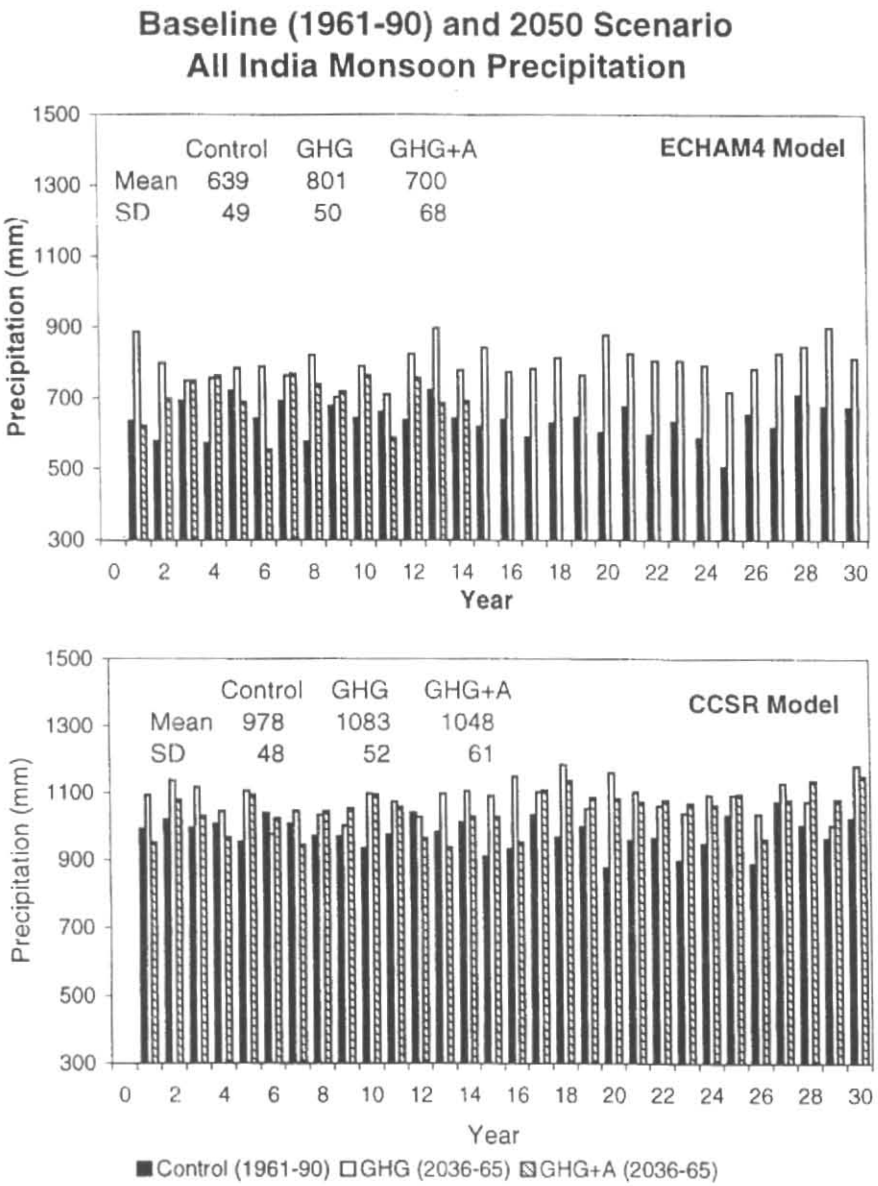

Fig. 10. Interannual variability in area-averaged monsoon rainfall over the Indian subcontinent as simulated by ECHAM4 and CCSR models in the control reference experiment (baseline period 1961-90) and under greenhouse gas forcing and combined greenhouse gas and aerosol forcing experiments (scenario period 2036-65)

of interannual variability observed over the region for the present-day atmosphere.

(e) *Indian monsoon as simulated in nested regional climate models*

The major impact of the monsoon is via the temporal and spatial variability of its precipitation. While the state-of-the-art A-O GCMs treat the complex interactions of atmospheric physics and planetary scale dynamics fairly well, coarse horizontal resolution in the models restricts realistic simulation of climatic details on spatial variability. Many investigations on the ability of GCMs in simulating the Asian monsoon have been reported in literature (e.g., Meehl & Washington, 1993; Chakraborty & Lal, 1994; Bhaskaran *et al*., 1995; Lal *et al*., 1995;

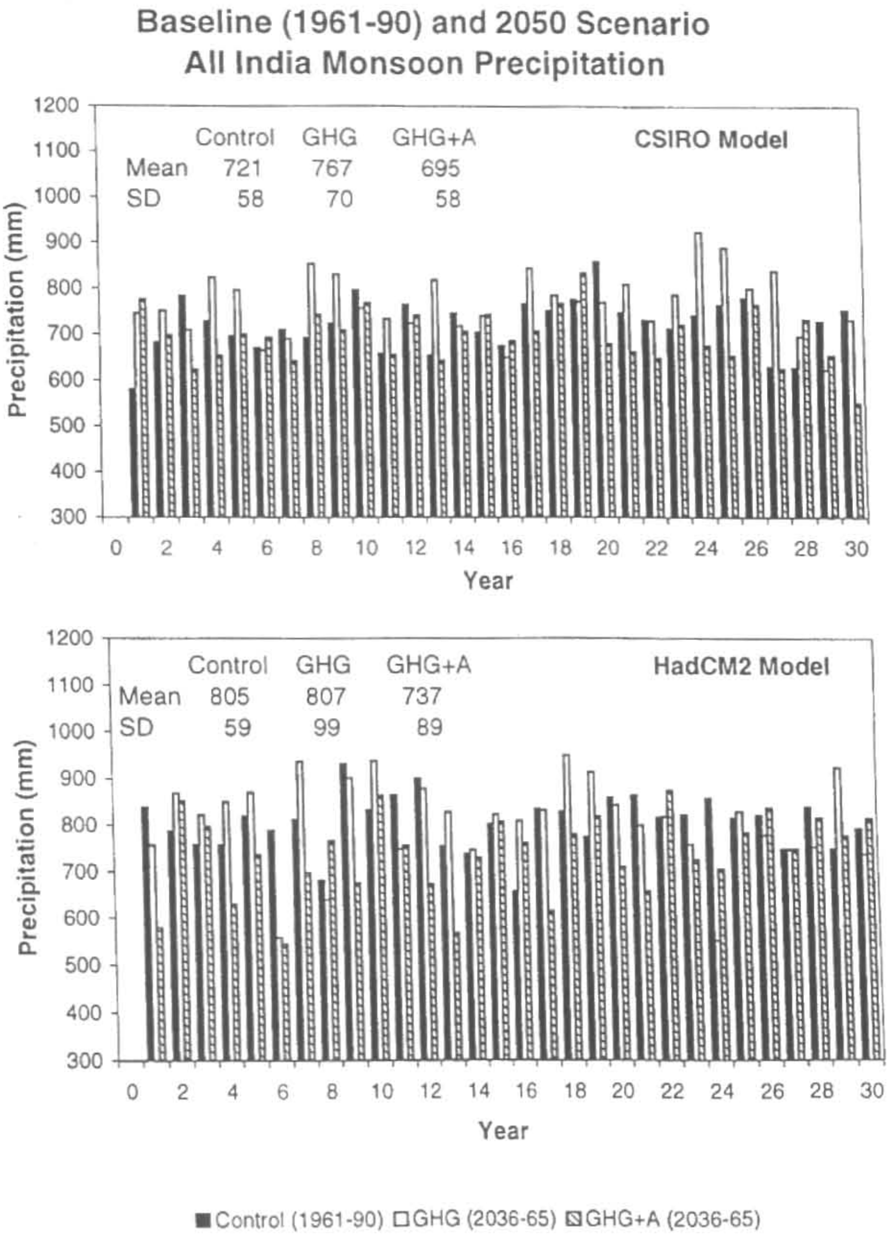

Fig. 11. Interannual variability in area-averaged monsoon rainfall over the Indian subcontinent as simulated by CSIRO and HadCM2 models in the control reference experiment (baseline period 1961-90) and under greenhouse gas forcing and combined greenhouse gas and aerosol forcing experiments (scenario period 2036-65)

1998a; 1998b). These suggest that while most GCMs are able to simulate the large scale monsoon circulation well, generally they are less successful with observed summer monsoon rainfall. A nested modelling approach has therefore been followed recently (Bhaskaran *et al.*, 1998; Lal *et al.*, 1998c; Hassell & Jones, 1999) to obtain more realistic mesoscale details and the response of greenhouse gas forcings to the surface climatology over the Indian monsoon region. The large scale patterns of temperature change simulated by GCM and nested regional climate model (RCM) are found to be generally similar under $2xCO_2$ forcing but the regional model results provide some additional details associated with coastline and local topographical features. Both GCM and RCM simulations suggest general increase in warming toward higher latitudes and greater warming in winter than in summer.

The rise in surface air temperature simulated by RCM over central and northern India is not as intense as GCM and does not extend as far south. These anomalies are linked with changes in surface hydrological variables. The intensification of heat low feeds back with decreases in soil moisture content (70%) and evaporation (50%). The summer precipitation exhibits more complex pattern of increases and decreases. While an increase in rainfall is simulated over the eastern region over India, the northwestern deserts see a small decrease in the absolute amount of rainfall in RCM simulation. Changes in soil moisture broadly follow the pattern similar to those in precipitation except in eastern India where they decrease due to enhanced drainage from the soil. Largest reductions (precipitation reduced to <1 mm day^{-1}; 60% decline in soil moisture) are simulated in the arid regions of northwest India and Pakistan. Projected increase in precipitation in flood prone Bangladesh is about 20%. The nested regional climate model simulations have the potential to simulate the onset of summer monsoon and its active/break cycle over India. The RCM but not the GCM captures the observed precipitation maxima over the southern tip of India during weak monsoon conditions. Under climate change scenario, the onset of summer monsoon over India is projected to be delayed by as much as 13 days (Hassell & Jones, 1999). The active/break periods in the lifetime of summer monsoon seem to increase in number but decrease in mean longevity.

6. Conclusion

The findings presented above highlight the potential influence of combined greenhouse gas and aerosol forcings on the rainfall scenario of the Indian subcontinent. As everywhere else, the demand for water is on the increase (and the availability on the decrease) in India as well. The situation in this regard tends to become more difficult as the population and their standard of living increase. The annual per capita availability of water in India has come down from 5236 m^3 at independence in 1947 to only 2267 m^3 in 1991, the year of the last national census. Obviously, the lean monsoon in the future could cause great hardship to people in India.

A good or bad monsoon makes all the difference in the availability of food in the region. Agriculture is not only the largest but the most crucial sector of India's economy. Out of the country's total arable area of about 140 million hectares (mHa), only about 75 mHa is irrigated and that also is monsoon dependent for rainfall in the catchment areas of the rivers that feed the reservoirs and canals. The productivity of this irrigated area seems to have reached a plateau and is showing signs of decline. As there is not much scope to expand the area under irrigation, it is essential for us to concentrate on increasing the productivity of the rainfed area which is about 60 mHa. It is in this context that the monsoon rainfall projections assume great importance because the rainfed areas (about 45% of the total arable area of the country) are almost totally dependent on the monsoon. Moreover, a large part of India's energy production is dependent on monsoon rains. A weaker monsoon, unable to fill hydel reservoirs, should lead to a fall in energy production creating severe power shortages in an already energy starved scenario. It has been estimated that the requirements of water for the energy sector would increase from approximately 20 km^3 per year in 1990 to 30 km^3 per year in 2000 and to 70 km^3 per year by the year 2025. This again underscores the crucial importance of monsoon rains and the proper utilization thereof in the coming years.

The scenarios presented here are based on the state-of-the-art A-O GCM experiments. Most of these GCMs have only been validated for the Indian subcontinent in respect to simulation of monthly mean temperature and rainfall climatology. Many other climatological features have not been verified in these simulations due to unavailability of simulated data. It is also evident from the illustrations that the GCMs considered here give varying estimates of the magnitude of regional climate change. There are uncertainties even with the future trends in atmospheric concentrations of greenhouse gases and aerosols. IPCC has recently adopted new emission scenarios (SRES scenarios) for the future. The state-of-the-art A-O GCMs used in this study have only recently been run for these new range of scenarios.

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. The simulation experiments referred to in here have considered only the direct cooling effect of sulfate aerosols produced by industrial activity. Considerable uncertainty prevails about the indirect effect of sulfate aerosols on tropospheric clouds which could strongly modulate the monsoon climate. We are still unclear about the implications of localized radiative forcing on the deep convection in the tropics and on Hadley circulation. 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 direct effect of biomass burning aerosols (Portmann *et al.*, 1997). However, geographical extent of increases in tropospheric ozone is considerably larger than that of aerosols. Precise magnitude as well as the role of these spatially localized potential forcings must be known before a confident prediction of regional changes in climate and its variability could be made.

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