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The Greenhouse Gas-Induced Climate Change over the Indian Subcontinent as Projected by General Circulation Model Experiments

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ABSTRACT

In order to assess the climatic impacts of increasing greenhouse gas concentrations in the atmosphere on the Indian subcontinent with a fair degree of confidence, we recently undertook an intercomparison study of a range of general circulation modelling experiments for which the data were available to us. This study (Lal *et al.*, 1998) reported our findings on the performance of each of the 17 global climate model experiments in simulating the present-day regional climatology over the Indian subcontinent. The analysis suggested that a few global climate models performed exceptionally well in their control simulation to represent the observed present-day climatological patterns over the region of interest. In this paper, we focus on the development of plausible climate change scenario for the Indian subcontinent based on selected model simulations with enhanced greenhouse gas forcings.

Our analysis suggests that, for a 1°C rise in mean annual global temperature, the seasonal surface air temperature increase over the Indian subcontinent is likely to range from 0.7°C to 1.1°C during winter and 0.6°C to 1.0°C during summer. The increase in summer precipitation associated with the projected scaled rise in surface temperature could be between 1.2% to 4.5%. The model results do not suggest any significant change in the winter precipitation over the region.

Taking into account the suggested range of climate sensitivity as well as the range of future greenhouse gas-induced global warming in selected general circulation model experiments, a plausible climate change scenario for the Indian subcontinent is developed for the years 2030 and 2070. A rise in mean winter surface air temperature of between 0.4°C to 1.7°C by the year 2030 and between 0.7°C to 3.4°C by the year 2070 is projected. During the summer season, the temperature rise is expected to range between 0.3°C to 1.4°C by the year 2030 and 0.6°C to 3.1°C by the year 2070. The study

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suggests intense spells of summer monsoon rainfall over the Indian subcontinent due to enhanced convective activity in a warmer atmosphere.

(Key Words: Global Climate Models, Global Warming, Regional Climate Change, Indian Subcontinent, Monsoon)

1. INTRODUCTION

A number of assessment studies to project the future changes in the observed climatology on a global scale as simulated by general circulation models (GCMs) have been reported (see IPCC, 1990; 1992 & 1996 for a detailed review). An assessment of future changes in the mean and / or variance of climatological parameters on regional scales due to anthropogenic increases in greenhouse gases is much warranted to evaluate the vulnerability of the region to such changes and to appropriately formulate adaptive response strategies. Some region-specific details on the climate change scenarios have been highlighted in IPCC Reports (1990, 1992 & 1996) and elsewhere in the literature (Whetton *et al.*, 1994, among others). The performance of a few of the GCMs in simulating the observed climate over the Indian subcontinent has been examined and the future climate changes over the region have been projected (Lal *et al.*, 1994; Chakraborty & Lal, 1994; Bhaskaran *et al.*, 1995). However, these studies focused mainly on the result of experiments with a particular model under consideration.

In order to gain a higher degree of confidence in the future climate change scenario due to enhanced greenhouse gases for the Indian subcontinent, a number of global climate models from different modelling groups of the world were considered in an intercomparison study (Lal *et al.*, 1998), and their skills in reproducing the observed climatology over the Northern Hemisphere and the Indian subcontinent were evaluated in control experiments. Three key climate parameters, namely the mean sea level pressure, surface temperature and precipitation, were examined for the purpose. To assess the model performance quantitatively, we calculated pattern correlation coefficients and root mean square errors between the model-simulated and the observed key climatological parameters in both winter and summer. In addition, the interseasonal temperature range over north-central India, the summer land-to-sea temperature gradient, the major circulation features associated with summer monsoon and the amount and seasonality of the rainfall over the Indian subcontinent were also compared to determine the relative skill of the individual model experiments (for further details refer to Lal *et al.*, 1998). This analysis suggested that, five of the seventeen model experiments (DKRZO, UKMOH, CCC, BMRC and CSIRO9) were able to simulate the present-day climatology over the study region with considerable skill (higher pattern correlation coefficients). Another four model simulations (GFDLQ, GFDLH, UKMO and DKRZL) had limited skill (moderate pattern correlation coefficients) for the region of interest. Based on the data from anomaly experiments with the models showing skill in their control experiment, in this paper we present and discuss a quantitative assessment of future climatic changes expected over the Indian subcontinent.

2. THE MODELS USED

The simulated climate data used for this study are obtained from the anomaly runs of different versions of the GCM developed at Max Planck Institute for Meteorology (experiments named DKRZO and DKRZL), Germany; United Kingdom Meteorological Office (experiments named UKMO and UKMOH), UK; Canadian Climate Centre (experiment named CCC), Canada; Bureau of Meteorology Research Centre (experiment named BMRC), Australia; Commonwealth Scientific and Industrial Research Organisation (experiment named CSIRO9), Australia; and Geophysical Fluid Dynamics Laboratory (experiment named GFDLQ and GFDLH), USA. A brief reference on these models and experiments is listed in Table 1. These models have many inherent differences as regards their vertical and horizontal resolution, convection and other parameterisation schemes, surface orography and the role and dynamicity of oceans. The list of experiments includes both slab ocean experiments (where the atmospheric model interacts with an ocean model which represents only the surface mixed layer of the ocean and has inferred oceanic transports), and coupled ocean experiments (where a full ocean model is coupled to the atmospheric model). Depending upon their skill in representing the observed Northern Hemispheric and Indian regional climatology in control simulation (high and moderate pattern correlation coefficients between observed and model-simulated mean sea level pressure, surface temperature and precipitation), the model experiments are grouped into two categories. The first group comprises best performing model experiments (DKRZO, UKMOH, CCC, BMRC and CSIRO9) while, the second group includes model experiments with limited skill (GFDLQ, GFDLH, UKMO and DKRZL).

3. REGION OF INTEREST & SPECIFIC CLIMATE ELEMENTS

The geographic region of interest for this study is the monsoon area bounded by latitude 1.6°N to 33.5°N and longitude 61.9°E to 95.6°E (Indian subcontinent and adjoining seas). For all assessment purposes, we have analysed the data from the enhanced greenhouse simulations

Table 1. A brief description of GCM experiments used in this study.

Classification	Experiment Acronym	Horizontal Resolution (Number of Waves or Lat x Long)	Reference
Low Resolution Flux Corrective Experiments	GFDLQ	R 15	Manabe & Wetherald (1987)
	UKMO	5^ox7.5^o	Wilson & Mitchell (1987)
Medium Resolution Flux Corrective Experiments	DKRZO	T 21	Lunkeit et al. (1994)
	DKRZL	T 21	Cubasch et al. (1992)
	CSIRO9	R 21	McGregor et al. (1993)
	BMRC	R 21	Colman et al. (1994)
High Resolution Flux Corrective Experiments	CCC	T 32	McFarlane et al. (1992)
	GFDLH	R 30	Houghton et al. (1990)
	UKMOH	2.5^ox3.75^o	Senior (1993)

for winter (December, January and February; DJF) and summer (June, July and August; JJA) seasons. The June to August period is regarded as the peak period for southwest monsoon activity and contributes about 55% of the observed total annual rainfall averaged over the Indian subcontinent. The December to February (DJF) period is the relatively dry winter season over the study region.

The climatic elements examined here are surface air temperature and precipitation. There are some additional elements representing the state of the free atmosphere, which could be considered, but they are of limited direct relevance to the impact assessment study and to some extent are themselves related to the selected fields. The choice of fields considered here is basically determined by the importance of respective parameters for impact assessment purposes and also on the availability of data sets.

4. ASSESSMENT OF FUTURE CLIMATE CHANGE

There are still many uncertainties involved in GCMs and the nature of future radiative forcings which limit our ability to provide precise global warming projections. The state-of-the-art GCMs used in climate change experiments suggest a range of global warming between 1.5 and 4.5°C for a doubled CO_2 atmosphere. Consequently, we have scaled the changes in regional climate with respect to global warming of 1°C in our assessment presented here.

Tables 2 and 3 list the area-averaged changes in the key climatic parameters quantitatively as inferred from the anomaly experiments of different GCMs under enhanced greenhouse gas conditions in the atmosphere for the December to February period (winter season), and for the June to August period (summer season), respectively. The best and moderately skilled models (in their control simulations on a regional scale) are listed herein in two different groups. The annual mean global surface air temperature changes (column II in Tables 2 and 3) obtained from different model experiments are not representative of similar greenhouse gas-induced radiative forcing in the atmosphere. The DKRZO and DKRZL model experiments represent the temperature increase under Business-as-Usual Scenario for greenhouse gases (an increase in equivalent CO_2 at a compounded rate of ~1.3% per year; Scenario A of IPCC, 1990) whereas, other model experiments consider the equilibrium doubled CO_2 concentration in the atmosphere. However, the global warming expected in the last decade of the 100 year simulation with coupled GCMs (DKRZL and DKRZO Scenario A experiments) should resemble the warming simulated by the GCMs with mixed layer ocean for instantaneously doubled CO_2 forcing since transient simulations attain only about 60% of the equilibrium warming at the time of doubling of CO_2 (Cao *et al.*, 1991; IPCC, 1992). Assuming a response time of the coupled GCMs of about 35 years (Meehl & Washington, 1995), they would have obtained the amplitude of the CO_2 equilibrium response in around 100 years of simulated time when the transient greenhouse gas forcing had just reached the 3 x CO_2 mark. The seasonal temperature changes over the Indian subcontinent are listed under column III of Tables 2 and 3. The next column in these Tables lists the regional temperature change likely to occur over the subcontinent if, the global temperatures were to rise by 1°C. These numbers (column IV) inferred from different models should be comparable with each other irrespective of whether the simulation was carried out with instantaneous doubling of CO_2 or with Busi-

Table 2. The area-averaged changes in key climatic parameters over the Indian subcontinent during NH winter as simulated by the selected GCMs in a greenhouse gas-induced warmer atmosphere.

MODELS	**Annual Mean Global Temperature Change, °C**	Regional Temperature Change, °C	**Scaled Temperature Change**	Regional Rainfall Change,%	**Scaled Rainfall Change**
DKRZO	1.70	1.83	1.08	4.09	2.41
UKMOH	3.49	3.50	1.00	21.01	6.02
CCC	3.51	2.59	0.74	-16.54	-4.47
BMRC	2.20	1.79	0.81	-17.34	-7.88
CSIRO9	4.84	4.08	0.84	15.54	3.21
Mean			**0.89**		**-0.19**
Standard Deviation			**±0.13**		**±5.22**
UKMO	5.28	4.78	0.91	-18.14	-3.43
GFDLQ	4.88	2.77	0.57	58.48	11.98
GFDLH	5.16	2.90	0.56	-10.13	-1.96
DKRZL	1.31	1.83	1.40	25.51	19.47
Mean			**0.86**		**6.52**
Standard Deviation			**±0.34**		**±9.60**

ness-as-Usual Scenario although there could be systematic differences in the pattern of warming between coupled and slab ocean models *e.g.*, faster warming over the land relative to the ocean. Column V in Tables 2 and 3 lists the percentage change in the amount of regional precipitation under enhanced greenhouse gas conditions while column VI represents the same for a 1°C rise in the annual mean global surface air temperature. In the following, we shall discuss individually the changes in these two climatic elements as simulated by the selected climate models over the region of interest.

4.1 Regional Surface Air Temperature Change

The area-averaged surface temperature change likely over the Indian subcontinent for a 1°C annual mean global warming (as simulated by the five best performing GCMs) ranges from 0.74°C (CCC model simulation) to 1.08°C (DKRZO model simulation) during the winter season (Table 2). The inferred mean change in surface air temperature from these five GCMs is 0.89°C with a standard deviation of ±0.13°C. The range of scaled temperature change projected by the moderately skilled GCMs is rather large in comparison to that projected by

Table 3. The area-averaged changes in key climatic parameters over the Indian subcontinent during NH summer as simulated by the selected GCMs in a greenhouse gas-induced warmer atmosphere.

MODELS	**Annual Mean Global Temperature Change, °C**	Regional Temperature Change, °C	**Scaled Temperature Change**	Regional Rainfall Change,%	**Scaled Rainfall Change**
DKRZO	1.70	1.77	1.04	7.69	4.52
UKMOH	3.49	3.45	0.99	8.86	2.54
CCC	3.51	2.09	0.60	13.85	3.95
BMRC	2.20	1.63	0.74	-3.03	-1.38
CSIRO9	4.84	3.24	0.67	5.85	1.21
Mean			**0.81**		**2.17 (3.06*)**
Standard Deviation			**±0.16**		**±2.11 (±1.29*)**
UKMO	5.28	4.00	0.76	13.05	2.47
GFDLQ	4.88	2.46	0.50	44.16	9.05
GFDLH	5.16	2.22	0.43	32.92	6.38
DKRZL	1.31	1.33	1.02	5.22	3.98
Mean			**0.68**		**5.47**
Standard Deviation			**±0.23**		**±2.47**

* Numbers excluding the BMRC model results.

the best performing GCMs. The GFDL model experiments simulate lower regional temperature change (~0.6°C in both the GFDLQ and GFDLH simulations), while the DKRZL model suggests a higher value (1.40°C) for a 1°C annual mean global warming. Obviously, though the mean scaled temperature change from the four moderately skilled GCM experiments is closer to the best performing GCMs (0.86°C), the standard deviation is higher (±0.34°C).

During summer (Table 3), the five best performing GCMs suggest an area-averaged temperature change of between 0.60°C (CCC model simulation) and 1.04°C (DKRZO model simulation) over the Indian subcontinent for a 1°C rise in annual mean global surface temperature. This suggests a mean simulated summer surface warming of 0.81°C with a standard deviation of ±0.16°C. The moderately skilled GCMs project a higher range in the scaled temperature change over the region (from 0.43°C in GFDLH model simulation to 1.02°C in DKRZL model simulation) with a mean rise in surface air temperature of 0.68°C for a 1°C annual mean global warming (standard deviation is ±0.23°C).

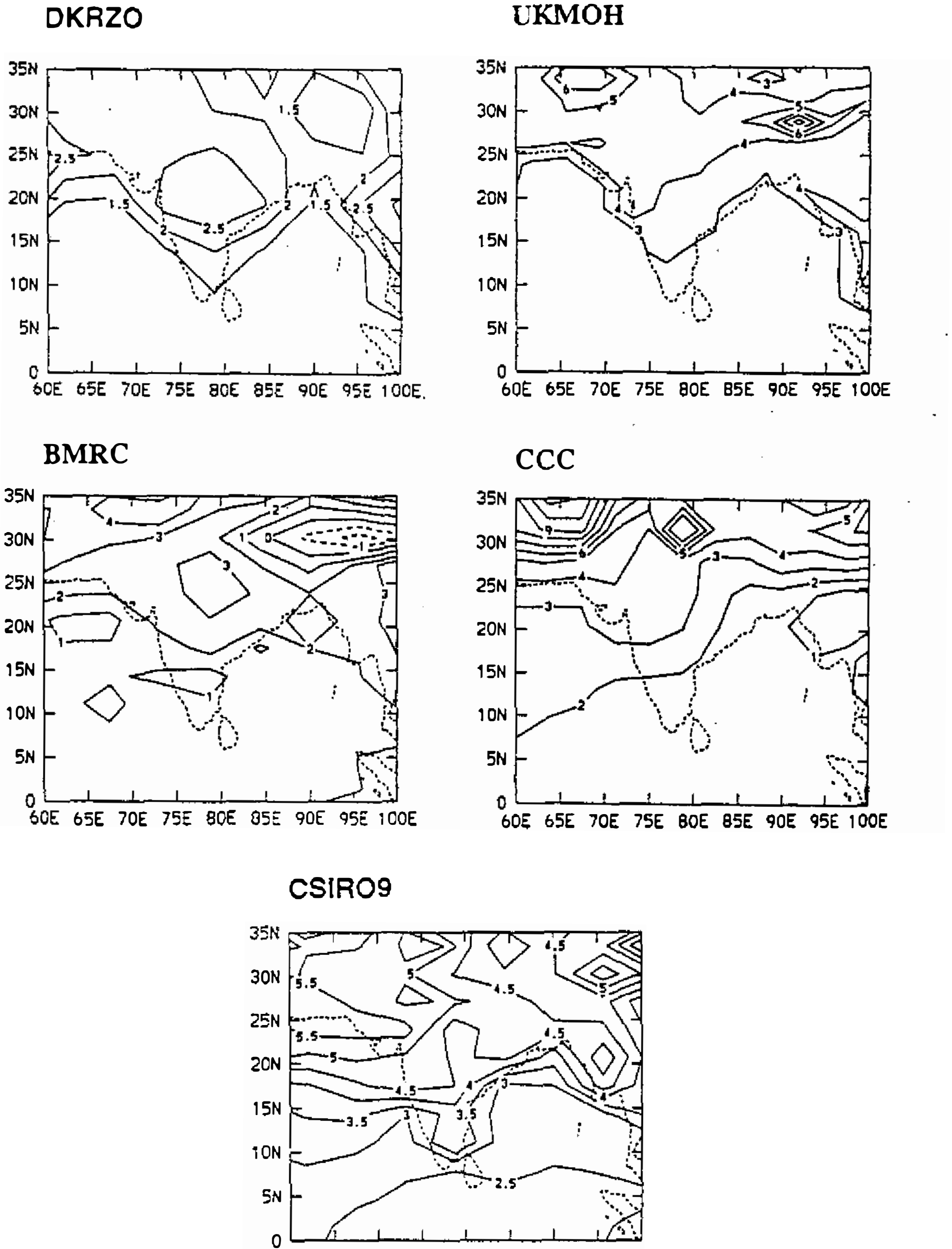
The spatial distribution of surface warming over the Indian subcontinent averaged for the winter season at the time of doubling of CO_2 in the atmosphere, as simulated by the five best performing GCMs, is depicted in Figure 1. The DKRZO experiment simulates peak warming of about 2°C over north and central India. The UKMOH simulation exhibits a surface warming of 4°C over north India during winter. Over most of the south Indian region, the warming is about 3°C during the winter season. The surface air temperature rise over north and central India as simulated by the CCC model ranges from 2 to 4°C whereas, over the southern India, it is lower than 2°C. The BMRC simulation projects a winter temperature rise of 2 to 3°C over most parts of north and central India under doubled CO_2 conditions. The surface warming due to doubling of CO_2 in the atmosphere simulated in the CSIRO9 experiment is the largest of all. The CSIRO9 experiment suggests that, during the winter months, the northern and central Indian region may experience a temperature rise of over 4.0°C and, the south Indian land temperature may rise from 3.0 to 4.0°C.

Figure 2 depicts the spatial distribution of model-simulated surface warming during summer season. The DKRZO experiment simulates a warming of 1.5 to 2.5°C over land regions of the Indian subcontinent. The model-simulated temperature rise over the south Indian region is close to 1.5°C. The UKMOH model simulates a surface warming of between 2 and 5°C over most parts of north, central and east India during the summer months. Over south India, a temperature rise of about 2°C is simulated. The CCC model simulation does not exhibit a substantial change in surface temperature over a large part of the central Indian region. Over south India, a rise of about 1 to 2°C in surface air temperature is simulated in the CCC model. The BMRC model also simulates a surface warming of between 1° and 2°C over the Indian subcontinent during summer season. In the CSIRO9 model simulation, the surface temperature rise is more pronounced over the northern and eastern regions of India (3 to 4°C) during summer months.

It is interesting to note that, although the range and spatial distribution of projected future warming varies considerably among the models, all models simulate an increase in regional average surface air temperature due to enhanced CO_2 concentration in the atmosphere. Moreover, the projected warming is more pronounced during the winter than during the summer in all the models considered in the study. A large part of the lack of consensus among various models could be attributed to the differences in their representation of highland orography due to varying horizontal resolution and to differences in their parameterisation schemes for treatment of clouds and other sub-grid scale processes. Greenhouse gas-induced surface warming may produce an increase in cloud water content (the water holding capacity of the air increases with a rise in temperature) and could 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 high clouds). Global climate models seem to disagree about the net cloud radiative effect which depends crucially on the optical properties of clouds at solar and infrared wavelengths.

4.2 Regional Precipitation Change

The projected precipitation change over the Indian subcontinent in the winter months is of relatively less practical importance than that likely during the summer months. The summer


DKRZO

UKMOH

BMRC

CCC

CSIRO9

Fig. 1. Spatial distribution of projected changes in surface air temperature (°C) over Indian subcontinent during winter as simulated by selected global climate models.

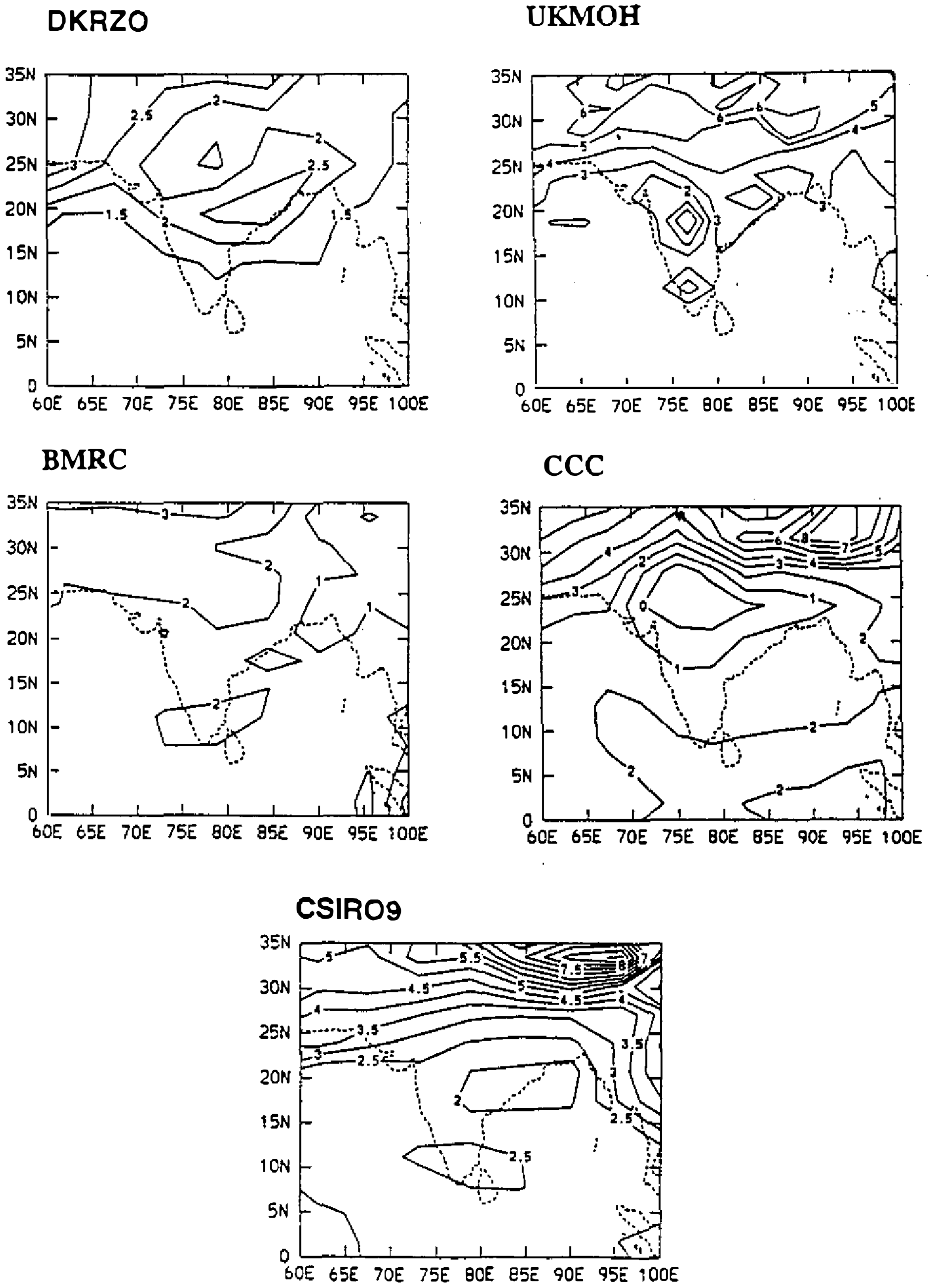


Fig. 2. Spatial distribution of projected changes in surface air temperature (°C) over Indian subcontinent during summer as simulated by selected global climate models.

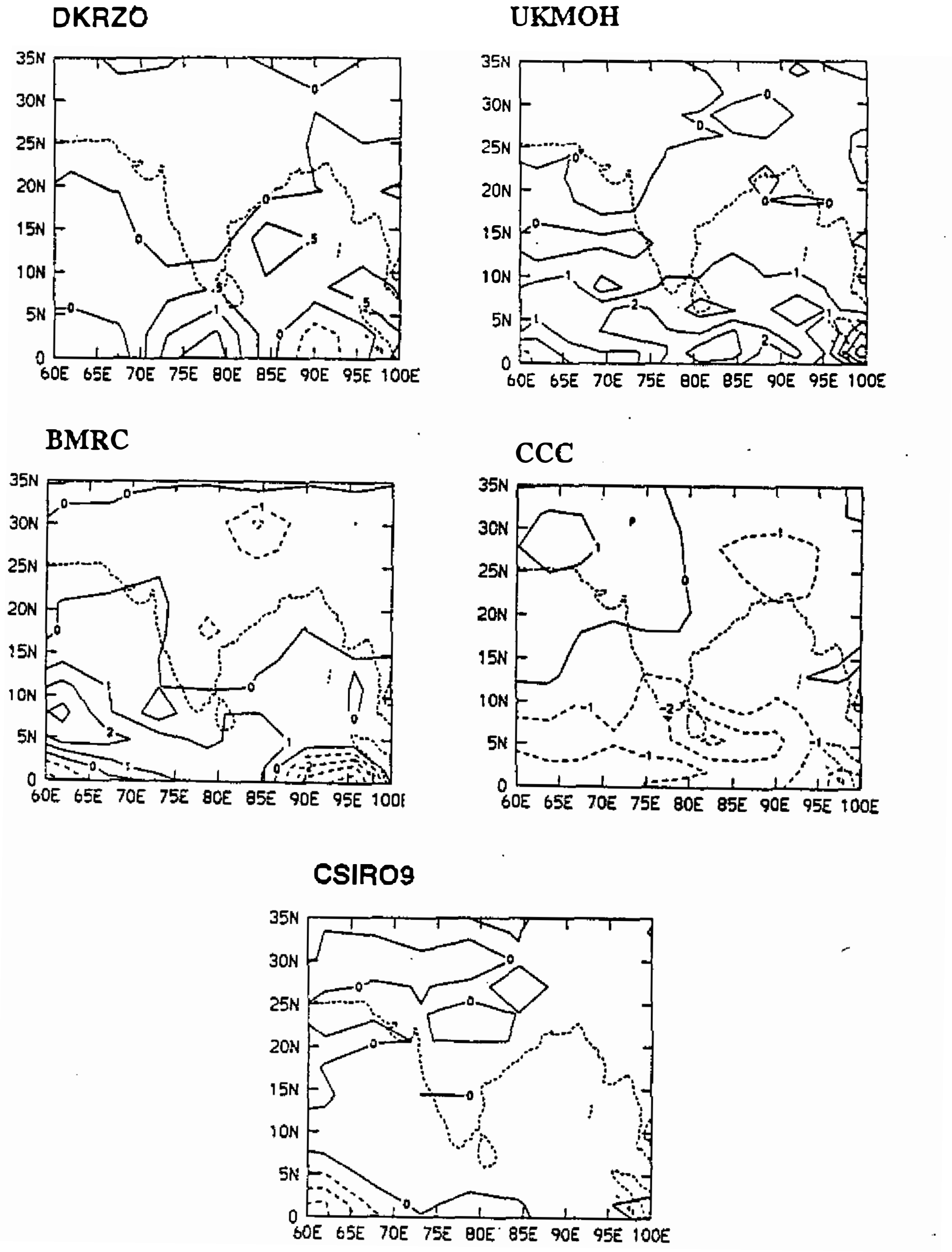
season is regarded as the peak period for southwest monsoon activity and contributes about 55% of the observed total annual rainfall averaged over the subcontinent. A marginal decline in the winter precipitation over the north east India is simulated in the CCC and BMRC model experiments, while all other best performing models simulate a small increase in area-averaged winter precipitation over India due to enhanced greenhouse forcing (Table 2). Among the moderately skilled models, the UKMO and GFDLH simulations exhibit a marginal decrease, whereas the GFDLQ and DKRZL simulations predict a rather sharp increase in area-averaged winter precipitation.

During the summer monsoon season, the BMRC model simulation projects a decrease in area-averaged rainfall over India while all other model experiments suggest an increase in area-averaged summer precipitation primarily due to enhanced convective activity in a warmer atmosphere (Table 3). A closer examination of the precipitation distribution patterns over the Indian region simulated by the BMRC model experiment suggests that all of north and central India experiences a decrease in precipitation in this model experiment under enhanced greenhouse forcing (Figure 3). One possible explanation for this could be that the monsoon trough in the BMRC model simulation (not shown) is placed further north along the foothills of the Himalayas in its doubled CO_2 simulation experiment, thus creating 'break monsoon' like conditions. The land-sea thermal contrast is less in a doubled CO_2 atmosphere than in the control experiment in the BMRC model simulation and this should lead to a general weakening of the monsoon circulation and hence to less moisture convergence over the region. It may also be recalled that the projected surface warming over the land regions of the Indian subcontinent in the BMRC simulation is less than in the other skilled GCM simulations.

Among the other skilled GCMs, the area-averaged precipitation increases from as low as 1.21% (CSIRO9 simulation) to as high as 4.52% (DKRZO simulation) for a 1°C annual mean global warming during the summer months. In model experiments of limited skill, the GFDLQ and GFDLH model experiments simulate sharper area-averaged increases in summer-scaled precipitation (9.05% and 6.38% respectively) as compared to the UKMO and DKRZL model experiments (2.47% and 3.98% respectively) over the Indian subcontinent.

The spatial distribution of changes in winter precipitation in a CO_2 enriched warmer atmosphere as simulated by the models with skill in their control experiment is presented in Figure 3. The DKRZO, UKMOH and CSIRO9 model experiments do not exhibit any significant change in spatial pattern of winter precipitation over land regions of the Indian subcontinent. The CCC and BMRC models, however, predict a marginal decrease in precipitation over some parts of south and east India.

During the summer season, the changes in precipitation distribution in a warmer atmosphere, as simulated by skilled model experiments, are depicted in Figure 4. The DKRZO model simulation suggests an increase in precipitation over almost all parts of the Indian subcontinent. The western semi-arid margins, southern and eastern regions of India are likely to experience increase in rainfall by 0.5 to 1.0 mm/day whereas, some parts of central India may receive rain in excess by 2 mm/day in a warmer atmosphere. The UKMOH experiment simulates an increase in precipitation of 2 to 6 mm/day along the west coast and of 3 to 4 mm/day over West Bengal and Bangladesh. Over the rest of the continent, no significant change in precipitation is simulated. The CCC model experiment suggests an increase of 2 to 8 mm/day



DKRZO

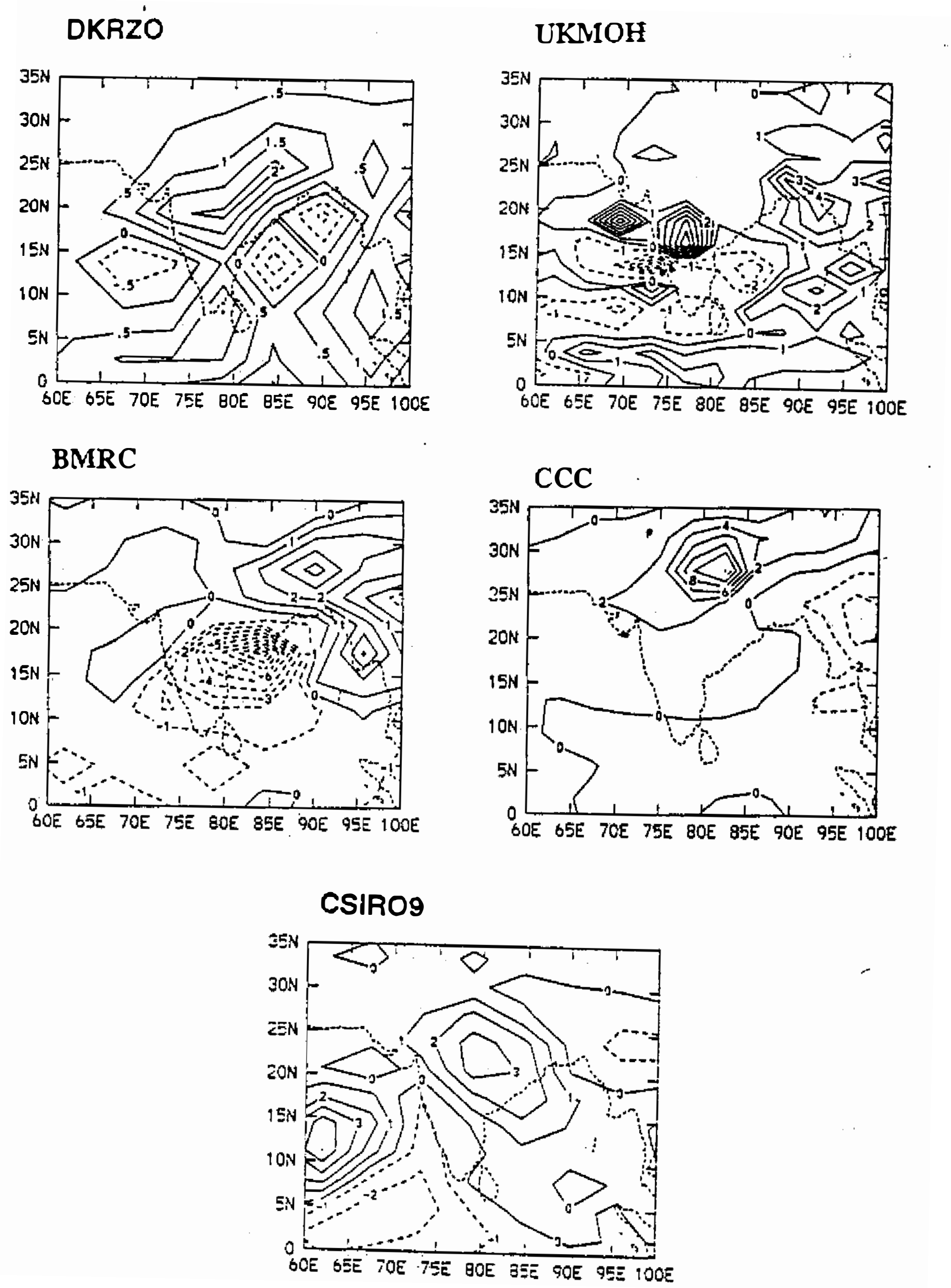
UKMOH

BMRC

CCC

CSIRO9

Fig. 3. Spatial distribution of projected changes in rainfall (mm day^{-1}) over Indian subcontinent during winter as simulated by selected global climate models.



DKRZO

UKMOH

BMRC

CCC

CSIRO9

Fig. 4. Spatial distribution of projected changes in rainfall (mm day^{-1}) over Indian subcontinent during summer as simulated by selected global climate models.

in precipitation over parts of north-central India during summer months in a doubled CO_2 atmosphere. The CSIRO9 model simulates a 1 to 3 mm/day increase in summer precipitation over the central plains with no significant change over other parts of India. A considerable decrease in summer seasonal precipitation is simulated in the BMRC experiment over the southern India (~ 6 mm/day) in a doubled CO_2 atmosphere.

5. CLIMATE CHANGE SCENARIO FOR THE INDIAN SUBCONTINENT

The results from the available global climate model experiments suggest that if the atmospheric CO_2 concentration be instantaneously doubled from its pre-industrial level and the climate were allowed to come down to a new equilibrium, the resultant increase in global mean surface air temperature would lie in the range of 1.5° to 4.5°C. This is generally referred to as climate sensitivity. A logical step in preparing regional climate change scenarios involves the reasonable estimates on the likely future course of global warming with an allowance made for the multitude of possible combinations of various greenhouse gas emission scenarios and sensitivities of the climate system. Scenarios of future global mean surface warming that take into account the range of climate sensitivity, as well as a range of future greenhouse gas emissions, have been reported in IPCC (1996). Based on these scenarios, the global warming is likely to range between 0.4° and 1.2°C by the year 2030 and between 0.7° to 3.0°C by the year 2070. A scenario for future climate change on a regional scale must allow for this uncertainty associated with global climate change scenarios. Using these scenarios of global warming as a scaling factor, we have generated the most plausible climate change scenario for the Indian subcontinent for the years 2030 and 2070.

Table 4 lists the likely changes in area-averaged temperature and precipitation over the Indian subcontinent by the years 2030 and 2070 based on GCM simulations as a consequence of greenhouse gas-induced global warming. The estimates suggest that, due to higher greenhouse gas concentrations, the average surface air temperature during the winter season over

Table 4. Projected scenarios of surface temperature and rainfall change over the Indian subcontinent for the years 2030 and 2070 based on skilled GCM simulations.

Climatic Elements	Regional Change for 1°C global warming	Anticipated Change by the year 2030	Anticipated Change by the year 2070
	Winter (DJF)		
Temperature, °C	0.7 to 1.1	0.4 to 1.7	0.7 to 3.4
Rainfall (%)	not significant	not significant	not significant
	Summer (JJA)		
Temperature, °C	0.6 to 1.0	0.3 to 1.4	0.6 to 3.1
Rainfall (%)	1.2 to 4.5	0.7 to 6.2	1.1 to 13.4

the Indian subcontinent could rise between 0.4° and 1.7°C by the year 2030 and between 0.7° and 3.4°C by the year 2070. During the summer season, the expected warming ranges between 0.3°C and 1.4°C by the year 2030 and between 0.6° and 3.1°C by the year 2070. No definite projections are suggested regarding the area-averaged changes in winter precipitation (land points only) over the Indian subcontinent. During the summer months, the average precipitation over land regions of India could rise by between 0.7% and 6.2% by the year 2030 and between 1.1% and 13.4% by the year 2070. In these projections, we have excluded the future precipitation changes simulated by the BMRC experiment due to its lack of agreement with the other GCM simulations on the sign of rainfall change over the region.

6. DISCUSSION OF RESULTS AND MODEL LIMITATIONS

In the preceeding section, we have summarized an assessment on the future climatology of the Indian subcontinent in a CO_2 enriched warmer atmosphere based on the enhanced greenhouse experiment results of all the GCMs considered in this study. In a study reported earlier (Lal *et al.*, 1998), these GCMs were identified as having substantial skill in simulating the present-day climatology of the Indian subcontinent and include the DKRZO, UKMOH, CCC, BMRC and CSIRO9 model experiments as the best performing GCM experiments and the DKRZL, GFDLQ, GFDLH and UKMO GCM experiments as those of moderate skill. A set of plausible climate change scenarios for the Indian region is developed taking into account both the range of climate sensitivities as well as that of future greenhouse gas emissions reported in IPCC (1996). Projections for future area-averaged temperature and precipitation changes over the Indian subcontinent in the next century are also highlighted.

Among the skilled model simulations, the DKRZO model experiment exhibited the highest regional mean warming for a 1°C rise in annual mean global temperature during both the summer and winter seasons over the Indian subcontinent, while the CCC model experiment simulated the anticipated warming to be the lowest. Among the model experiments of limited skill, the DKRZL experiment showed the highest while the GFDLH experiment exhibited the lowest relative magnitude of warming for a 1°C rise in annual mean global temperature. It is thus evident that the models with a dynamic ocean component (DKRZO and DKRZL) are more sensitive indicators of regional warming with respect to the simulated rise in mean annual global temperature. In contrast, the magnitude of global and regional warming is more pronounced in the enhanced greenhouse simulations of the atmospheric models attached to a slab ocean component. The CSIRO9 model simulates the highest area-averaged warming over the Indian region during both seasons in a doubled CO_2 atmosphere. In general, the model results suggest that north India is likely to be more vulnerable to greenhouse gas-induced warming than the southern peninsula.

During the summer season, increased surface air temperature over India due to higher greenhouse gas-induced radiative forcing in the atmosphere is expected to increase the convective activity and hence the monsoon rainfall. This increment is noticed in all the model simulations except in the BMRC experiment results. Among the best performing models, the DKRZO experiment results exhibit maximum increase in summer rainfall for a 1°C rise in simulated annual mean global temperature. A significant increase in area-averaged summer monsoon precipitation is also observed in the GFDLQ and GFDLH simulations amongst the model experiments of limited skill. The changes in the amount of monsoon rainfall over India in the GFDLQ and GFDLH model simulations are found to be more sensitive to the simulated increase in annual global mean temperature.

Changes in the simulated spatial distribution of seasonal rainfall pattern over the Indian subcontinent depend on adequate representation of surface orography and hence on model resolution (which vary considerably from one model to another). The Global Climate Models are principally designed to simulate the large scale features of the global climate. The regional climates from these global climate models lack the finer scale details which could be attributed to poor representation of mesoscale climate forcings (*e.g.*, orography, complex coastline, vegetation characteristics and inland water bodies) in a coarse resolution model. With the high resolution GCM experiments being currently conducted by leading modelling groups, we expect that the uncertainty in projections of future rainfall scenarios will be reduced substantially in the coming years owing to better representation of surface topography and implementation of improved parameterisation of sub-grid scale physical processes in climate simulation experiments.

The climate experiments, using atmospheric GCMs coupled to a simple representation of the ocean, are aimed at quantifying an equilibrium climate response to an instantaneous doubling of the concentration of equivalent CO_2 in the atmosphere. Such a response portrays the final adjustment of the climate to the change in atmospheric CO_2 concentration. The temporal evolution and the regional patterns of climate change may depend significantly on the time dependence of the changes in radiative forcing. It is, therefore, more appropriate to rely on future projections made using plausible evolving scenarios of anthropogenic greenhouse gas forcing and transient experiments with coupled atmosphere-ocean models (*e.g.*, DKRZL and DKRZO experiments considered in this study). More recent long-term transient simulations with coupled A-O GCMs are now available from several modelling groups and their results should be analysed in the future.

The IPCC Report (1995; 1996) has identified sulphate aerosols as a secondary, but potentially important, component that can also affect the climate system by changing the radiative balance of the atmosphere. Sulphate aerosols interact with solar radiation and enhance the earth's albedo, thereby reducing the surface temperature. As the anthropogenic sulphate aerosol burden in the troposphere would have large spatial and temporal variations in the atmosphere, its future impact on a regional scale would be in striking contrast to that from greenhouse gases for which the concentration changes, in most cases, are likely to be uniform throughout the globe. A recent study (Lal *et al.*, 1995) has suggested that the model-simulated past trends in mean surface warming over the Indian subcontinent can be reconciled with the observed warming trends only when the cooling effect of aerosols on climate has been accounted for. In contrast to simulations which consider only greenhouse gas-induced radiative forcing, a decline in summer monsoon rainfall over India has been simulated in a few recent GCM experiments which have included the combined greenhouse gas and sulphate aerosol forcings (IPCC, 1996). However, only the direct effects of sulphate aerosols have been considered herein. In view of this, the future projections of summer monsoon rainfall reported here are highly uncertain.

7. CONCLUSIONS

The results of simulations with enhanced greenhouse gas forcings from a set of selected general circulation models (nine in total) have been analyzed to assess the possible future greenhouse gas-induced changes in the climate of the Indian subcontinent. These models demonstrated reasonable skill in simulating the observed present-day climatology in their control experiments. A plausible climate change scenario for the Indian subcontinent for the years 2030 and 2070 has also been developed.

Our study was confined only to the assessment of the expected greenhouse gas-induced changes in the two key climatic elements, namely temperature and precipitation. Over the Indian subcontinent, all the models suggest an increase in seasonal mean temperatures. The projected warming is more pronounced during the winter than during the summer. The model results also suggest that increased convective activity in the summer season due to this warming could lead to intense rainfall over the land regions of the continent.

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 GCM experiments performed so far have considered only the direct cooling effect of sulphate aerosols produced by industrial activity. Considerable uncertainty prevails about the indirect effect of sulphate 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 the 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 climate and its variability could be made.

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