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Monsoon Climate and Its Change in a Doubled CO_2 Atmosphere as Simulated by CSIR09 Model

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ABSTRACT

In this paper, the author present an assessment of the likely climate changes over the Indian subcontinent and the intraseasonal and interannual variability in summer monsoon rainfall as a consequence of increasing greenhouse gas concentrations in the atmosphere as inferred from CSIRO9 climate model simulations. The data obtained from the control and doubled CO_2 experiments with the model, each for 24-equilibrium years, are analyzed in this study.

The model demonstrates a reasonable skill in simulating the present-day climate and its interannual variability over the Indian subcontinent. The total seasonal rainfall over India under the influence of southwest monsoon activity as inferred from the control run is in fair agreement with the observed climatology. A rise in area-averaged surface temperature of 2.98° during the monsoon season over India (for land points only) is projected by the model in a doubled CO_2 atmosphere. Though no significant change in the monsoon onset date is found, an intensification of monsoonal rainfall is simulated by the model in a warmer atmosphere. The seasonal changes in the other hydrological parameters (evaporation and soil moisture) simulated by the model for the doubled CO_2 atmosphere are also discussed.

(Key words: Global warming, Climate models, Indian subcontinent, Monsoon, Inter-annual variability)

1. INTRODUCTION

In the tropics, the amplitude of the annual cycle in surface temperatures is far greater over land than over the oceans. This results in the seasonal reversal of the land-ocean temperature difference that drives the regional monsoon circulation. While the rainy season is short and unreliable along the western semi-arid margins of the Indian subcontinent, a series of monsoon depressions forming over the Bay of Bengal travels in a northwesterly direction and leads to recurrent flooding in Bangladesh and the adjoining hilly regions of

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India. More or less than the normal monsoon rainfall over the Indian subcontinent may be catastrophic or beneficial depending upon the timing, location and intensity.

To study the effect of the doubling of CO_2 concentrations in the atmosphere on the earth's climate, a hierarchy of climate models have been developed. Prior to assessing the climate change due to greenhouse forcing, it is important to determine how well each model simulates the present-day climate over the region of interest. This paper attempts to validate the performance of the CSIRO9 R21 general circulation model over the Indian monsoon region based on the output available from the reference control experiment. An assessment of the possible change in the monsoon climate under doubled CO_2 conditions likely by the middle of the next century is discussed as well.

2. THE MODEL

The 9-level general circulation model (CSIRO9) was developed at the commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, following the spectral AGCM of the Numerical Meteorology Centre (Gordon 1983; Gordon and Hunt 1987; Hunt and Gordon 1988, 1989) . A slab ocean model with prescribed heat convergence was coupled with this model to implicitly determine sea surface temperatures. A comprehensive range of "Physical" processes including radiation and precipitation acting as forcings of dynamical equations were included in the model. The diurnal and seasonal cycles were appropriately represented in the model. The lower boundary condition of the atmosphere was determined by an interactive land surface scheme. The cloud cover, snow and sea ice were self determining properties in the model. A "flux" form of the dynamical equations which ensures that conservation of mass and energy can be readily achieved was used in the model to perform multi-year integrations for climate studies. The truncation wave number of rhomboidal 21 enabled the model to have a 3.26° latitude × 5.62° longitude grid spacing. The annual and seasonal mean global distribution of key climatic elements simulated by the model appears to be comparable to other atmospheric GCMs. The global mean surface temperature increase of 4.8°C in this model due to the doubling of CO_2 is, however, larger than the best estimate of 2.5°C as reported by the Intergovernmental Panel on Climate Change (Houghton *et al.*, 1990). For further details on the description of the model and its performance in simulating the general structure of the mean atmospheric circulation on global as well as temporal scales, the reader is referred to Gordon (1993) and McGregor *et al.* (1993).

3. RESULTS

The monsoon region selected for the study presented here is bounded by latitudes 1.59°S to 30.26°N and longitudes 61.88°E to 106.88°E (Indian subcontinent and the adjoining seas). The study area has a total of 99 grid points (45 points over land and 54 points over ocean). For validation of the present-day climate as well as its change over the region, the authors analyzed the data for control experiments for four seasons, namely winter (December-February), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November) or the representative months, namely January, April, July and October. For the assessment of intraseasonal and interannual variability in the model-simulated key hydrological parameters, however, the data analyzed and presented here relate only to the monsoon season. This season is regarded as the most vital in that over 70% of the total annual rainfall occurs in India from June to September in association with the southwest monsoon.

3.1 Regional Scale Model Climate: The Control Experiment

In the CSIRO9 climate model, the spatial distribution of the seasonal mean surface pressure, temperature, wind and precipitation over the selected region as inferred from the average of 24 equilibrated years of control run all exhibit similarity to the observed climatological pattern. The model-simulated mean patterns of surface pressure and temperature for the four months namely January, April, July and October representing winter, pre-monsoon, monsoon and post-monsoon seasons respectively over the region were analyzed. Figure 1 depicts the seasonal changes in the spatial pattern of mean sea level pressure as simulated by the model. The simulation of an elongated zone of low pressure along the Indo-Gangetic Plains of north India during July is in fair agreement with the climatology. In model-simulated as well as observed surface pressure fields, the axis of this low pressure area (known as a monsoon trough) is oriented roughly from northwest to southeast. The high pressure over the Tibetan Plateau in January and the low pressure over the Central Plains of India in April and October were realistically simulated by the model in terms of their intensity and location.

The seasonal changes in surface air temperature as reduced to mean sea level were simulated by the model quite satisfactorily when compared with the climatology over the region (Figure 2). The semi-arid region of northwest India is an area of high surface temperature during July which gradually builds up through the pre-monsoon season. The geographic location of the thermal high over northwest India coincides fairly well with the area of low pressure in the model simulation.

One of the most dramatic examples associated with the Asian summer monsoon is the reversal of wind flow over south India and the adjoining seas from the northeast during January to the southwest during July. This feature was distinctly observed in the model-simulated 800 hPa wind field (Figure 3). The location and strength of the model-simulated tropical easterly jet over the Indian subcontinent which is a typical upper air circulation feature associated with the Asian summer monsoon, coincides well with the observed climatology (Figure 4; cf. Rao, 1976). This easterly jet is well marked at about the 150 hpa level over the region during the monsoon season but disappears during winter while the subtropical westerly jet located beyond the northern limits of the study region during the monsoon season strengthens and shifts further south over north India in the model-simulated upper air circulation.

A realistic simulation of the total precipitation and its spatial distribution over the Indian subcontinent associated with the summer monsoon is of considerable practical importance. The model-simulated total seasonal rainfall of 80.7 cms over the Indian subcontinent (land points only) in the reference control experiment is close to the observed climatological seasonal rainfall (85 cms) over India. The seasonal spatial distribution of the precipitation over the land part of the Indian subcontinent is simulated satisfactorily as compared with the observed climatology (Figure 5). During the pre-monsoon season, enhanced convective activity over northeast India and the associated precipitation is simulated by the model. Of the annual rainfall simulated by the model over the study area (land points only), about 72% is found to occur during the monsoon months. The model is, however, unable to reproduce the sharp gradient from the west to the east coast over the south peninsula. This could possibly be attributed to the coarse resolution of the model. The seasonal spatial distribution of convective rainfall over the Indian subcontinent simulated by the model suggested that for each season, the total rainfall maxima is primarily due to enhanced convective activity over the region.

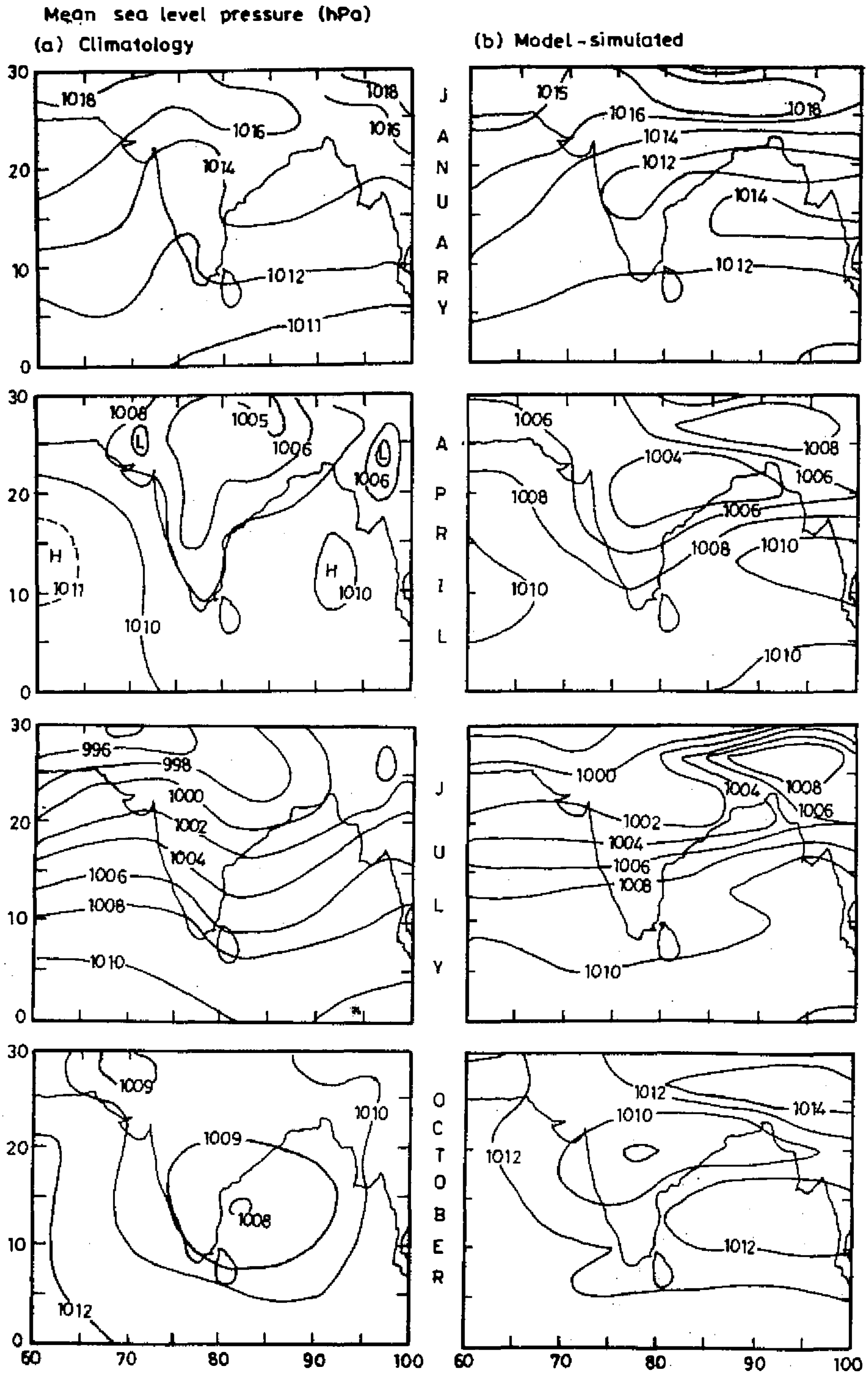

Fig. 1. Seasonal variation in mean sea level pressure (hPa) as (a) observed, and (b) simulated by the CSIRO9 Climate Model (control experiment) over the study area.

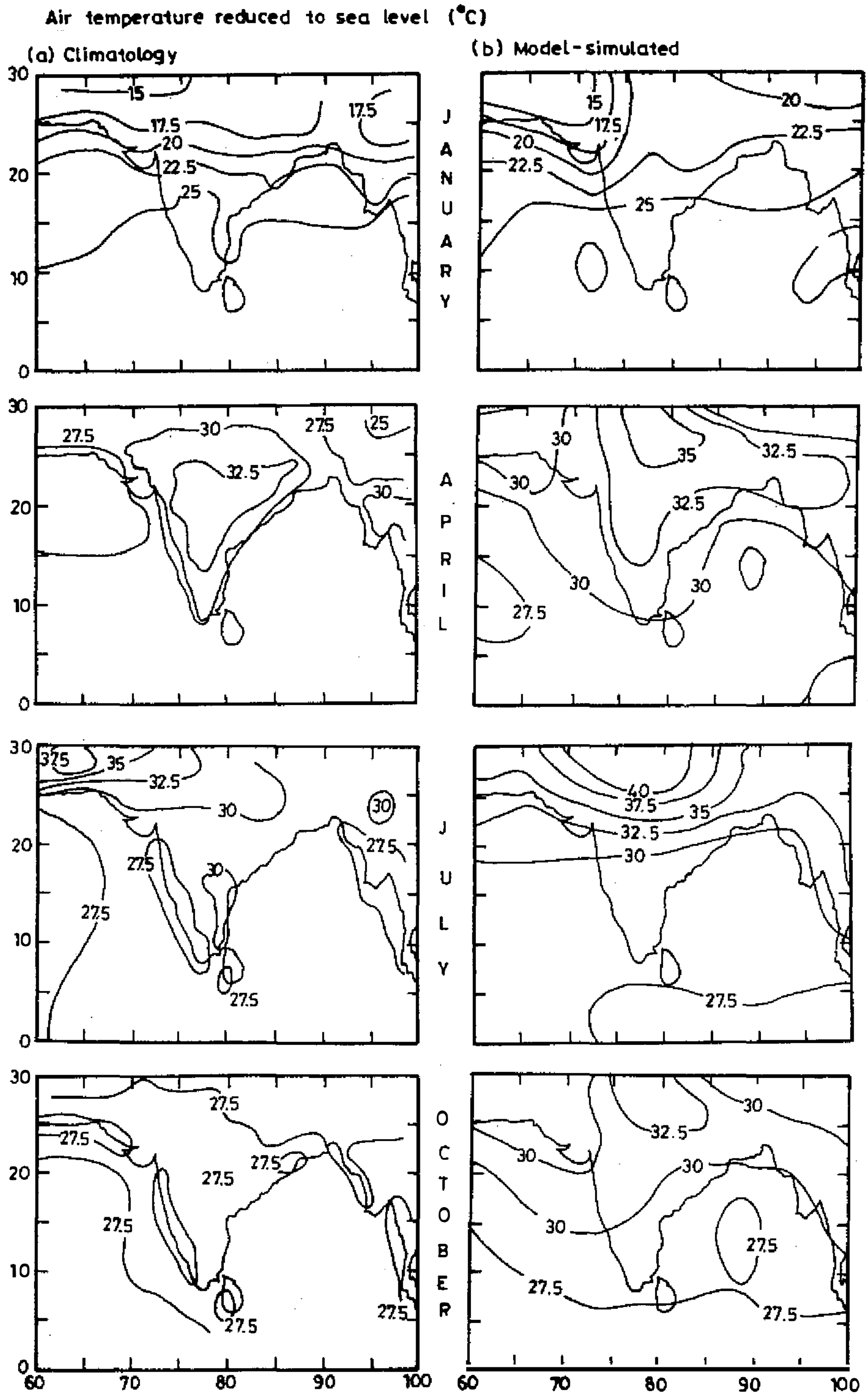

Fig. 2. Seasonal variations in surface air temperature (°) as (a) observed, and (b) simulated by the CSIRO9 Climate Model (control experiment) over the study area.

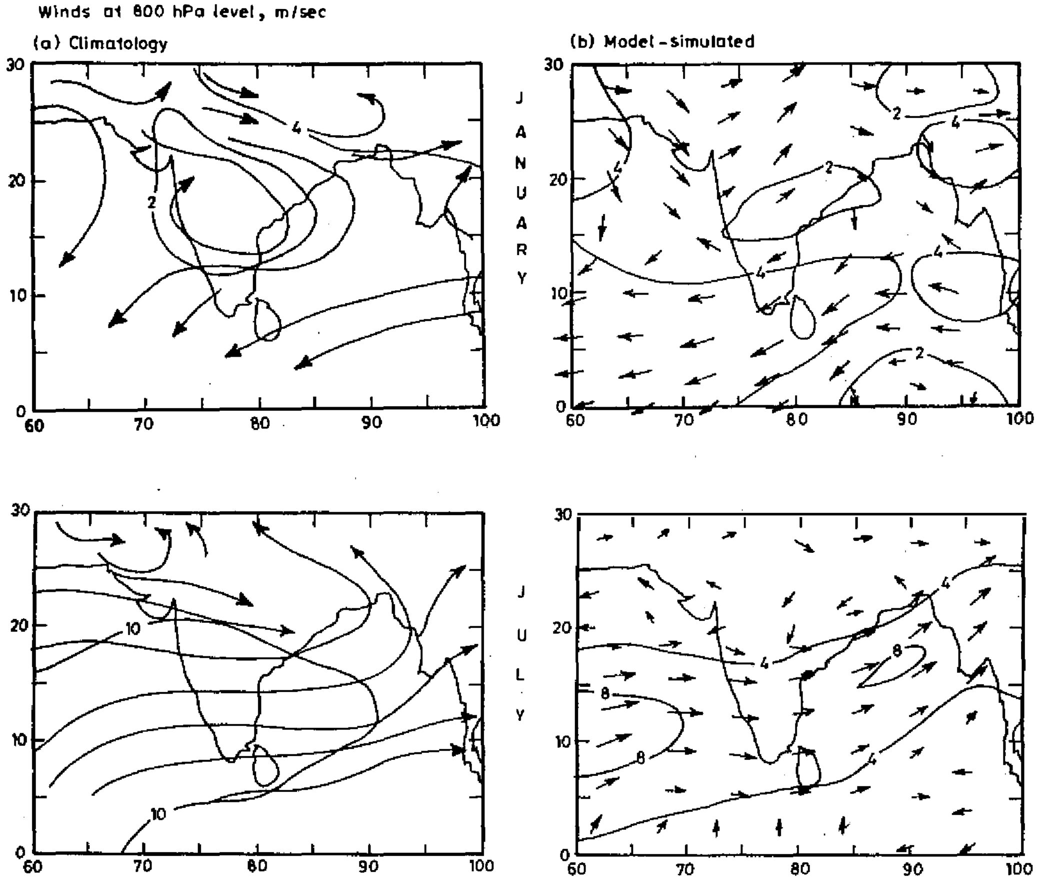

Fig. 3. The (a) observed, and (b) model simulated 800 hPa winds during January and July over the Indian subcontinent.

The evaporation over the land surface has a significant impact on the ecosystem, agriculture and water resources. At higher temperatures, the increased radiative heating of the surface causes increased evaporation. But when the land surface becomes sufficiently dry enough to restrict evaporation, further drying reduces evaporation and, hence, evaporative cooling. Reduction in evaporation also causes a decline the amount of cloud and associated rainfall. The model-simulated spatial distribution of evaporation in different seasons are found to be in close proximity to the observed climatological pattern (Figure 6). The surface evaporation is higher in the southern peninsular and northeast India in comparison to the north and central plains of India. This pattern is consistent with the locations of rainfall maxima simulated by the model.

Soil moisture is a fundamental factor in determining the growth of plants but is seldom actually measured. Generally, it is calculated following the water balance approach and under certain physical assumptions. In climate models, it is possible to compute the soil moisture by considering that, over a period of many days, the water that has accumulated in the soil is determined by the difference between precipitation and evaporation (P-E). The soil becomes saturated when the accumulated water in the soil exceeds the maximum field

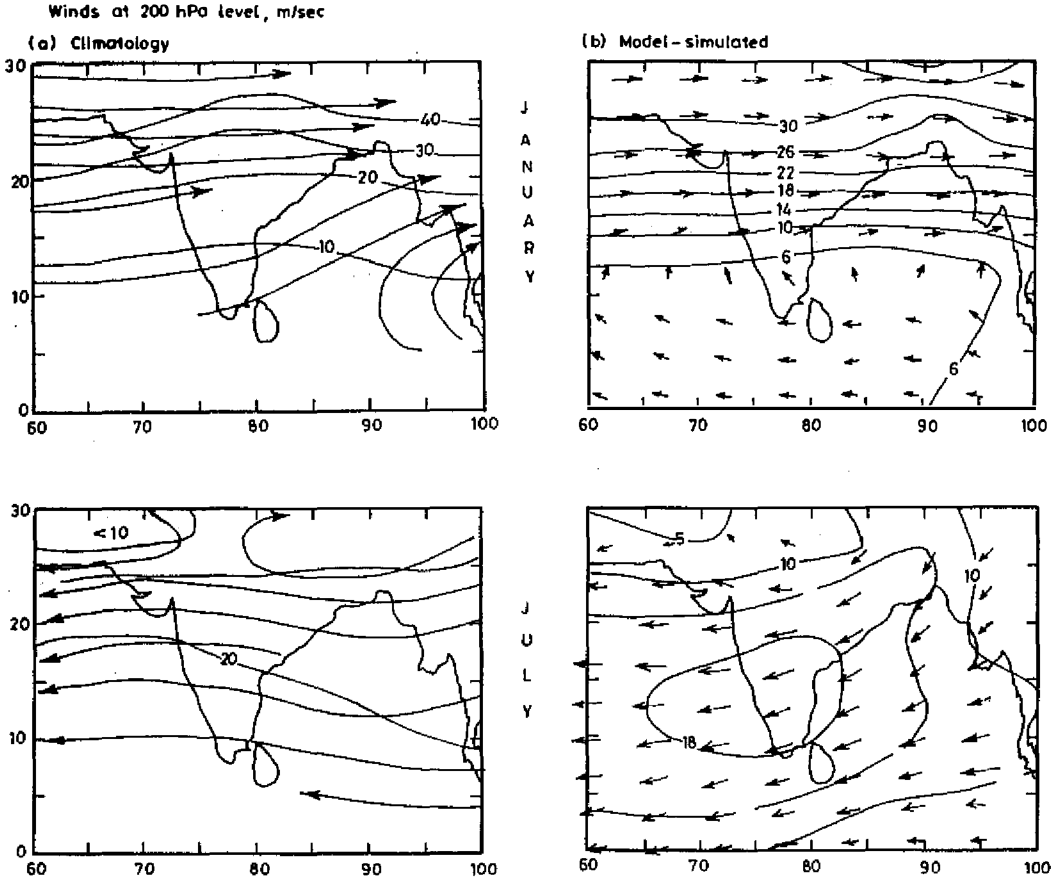

Fig. 4. The (a) observed, and (b) model simulated 200 hPa winds during January and July over the Indian subcontinent.

capacity, and further precipitation is discharged through surface runoff. In the CSIRO9 model experiment, the authors find that the soil moisture distribution for different seasons over the Indian subcontinent (Figure 7) is in fair agreement with those reported in climatological atlases (Mintz & Serafini, 1989). During both the winter and summer seasons, the maximum soil moisture is seen over northeast India, and this is consistent with the heavy rainfall simulated over the region by the model.

The date of monsoon onset over Kerala along the west coast of India (mean date: 2 June) is defined as the first day of transition from a light to heavy rain spell category with the proviso that the average daily rainfall during the first five days after the transition must not be less than 10 mm at each of the five selected observing stations (Cochin, Kozhikode, Alleppey, Trivandrum and Colombo). Over the north of India, the advancement of the monsoon takes place from south to north, and after about five weeks of the onset over the southernmost tip of India, the monsoon normally spreads to the whole of the country. In the CSIRO9 climate model, three grid points along 20.7°N over the Indian subcontinent, one each over the west and east coasts of India and one over central peninsular India, were selected in an attempt

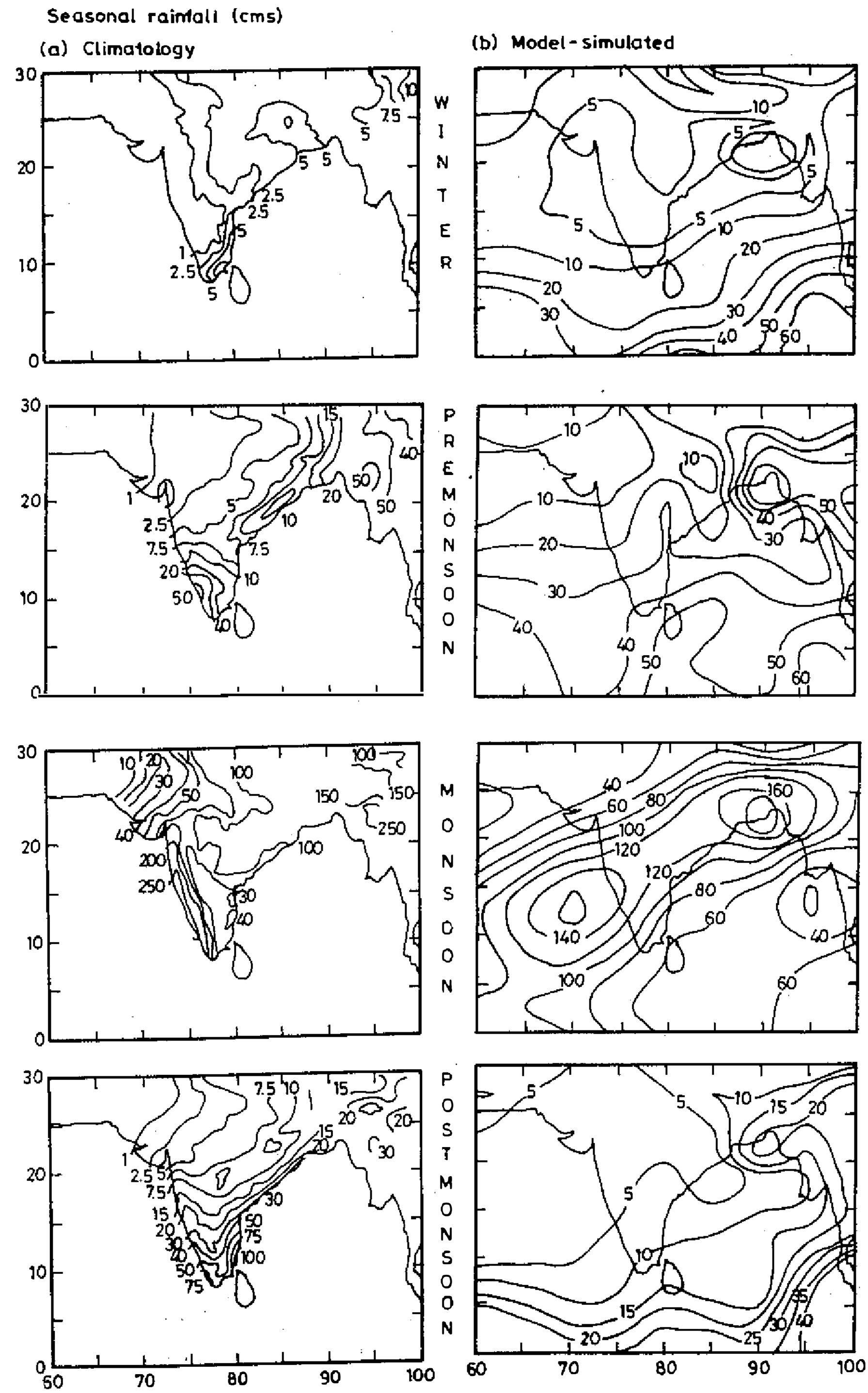

Fig. 5. Distribution of seasonal rainfall (cms) over the study area during winter, pre-monsoon, monsoon, and post-monsoon seasons as (a) observed, and (b) simulated by the CSIRO9 Climate Model.

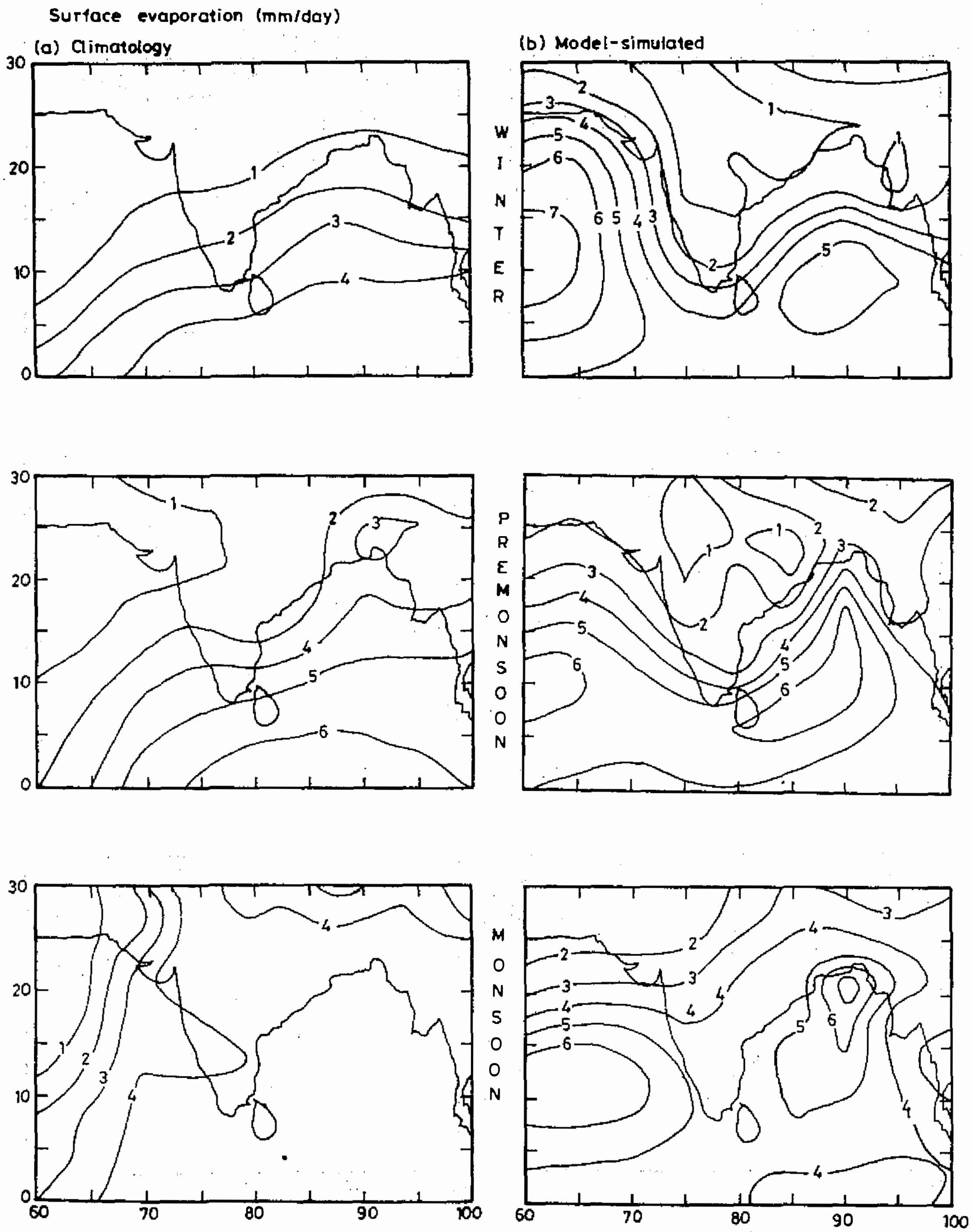

Fig. 6. Spatial distribution of (a) observed, and (b) model-simulated surface evaporation (mm/day) during winter, pre-monsoon and monsoon seasons over the study area.

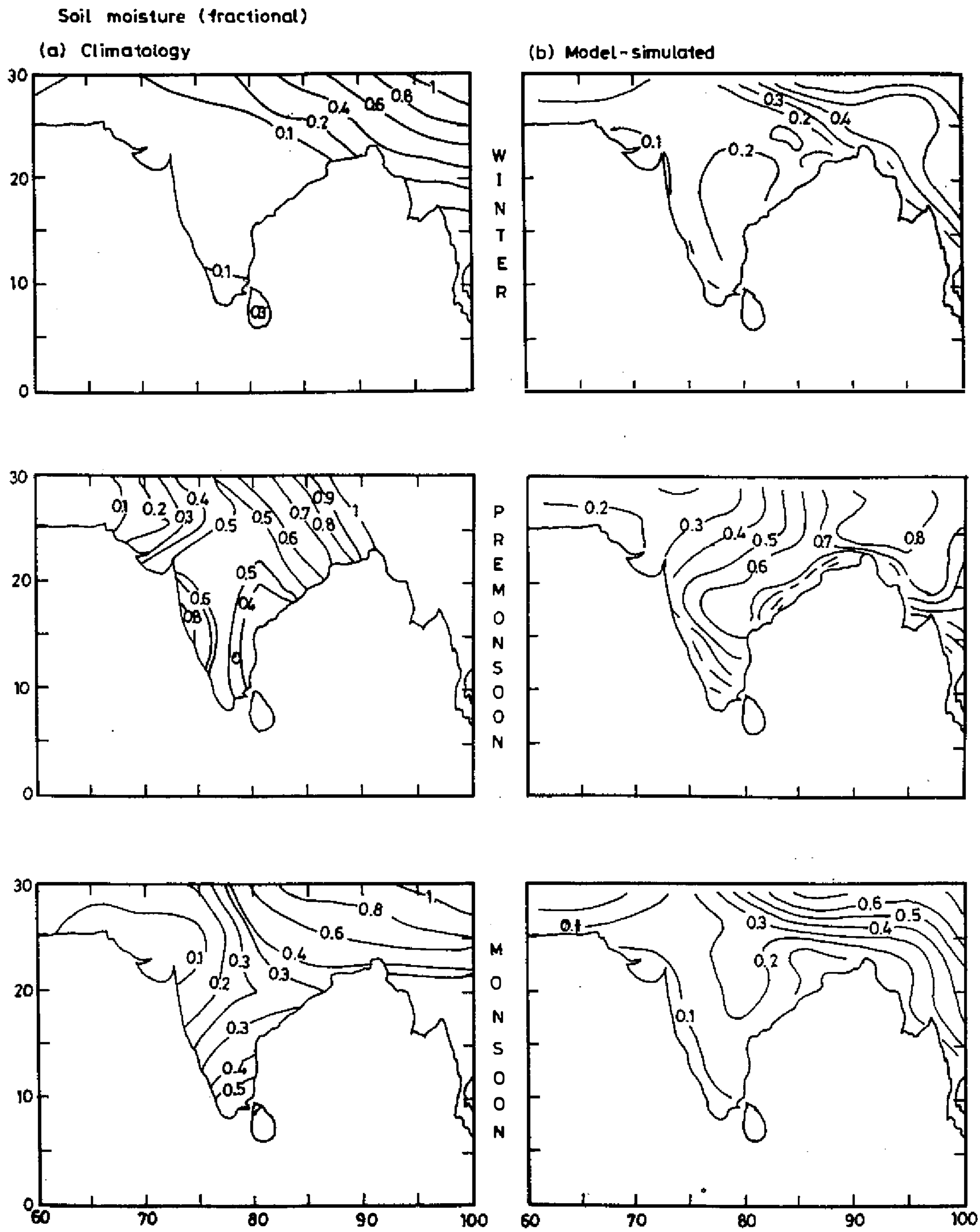

Fig. 7. Spatial distribution of (a) observed, and (b) model-simulated soil moisture (fractional) during winter, pre-monsoon and monsoon seasons over the study area.

to infer the date of onset of the model-simulated monsoon rainfall. The date of the onset of the southwest monsoon over India in the model simulation was defined following the criteria that, from the first day, all the three points had to have had at least 3 mm/day of rainfall for three consecutive days. The selection of the three grid points in the derivation of monsoon onset was made to ensure that a uniform precipitation distribution associated with the summer monsoon was appropriately accounted for and that any local effect such as the orographic effect along the west coast, was filtered out. The precipitation criterion chosen was close to the observed average rainfall rate over central peninsular India. Following this definition, the onset date derived from 24 years of equilibrated run in the control experiment varied between 30 May to 28 June with a mean date of 11 June. This mean onset date inferred from the control run is close to that reported for Bombay (19°N) based on observations for the 1879-1975 period (cf. Rao, 1976). Moreover, the interannual variability in the onset date as inferred from the control run is not significantly different from the observed variability (Figure 8). Practically all the dates of onset derived from the daily rainfall data of the control experiment lie within ± 1 SD from the mean date.

An analysis of 10 years of mean daily rainfall averaged over the land points of the Indian subcontinent for the control experiment illustrates that the monsoon rainfall attains a peak during the third week of July which is in fair agreement with the observed climatology. The daily rainfall time series for each of the selected 10 years were detrended using a high pass filter which used a 5-day running mean at the original daily rainfall series. The detrended series was analyzed in the frequency domain using the Discrete Fourier Transform (DFT) technique to identify the possible oscillations if any, in daily rainfall simulated by the model. This analysis for the all of India rainfall series shows a quasi-periodic oscillation

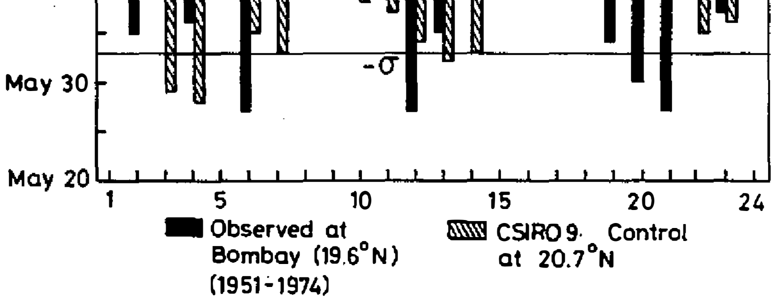

Fig. 8. Intercomparison of dates of onset of a south west monsoon inferred from the model-simulated daily rainfall data at three land grid points along 20.7* N in the control experiment (years 1-24) and the dates of onset actually recorded at Bombay (19°N, period 1951-1974).

with a mean period of 8.6 days (Figure 9) in the daily rainfall series. A similar analysis has also been carried out for the central Indian region bounded by 73.13°E - 84.38°E and 14.33°N - 23.89°N (9 land points) in order to isolate the effect of convective activity associated with life cycles of monsoon depressions over this region. The model shows only marginal change in the period of oscillation from that of the whole subcontinent (6.7 days). This is comparatively lower than the 13.1-day period of oscillation in the observed rainfall over the Central Plains of India for a normal monsoon year (Krishnamurty and Bhalme, 1976).

The mean seasonal precipitation over the Indian subcontinent (land points only) in the model-simulated control experiment (6.54 mm/day) was close to the observed Indian monsoon rainfall (7.08 mm/day). The standard deviation (SD) of the area averaged precipitation simulated by the model in the control case (±0.30 mm/day) was, however, less than that observed (±0.71 mm/day). Thus, the control simulation appears to have had some limitations in generating the right range of observed interannual variability in seasonal rainfall over India.

It is evident from the above that the CSIRO9 model has some capability of reproducing the observed climatological features over the Indian subcontinent on temporal and spatial scales.

3.2 Regional Scale Climate Change: 2×CO_2 Experiment

In the CSIRO9 model simulation, the area-averaged surface temperature over the Indian subcontinent (land points only) increased by 2.98°C in a doubled CO_2 atmosphere during the monsoon season. During winter the surface warming ranged between 3°C to 4°C over most of the land regions of India (Figure 10). The model simulated warming over the Indian subcontinent was least during the monsoon season. Both during pre- and post-monsoon seasons, the surface temperature rise was of the order of 2.5°C to 3.0°C over southern peninsular India, while it could reach up to 5°C in the northern latitudes. The CO_2-induced

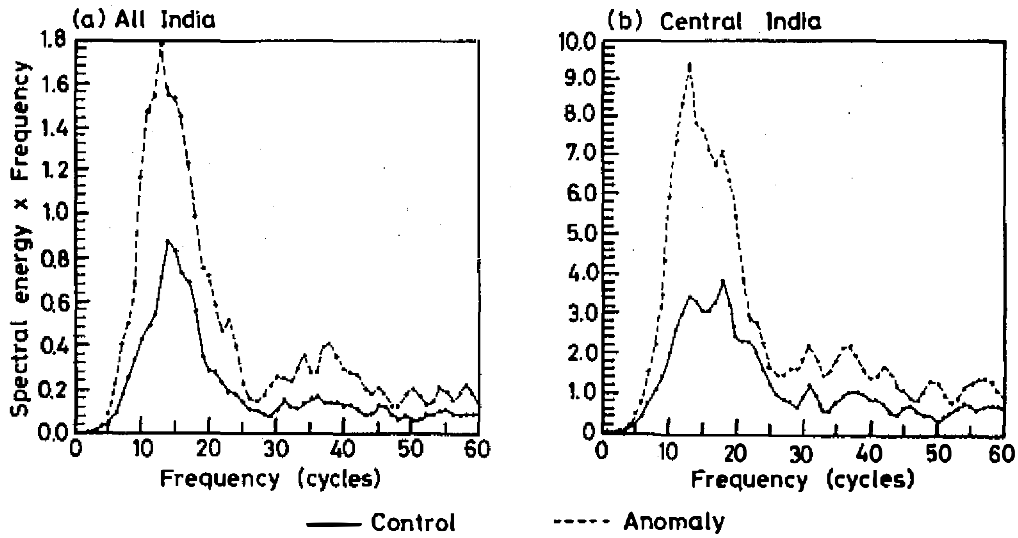

Fig. 9. Intraseasonal oscillations in monsoon rainfall for (a) all India, and (b) central India simulated by the model in control and doubled CO_2 conditions.

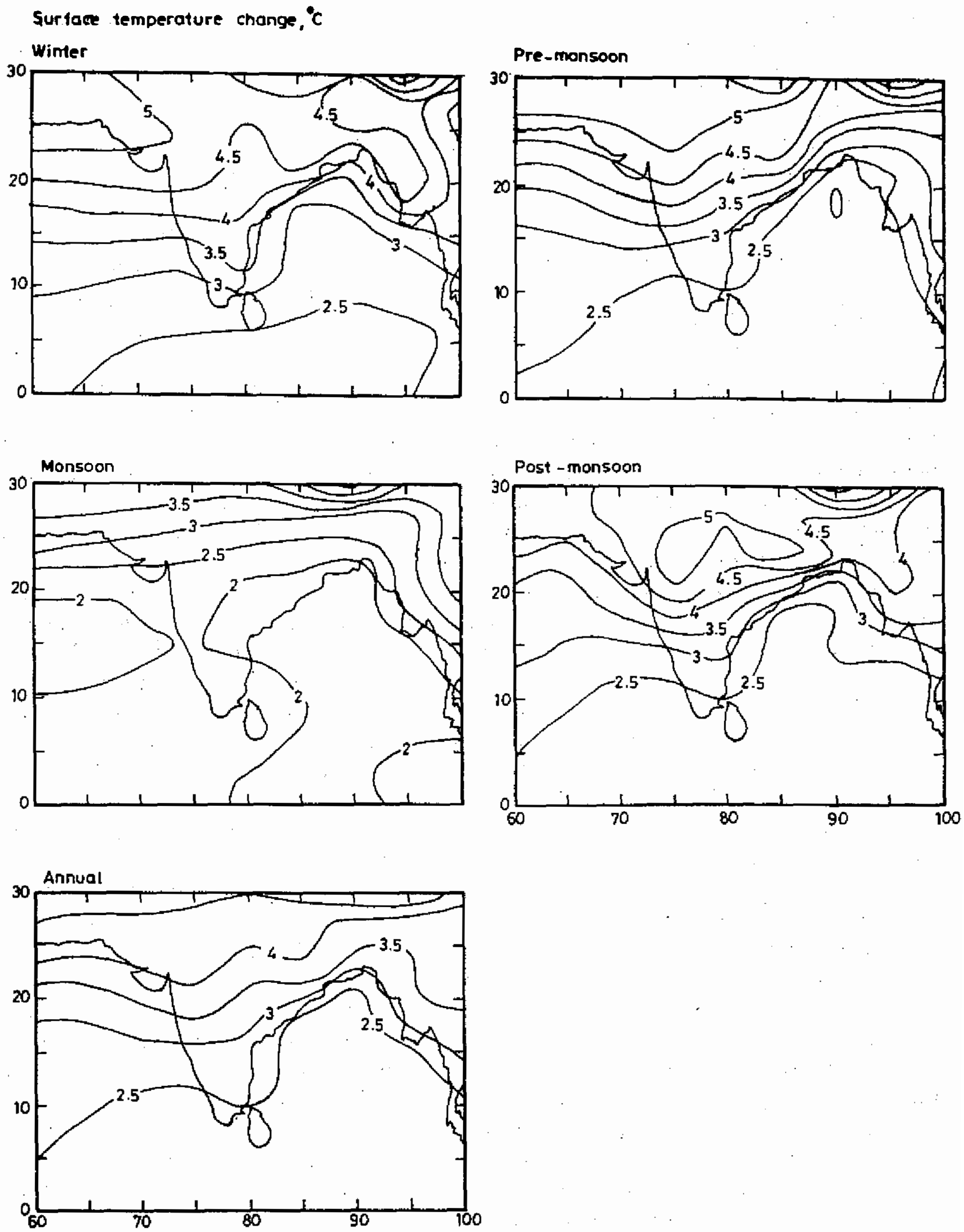

Fig. 10. Spatial distribution of the model-simulated changes in surface air temperature (°) over the study area expected in a doubled CO_2 atmosphere.

annual mean surface temperature change was most pronounced in the northern latitudes of the Indian subcontinent. Similar features have also been observed in more recent coupled A-O climate models, although the magnitude of warming simulated by the CSIRO9 model is on the higher side of climate sensitivity, a feature observed in most slab ocean coupled atmospheric GCMs.

The winds at 800 hpa level as inferred from the CSIRO9 model simulation in a doubled CO_2 atmosphere suggested no significant intensification in 800 hPa level winds during the winter or monsoon season over India and the adjoining seas as a consequence of CO_2 induced warming. An intensification of the westerly jet stream over the northern latitudes of the Indian subcontinent during the winter season was simulated by the model in a warmer atmosphere.

The model simulated an increase in annual precipitation over most parts of India as a consequence of the surface temperature rise associated with the doubling of CO_2 in the atmosphere. This increase is most pronounced (>1 mm/day) over the central plains of India and along the east coast (Figure 11). While no significant change in winter precipitation is observed over the Indian subcontinent during the winter season, substantial enhancement in precipitation (close to 2.0 mm/day) is projected over West Bengal and adjoining Bangladesh during the pre-monsoon season in a doubled CO_2 atmosphere. During the monsoon season, the model simulates an increase in precipitation (2 mm/day) over the central plains of India. A marginal increase in precipitation only confined to south peninsular India was also simulated during the post-monsoon season.

The increase in the moisture holding capacity of the warmer atmosphere enables the convective activity to intensify in a doubled CO_2 atmosphere. During the winter and post-monsoon seasons, no significant change in convective rainfall is observed over the land regions of the Indian subcontinent. In the pre-monsoon season, coastal West Bengal, Bangladesh and adjoining oceanic regions are likely to experience enhanced convective activity, while during the monsoon season, the region of maximum change in convective activity is located over the Orissa and Bihar Plateau in the model simulation under enhanced CO_2 conditions.

No significant change in evaporation is observed over the Indian region during the winter and post-monsoon months, as a consequence of doubled CO_2 (Figure 12). The surface evaporation increases over most parts of the Indian subcontinent during both the pre-monsoon and monsoon seasons. In the pre-monsoon season, a significant increase in evaporation is simulated over Bangladesh and the adjoining seas. During the monsoon months, maximum enhancement in surface evaporation is possible over the northwest of northwest India.

The changes in the temperature and precipitation over the subcontinent due to the doubling of CO_2 in the atmosphere also affect the amount of moisture present in the soil. The model results indicate that, in a warmer atmosphere, the northern and central plains of India could be relatively drier in the winter months (Figure 13). During the pre-monsoon season, the soil moisture is expected to increase significantly over northeast India. Increased precipitation during the monsoon season leads to an enhancement in soil moisture over the central plains in a warmer atmosphere. No significant change in the soil moisture is predicted over southern peninsular India throughout the year.

The total seasonal rainfall simulated by the model in a doubled CO_2 atmosphere is 10.7% more than the present-day rainfall. In a doubled CO_2 atmosphere, the monsoon rainfall appears to intensify over the land regions of India. An analysis of the daily rainfall frequency

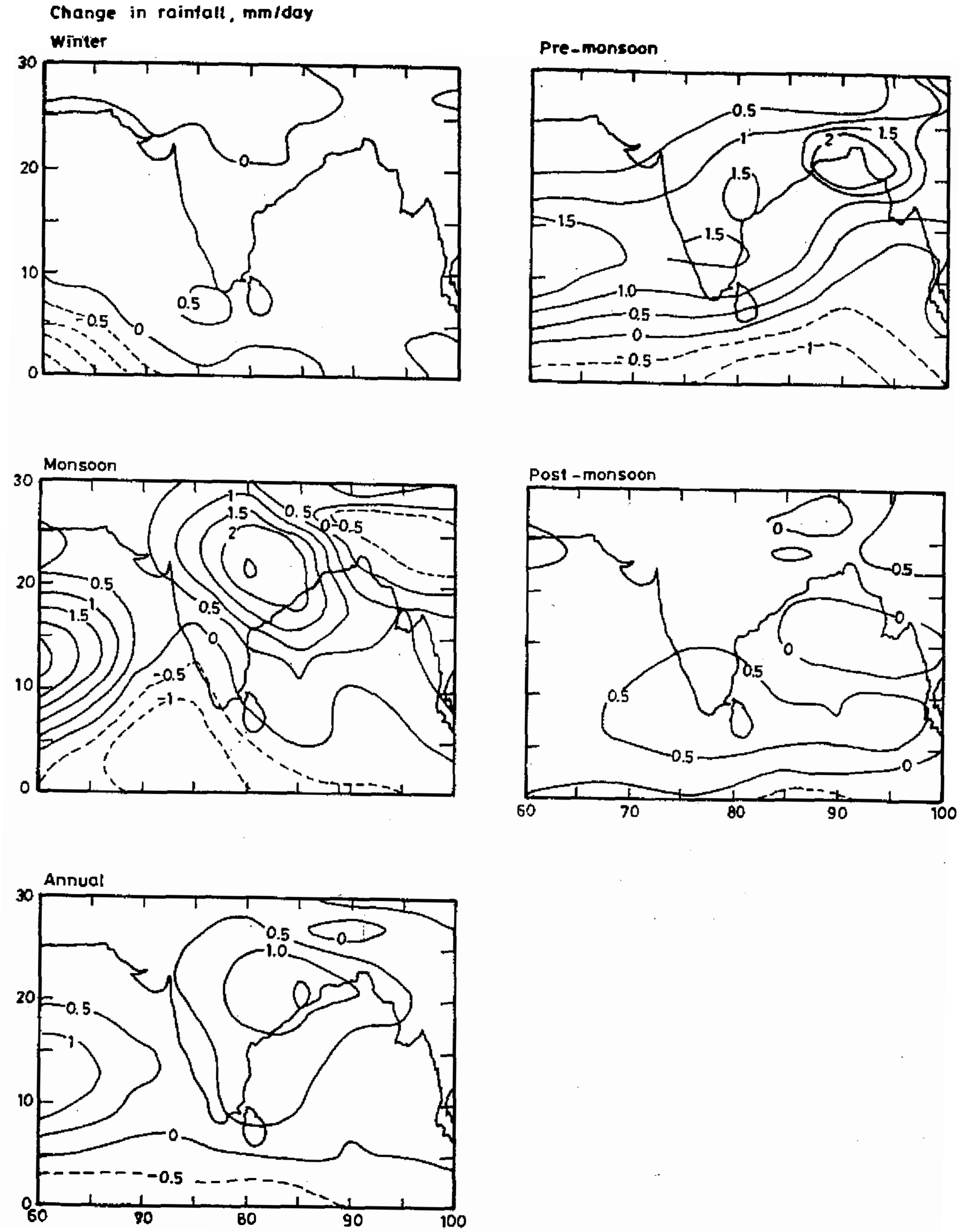

Fig. 11. Spatial distribution of the model-simulated changes in rainfall (mm/day) over the study area expected in a doubled CO_2 atmosphere.

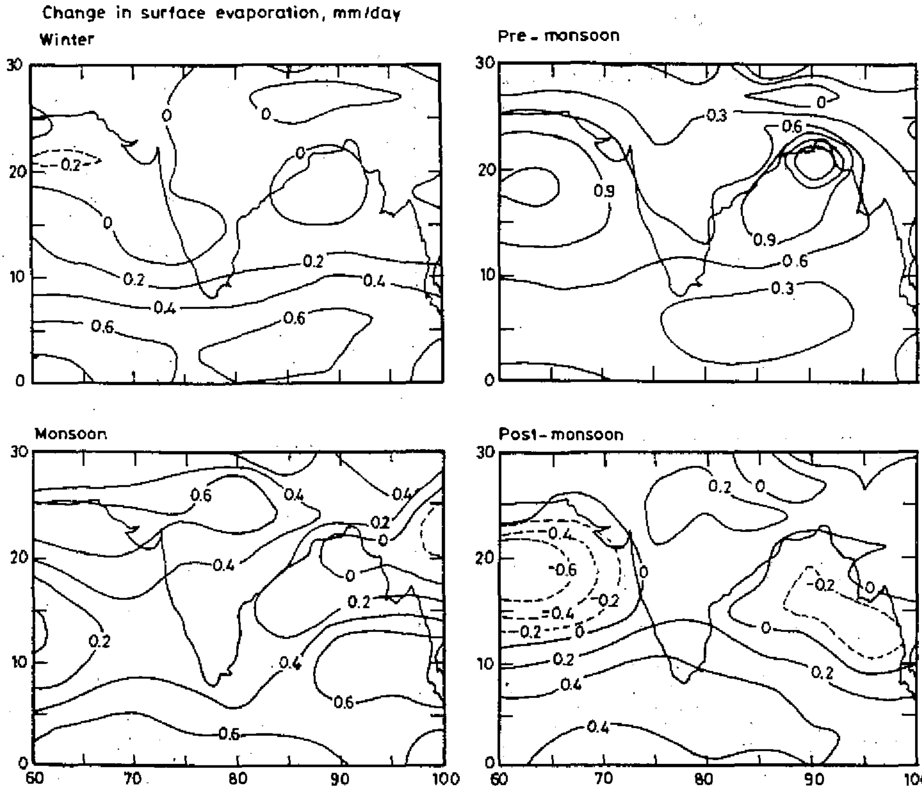

Fig. 12. Model-simulated changes in convective precipitation (mm/day) over the study area expected in a doubled CO_2 atmosphere.

distribution suggests more frequent heavy rainfall events over the Indian subcontinent in a doubled CO_2 atmosphere (Figure 14). The spectral analysis of daily rainfall over India in a warmer atmosphere suggests a quasi-periodic oscillation a period of 9.2 days, not significantly different from that observed for in the control experiment (Figure 9).

Figure 15 depicts a plausible scenario of the greenhouse gas-induced temperature change (annual and seasonal means) expected over the Indian subcontinent as simulated by the CSIRO9 model and associated impacts (in terms of percent change) on hydrology of the region.

3.3 Interannual Variability of Monsoon Rainfall

An understanding of the interannual variability in the Indian summer monsoon and associated extreme events (droughts and floods) in a warmer atmosphere is of more practical relevance. In a doubled CO_2 simulation, the area averaged monsoon precipitation over India increased by 10.6% to 7.23 mm/day, with a standard deviation of ± 0.35 mm/day. This increase in mean precipitation may have been attributed to the warming of the land surfaces due to additional IR trapping as a result of the doubling of the CO_2 concentration. The variability in the monsoon precipitation was only marginally higher in the doubled CO_2 case as compared to that in the control run (SD increased from ± 0.30 mm/day to ± 0.35 mm/day).

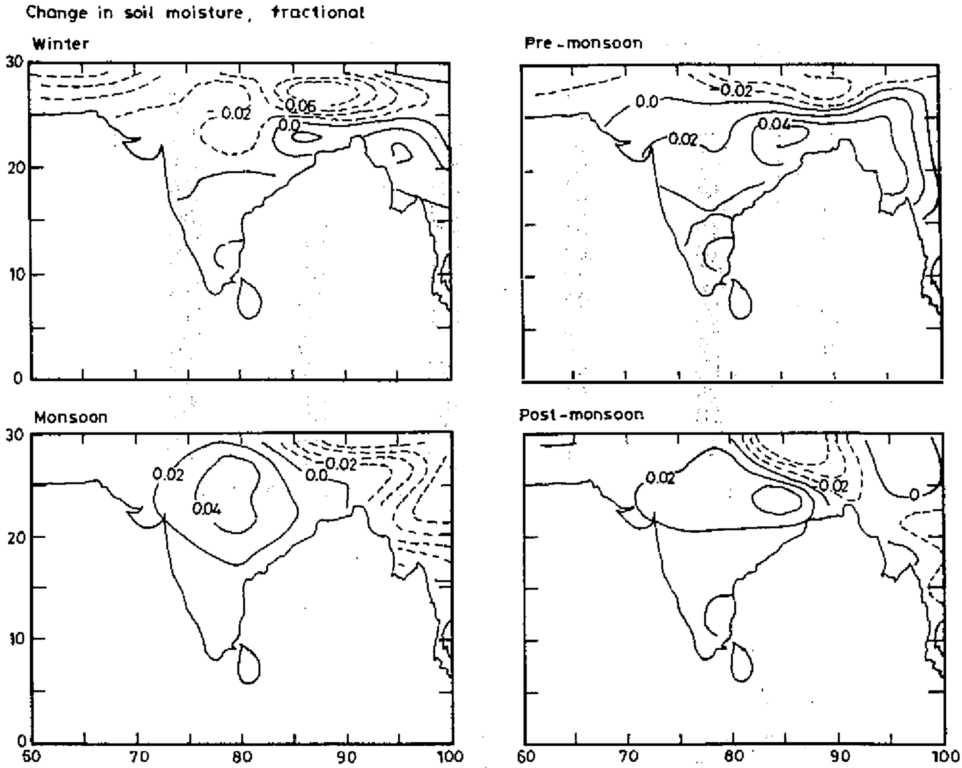

Fig. 13. Model-simulated changes in Soil moisture (fractional) over the study area expected in a doubled CO_2 atmosphere.

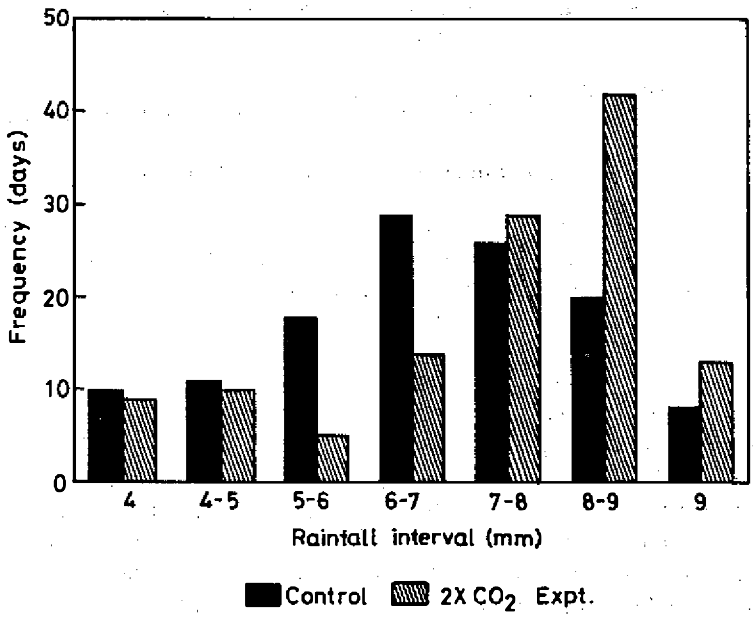

Fig. 14. The frequency distribution of monsoon rainfall-days simulated by the model in control and doubled CO_2 conditions.

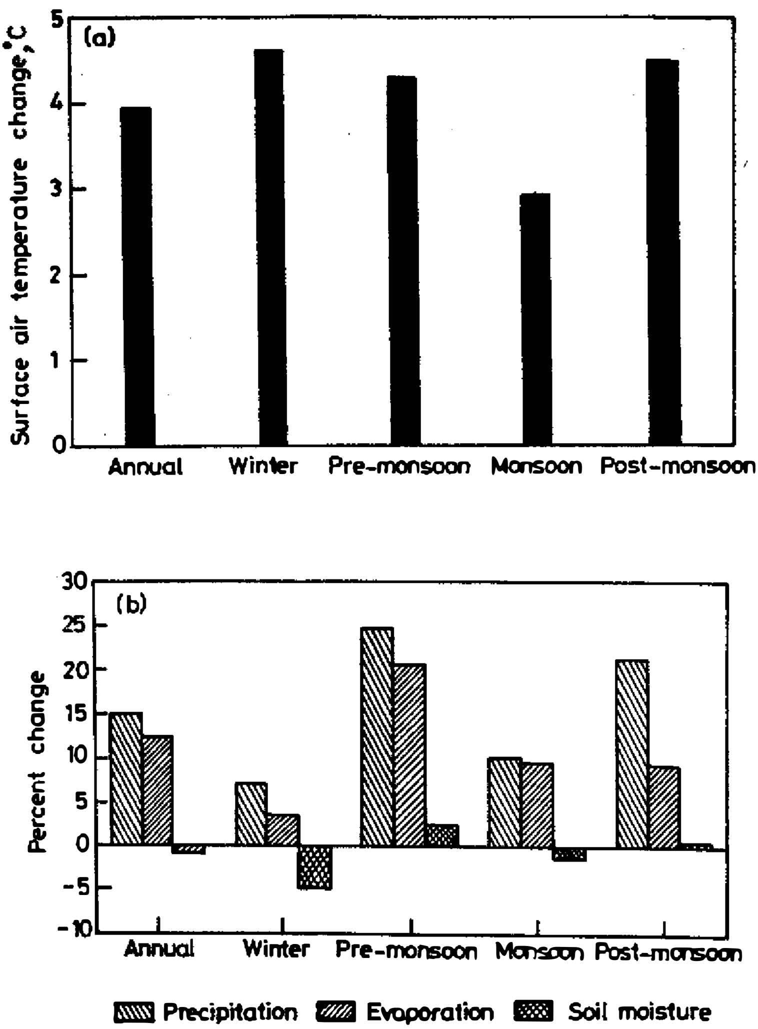

Fig. 15. Area-averaged changes in annual an seasonal mean surface air temperatures (a), and precipitation, evaporation and soil moisture (b, in percent) simulated by CSIRO9 model for the Indian subcontinent (land points only).

To examine the changes in the absolute amount of precipitation on a year to year basis, the authors define a strong (weak) monsoon season as occuring when area-averaged precipitation is more (less) than plus (minus) one SD from the mean. The mean precipitation in both the strong and weak monsoon years are higher for the doubled CO_2 case than for the control case. The differences between the weak and strong monsoon cases for total as well as convective precipitation over India in the control case were found to be within the range of the observed interannual variability of monsoon rainfall over India.

In a doubled CO_2 atmosphere, the authors found find only a marginal increase in the magnitude of variability in the key hydrological parameters with respect to the control simulation (Table 1) which could be attributed to the increased temperature gradient between the land region and the adjoining oceanic areas. The geographical distribution of the interannual variability in monsoon rainfall reveals that the central plains of India are likely to have only a marginally enhanced variability in rainfall in a doubled CO_2 atmosphere, and this enhanced variability is largely due to an increase in convective precipitation over this region (Figures 16, 17). The geographical distribution of differences in other hydrological parameters from weak to strong monsoon years over India in a doubled CO_2 condition does not suggest any substantial enhanced interannual variability as compared to the present-day atmosphere.

Table 1. Area-averaged Hydrological Parameters (7.96°N - 30.26°N and 67.50°E - 95.63°E, land points only) for weak and strong monsoon years of control and 2×CO_2 experiments with the CSIRO9 climate model.

Elements	Control			2 x CO_2		
	Weak	Strong	Difference	Weak	Strong	Difference
2m Temperature (°C)	25.02	24.54	+0.48	28.28	27.49	+0.79
Precipitation (mm/day)	6.04	6.97	-0.93 (-15.0%)	6.74	7.85	-1.11 (-16.0%)
Conv. Precipitation (mm/day)	5.01	5.70	-0.69 (-13.8%)	5.41	6.38	-0.97 (-17.9%)
Evaporation (mm/day)	2.95	3.16	-0.21 (-7.1%)	3.24	3.54	-0.30 (-9.3%)
Soil Moisture (fraction)	0.54	0.58	-0.04 (-0.63%)	0.53	0.59	-0.06 (-11.3%)

4. CONCLUSION

The results presented above demonstrate that the CSIRO9 model has some capability of simulating the present-day climatic conditions over the Indian subcontinent. The onset date of Indian summer monsoons as well as the area-averaged monsoonal rainfall, is reasonably well simulated by the model.

In a doubled CO_2 condition, the model-simulated warming is expected to range between 2.5°C and 4.5°C over the land regions of India. The monsoon onset dates inferred from the CSIRO9 model experiments do not exhibit any significant deviation in a warmer atmosphere. However, an intensification of monsoonal rainfall is possible over the Indian region in a doubled CO_2 atmosphere. Moreover, in a warmer atmosphere, the total number of heavy rainfall days is likely to increase over the Indian subcontinent. The analysis in this study suggests no significant increase in interannual variability of key hydrological parameters over north and central India in a warmer atmosphere.

There are a number of caveats to be kept in mind while assessing the regional climate change scenario based on atmospheric general circulation models. The control simulations still contain a number of systematic errors in comparison to the observed climate and the causes are not yet understood. The sub-grid scale physical processes could contribute further to the uncertainty in the simulation of the regional climate. These issues may have a direct bearing on the confidence that can be placed on the regional climate change scenario reported in this paper.

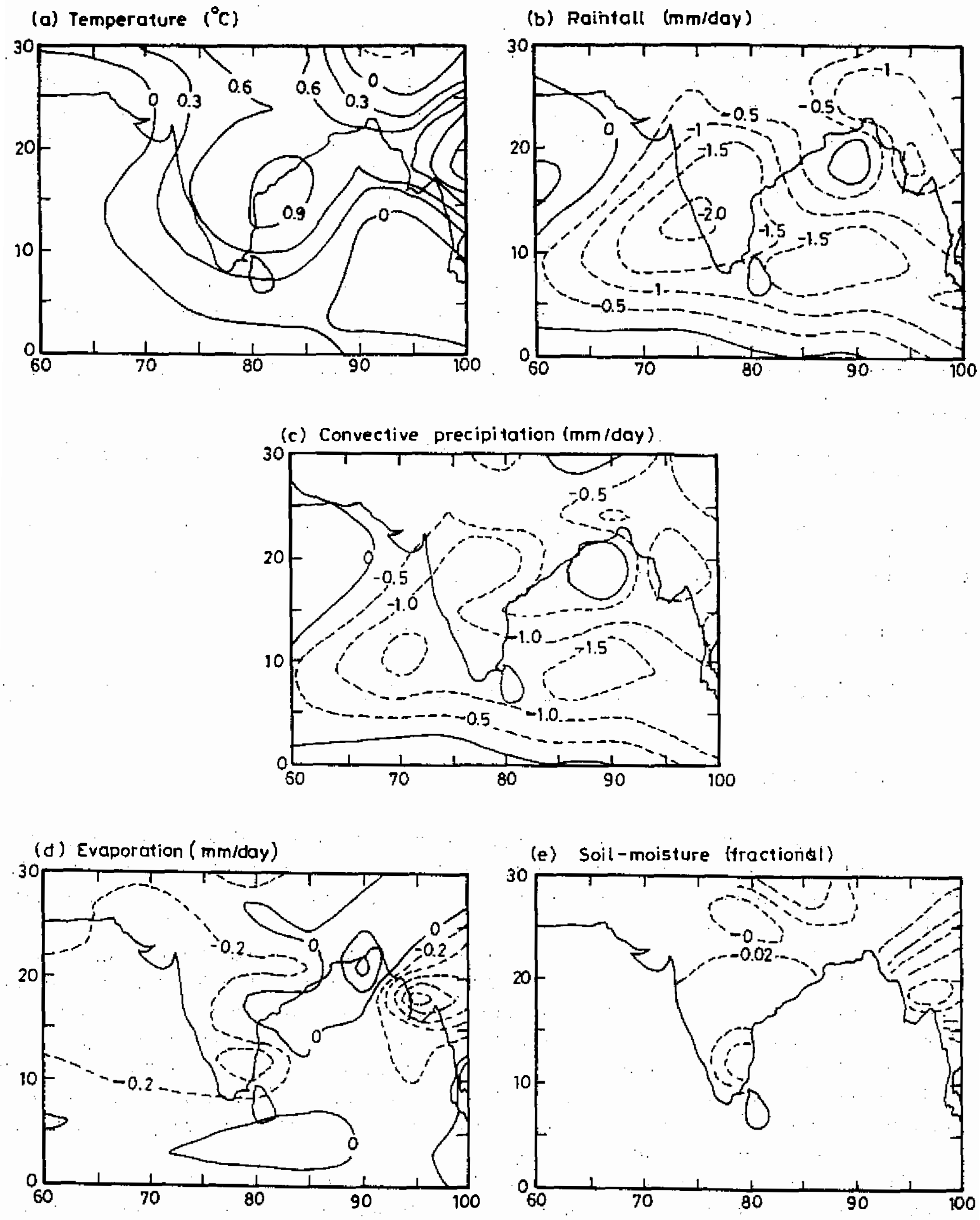

Fig. 16. Weak minus strong monsoon composite differences in (a) temperature (°C), (b) precipitation (mm/day), (c) convective precipitation (mm/day), (d) evaporation (mm/day) and (e) soil moisture (fractional) in control simulation of the model atmosphere.

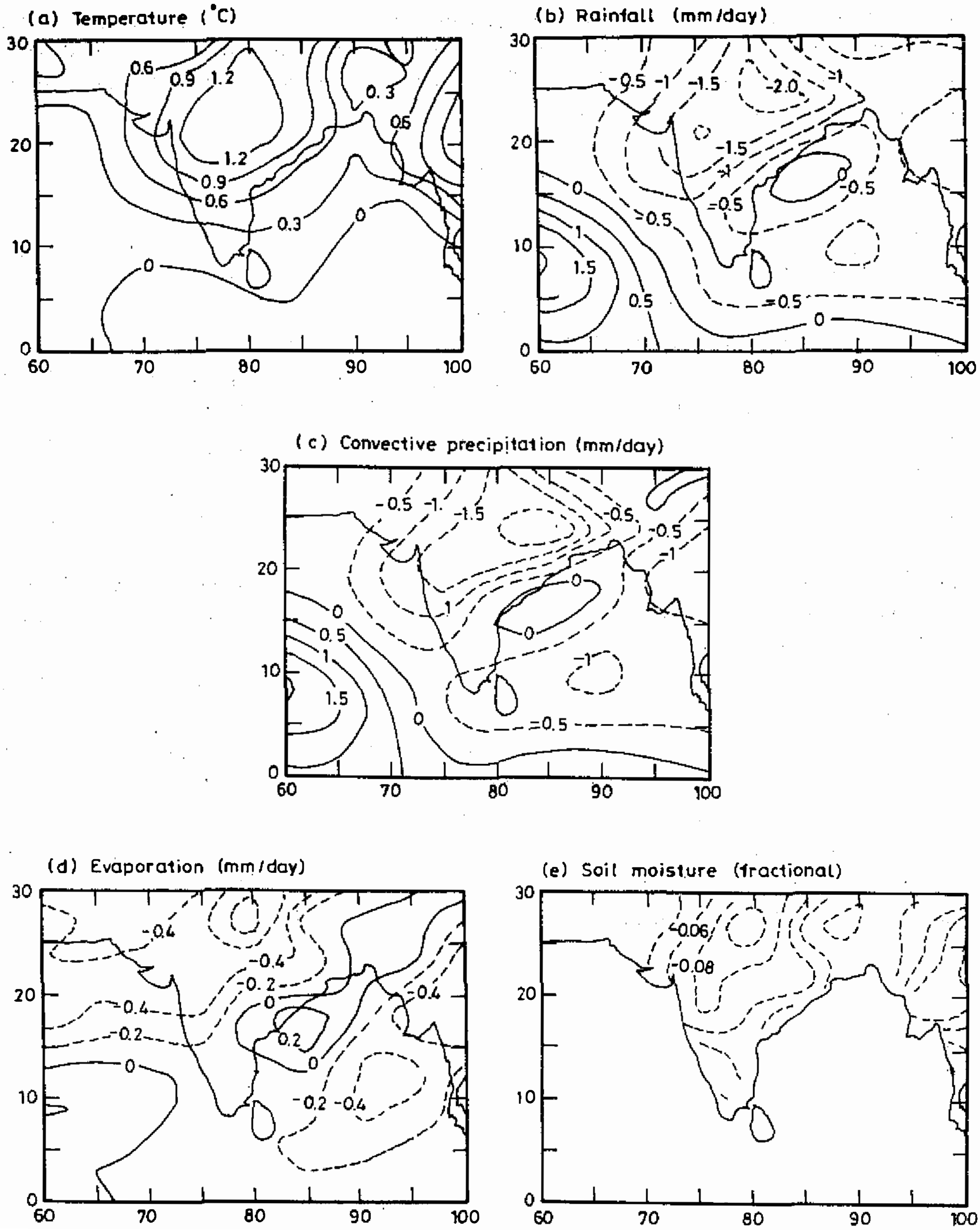

Fig. 17. Weak minus strong monsoon composite differences in (a) temperature (°C), (b) precipitation (mm/day), (c) convective precipitation (mm/day), (d) evaporation (mm/day) and (e) soil moisture (fractional) in doubled CO_2 simulation of the model atmosphere.

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