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Greenhouse warming over Indian sub-continent

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Abstract. A hierarchy of climate models have been developed and applied to the problem of doubling the CO_2 concentration in the atmosphere. Currently available general circulation models include the most complete treatment of the global warming and are capable of providing changes in several of the meteorological parameters in time scales of half a century or even more. Much skill is gradually being achieved now for future climate simulations. In this paper, we have attempted to describe the response of the National Center for Atmospheric Research Climate Community Model (NCAR CCM), whose performance for northern hemispheric climate simulations was reported to be very satisfactory to Indian region. The seasonal (winter and summer) changes in surface temperature, rainfall and soil moisture expected over the Indian sub-continent due to doubling of CO_2 in the atmosphere as inferred from model output statistics are discussed. A probable scenario for sea level rise along the Indian coastline by the year 2030 AD as a result of ocean water's expansion due to global warming is outlined. These projections should not be treated as predictions of what is going to happen over the Indian sub-continent. Rather, they merely illustrate to what extent we might be affected by the future climate change.

Keywords. Global warming; climate models; ocean's thermal expansion; sea level rise; climate change over Indian sub-continent.

1. Introduction

A great deal of attention in the past few years has been focused on the scientific aspects of climatic change. Even though several groups in the world are today involved in monitoring and predicting those climate changes that may result from increase in atmospheric trace gases due to anthropogenic activities, it appears that a precise assessment of regional impact of the global warming still remains largely qualitative. While all scientists seem to agree that an increased loading of the atmosphere with radiatively active trace gases has been occurring and that these gases have been producing a greenhouse-like effect in the lower atmosphere, they do not agree on what the greenhouse effect may mean for precipitation or soil moisture in specific regions around the world. Nor is it clear yet how global warming might change the frequency and intensity of tropical cyclones. Nonetheless, global climate change as a result of increasing levels of trace gases in the atmosphere will surely be reflected in regional climate and at present a numerical modelling approach seems the only reliable way to assess the regional impacts of global warming.

The general circulation models (GCMs) have now reached a stage of development when they can be applied to give useful estimates of at least some aspects of climatic

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change. Already detailed model output statistics are beginning to show encouraging similarities to the observed climate (WMO 1991). It is true, however, that the climate simulations by the best of the present GCMs may have many deficiencies. The time scale of the ocean behaviour is much longer than the time scale of the atmospheric behaviour. The state-of-the-art ocean models are less successful than their atmospheric counterparts. It is for this reason that most GCMs of the atmosphere use a simple representation of the ocean which allows only a vertical exchange of heat in the upper layers of the ocean. Modelling the regional impact of increasing trace gases hinges fundamentally on getting the ocean response right. The recent simulations of CO_2-induced climate change performed with GCMs having appropriate ocean-atmosphere interaction and better representations of the cloud feedback and seasonal cycle have yielded a global mean surface temperature warming of 3·5 to 4·2°C, and an increase in global mean precipitation of 7 to 11% for about 2030 AD when it is expected that the equivalent CO_2 concentration in the atmosphere will have doubled (Schlesinger and Mitchell 1987). Moreover there is consistency between various GCMs for these global average results despite the fact that in terms of geographic distribution there is only qualitative rather than quantitative agreement. Difficulties in understanding the reasons for regional differences between the simulations of different models, and between these simulations and the real atmosphere have been discussed by Mitchell *et al* (1987), who showed that the regional response of climate models is highly dependent on the unperturbed simulation i.e., on the control run in which the model is used to simulate present-day conditions. They pointed out that differences in control simulations must be taken into account when comparing results for different models (for example, on doubling the atmospheric CO_2); otherwise unduly pessimistic conclusions may be reached concerning the consistency of model results.

With these unpalatable facts before us, it might still be worthwhile to infer a plausible future climate for the Indian region based on the numerical results from NCAR CCM, one of the best known global climate models in the world, solely for the purpose of examining the type and magnitude of the likely impacts of climatic change. While the predicted changes in the gross features of the regional climate as inferred from NCAR CCM may be regarded as highly probable, it should be useful as a basis for sensitivity studies which can identify potentially important practical effects, and to plan on how best to cope with those effects which cannot be avoided.

In this paper, we present the distributions of temperature, rainfall and soil moisture over the Indian sub-continent for control and doubled CO_2 experiments performed with the NCAR general circulation model (known as CCM). These model-generated data sets were made available to us by the Climate and Global Dynamics Division of NCAR. Based on these model output statistics, the regional scenarios of possible changes in temperature, rainfall and soil moisture are examined and discussed. We have also applied the predicted surface temperature change due to doubling of CO_2 to a simple thermal expansion ocean model to estimate the probable increase in sea level by the year 2030 AD as a result of greenhouse warming. The expected change in sea level along the Indian coastline as inferred from these calculations is discussed here. It may be stressed that the projected scenario should be taken only as a broad picture of what the changed climate might be like in 2030 AD for the Indian sub-continent and should primarily be useful to set out our priorities for research and adapt planning strategies which are appropriately flexible and adaptable.

2. Brief description of model

The NCAR community climate model originally evolved from the Australian spectral model described by Bourke *et al* (1977) and McAvaney *et al* (1978). The model uses a sigma vertical coordinate system with nine levels ($\sigma = 0{\cdot}991$, 0·926, 0·811, 0·664, 0·500, 0·336, 0·189, 0·074 and 0·009) and the spectral transform method for computing horizontal nonlinear transport terms. The truncation wave number is rhomboidal 15, and the associated Gaussian grid has 40 latitudes between poles and yields approximately a 4·5° resolution in latitude. There are 48 longitudinal grid points that gives a 7·5° longitudinal resolution. The time step for the computation is 40 min. The solar constant is 1370 Wm^{-2}. The principal change in the model undertaken at NCAR from that described by McAvaney *et al* is a new radiation cloudiness scheme described by Ramanathan *et al* (1983). The absorptance formulation for CO_2 in the new scheme is in excellent agreement with observed absorptances (Kiehl and Ramanathan 1983). The cirrus formulation assumes that upper layer clouds have emissivity of 1 and thus are treated as perfect black bodies independent of liquid water or ice equivalent content. The model forms several types of interactive clouds, including both convective and non-convective adjustment processes. Convective clouds are formed when one or more layers in the model are undergoing moist convective adjustment. For non-convective clouds, the fractional cloud cover is assumed to be 95%. For convective clouds, the maximum cloud cover is assumed to be 30%. The radiation model assumes that the clouds are randomly overlapped. In the vertical direction, clouds are assumed to fill a layer completely, i.e., cloud tops and bottoms are located at the upper and lower half levels respectively adjacent to the sigma level. Clouds are not allowed to form in the first sigma layer adjacent to the ground since the cloud radiation model does not take such thin layers into account. The surface hydrology makes use of the model-derived precipitation and evaporation/sublimation rates to simulate the change of soil moisture and snow cover following Washington and Williamson (1977). The ocean part of the model makes use of a simple thermodynamic equation for the heat storage in upper layer. The model is integrated through 11 solar cycles with the standard 365-day year phase for a total of 15 years in $1 \times CO_2$ and $2 \times CO_2$ simulations to attain near equilibrium at the end of the experiments. The last 3 years of the 11-full year phase of the experiments have been used in the time average of the model output. For further details on the model description as well as on the numerical experiments performed with the model for $1 \times CO_2$ (control) and $2 \times CO_2$ (doubled CO_2) cases, the reader is referred to Washington and Meehl (1984).

3. Simulation of observed climate

The ability of the climate model to simulate the change in climate caused by doubling of CO_2 depends in part on how well it reproduces the present climate and its change from winter to summer. In this respect the merits of NCAR CCM's performance have been well documented in recent literature (e.g., Climate Change: IPCC report-1; 1991). The global annually-averaged surface air temperature (at $\sigma = 0{\cdot}991$) taken over the last three years of the numerical experiments with the NCAR CCM is 287·5 K (compared to the observed estimate of 287·2 K) for $1 \times CO_2$ and 291·0 K for $2 \times CO_2$

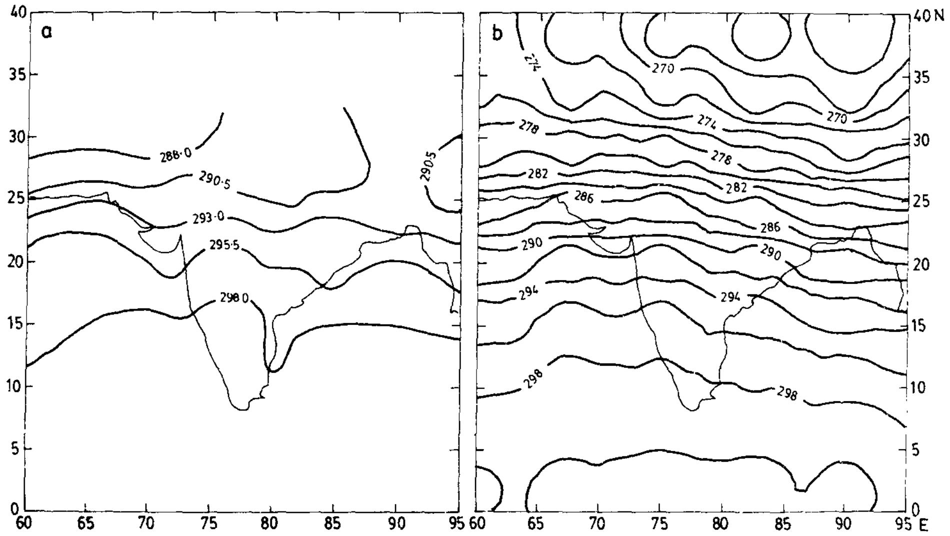

Figure 1. Observed (**a**) and model-simulated (**b**) surface air temperature distributions (K) for winter over the Indian sub-continent.

which yields global warming of surface air temperature of 3·5°C. In this paper, we have used the regional (region bounded by 0–40°N, 60°E–95°E) grid point estimates of surface temperature, precipitation and soil moisture derived from means for Dec–Jan–Feb (referred to as winter) and Jun–Jul–Aug (referred to as summer) based on three-year averages both for control ($1 \times CO_2$) and enhanced greenhouse gas ($2 \times CO_2$) simulations.

The general pattern of the model temperature for winter over the Indian sub-continent is quite similar to that observed (figure 1). The simulated surface temperatures over south peninsular India are close to the observed values of 294 to 298 K. For summer, the surface temperature simulated by the model qualitatively agrees with the observed surface temperature (figure 2). The model-simulated temperature distribution over the Indian sub-continent in the summer season is somewhat underestimated over the northwest India. It is possible that the physical mechanisms of intense land heating over the desert regions of northwest India are not appropriately parameterized in the model physics.

The rainfall distribution simulated by the model for winter is in qualitative agreement with the observed rainfall distribution (figure 3). The model-simulated gradient of precipitation from west to east over north India is in fair agreement with the observed rainfall distribution. However, the observed rainfall over south peninsular India is less than 50% of the model simulated precipitation estimates for winter. The heavy rainfall over Kashmir valley and northeast India has not been realistically simulated by the model. Possibly, the model's resolution is not sufficient to appropriately treat the orographic effects which lead to widespread downpours associated with western disturbances. The model also underestimates the rainfall during summer (figure 4) over the Indian sub-continent. The sharp gradient of the precipitation across the Western Ghats has not been reflected in the rainfall distribution simulated by the model obviously due to the coarse resolution of the model. In addition, the model-simulated rainfall over northwest India is almost twice

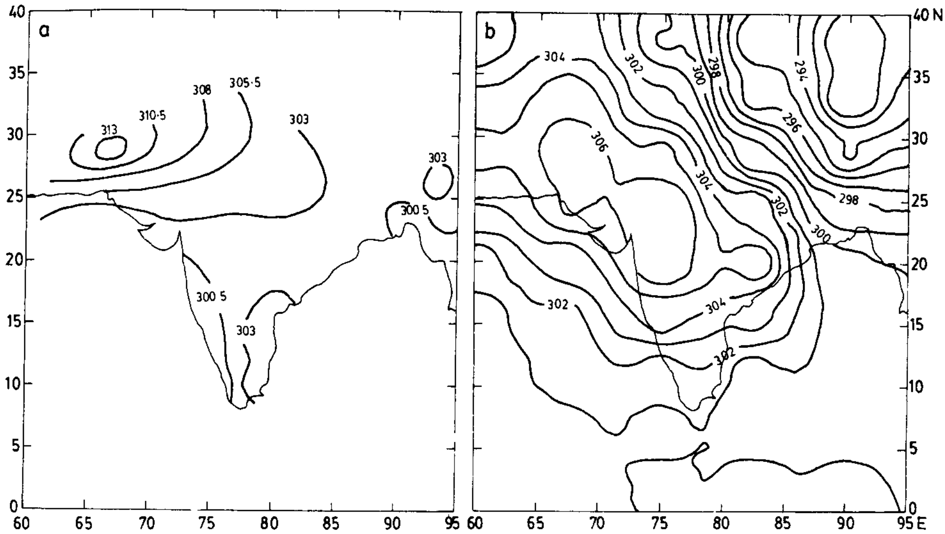

Figure 2. Observed (**a**) and model-simulated (**b**) surface air temperature distributions (K) for summer over the Indian sub-continent.

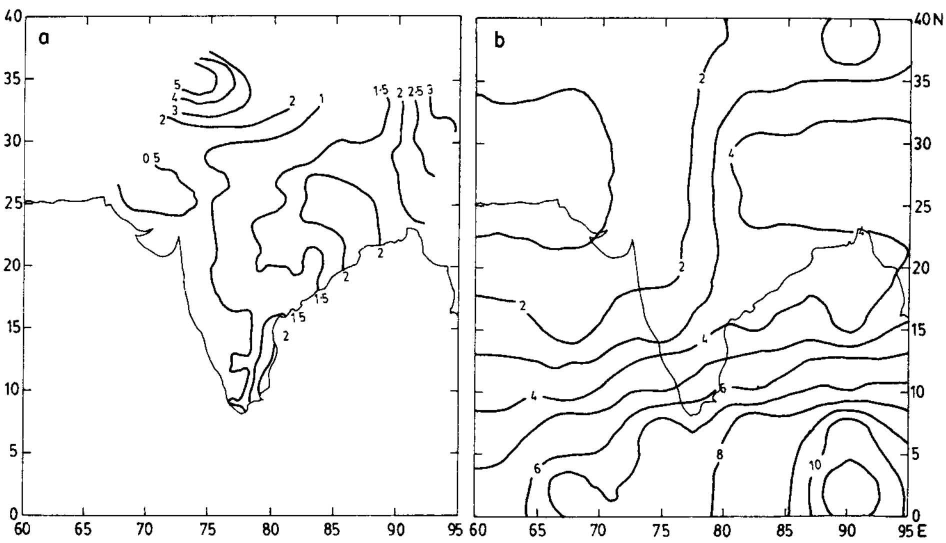

Figure 3. Observed (**a**) and model-simulated (**b**) rainfall distributions (mm/day) for winter over the Indian sub-continent.

as large to the observed distribution of rainfall. It is possible that the dominant subsidence over this region during summer as a result of radiational cooling of the upper and middle troposphere which prohibits convective activity is rather poorly resolved in the model. It is expected that further research on improvements in parameterization of physical processes relevant to Asian monsoon region should lead to better consistency between model results and observations.

While soil moisture is a fundamental factor in determining the growth of plants, it is seldom actually measured. Thus, it has to be calculated, making certain

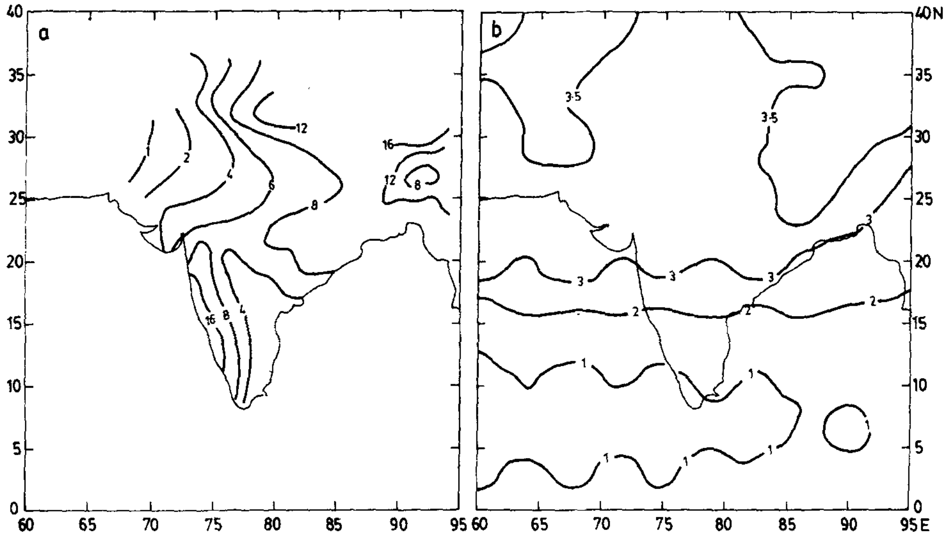

Figure 4. Observed (**a**) and model-simulated (**b**) rainfall distributions (mm/day) for summer over the Indian sub-continent.

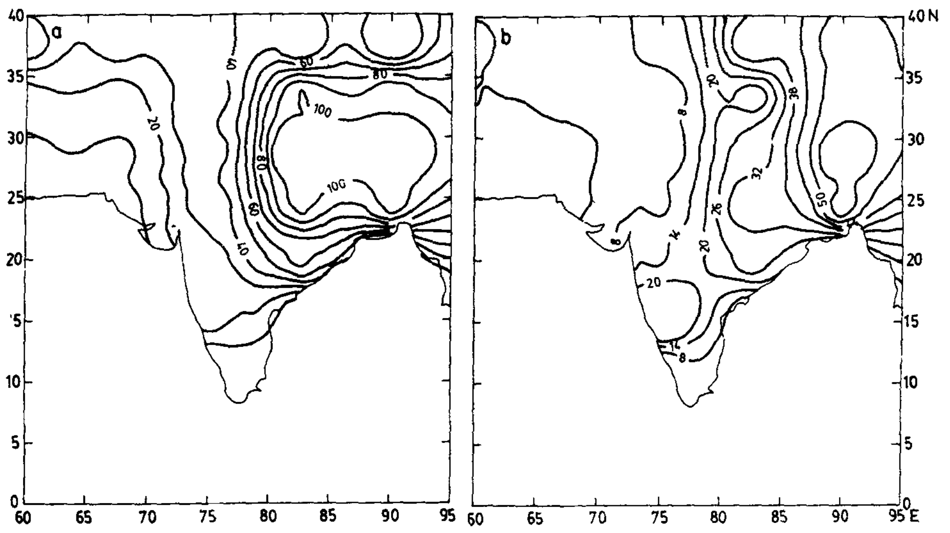

Figure 5. Model-simulated soil moisture distributions (liquid water equivalent) in mm for winter (**a**) and summer (**b**) over the Indian sub-continent.

assumptions about the physics involved. In the climate models it is possible in principle 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 ($P - E$); when the accumulated $P - E$ exceeds some maximum field capacity (W_{fc}) the soil becomes saturated and any further precipitation runs off into the nearest river (R_0). On the other hand, as the ground becomes drier and the level of soil moisture drops below some critical value the rate of evaporation is restricted, and of course it approaches zero as the soil moisture approaches zero.

When there is snow on the ground the water from melting snow (S_m) sinks into the ground as the ground temperature exceeds 0°C. In a recent study Zong-ci Zhao and Kellogg (1988) concluded that the large-scale features in the soil moisture distribution over the Asian monsoon region were generally faithfully reproduced by all the five GCM simulations considered in their study. Most of the GCMs showed the alternation between relatively wet conditions in the north and dry conditions in the south in winter and the reverse in summer, an obvious feature of the Asian monsoon circulation.

The soil moisture distributions over the Indian sub-continent for the two seasons (figure 5) as simulated by NCAR CCM are in fair agreement with the observed soil moisture distribution except that during winter, the predicted soil moisture over northeast India is substantially in excess to that observed over the region. 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 by the model over the region (figures 3 and 4). The magnitude of the maximum soil moisture simulated by the model for winter is twice that of summer. The gradient of soil moisture is from west to east, for both the seasons, over north India. Moreover, the model-simulated distribution pattern of soil moisture is similar to the rainfall distribution over the Indian sub-continent.

4. Simulation of regional climate for doubled CO_2

In general, the model-simulated temperatures in a doubled CO_2 atmosphere are higher over the southern tip of the Indian sub-continent and lower over its northern extremes during winter (figure 6a). During summer, the maximum temperatures shift over the northwest India in such a fashion that the gradient is more or less oriented towards east-west with lower temperatures in the east (figure 7a). The distribution pattern in precipitation over the Indian sub-continent in a warmer atmosphere (due to doubling of CO_2) does not show any significant change over the north and northwest India as well as over much of the south peninsular India during winter as compared to that simulated for the present-day atmosphere (figure 6b). However, over northeast India there appears a substantial enhancement in rainfall activity for the $2 \times CO_2$ case. In summer, rainfall activity is enhanced both over the south peninsular India as well as over the northeast regions of the sub-continent in doubled CO_2 case (figure 7b). A significant feature of the global warming in terms of rainfall distribution in a warmer atmosphere is the decrease over the central plains of India (Bihar and east U.P). This feature is very relevant in view of the major agricultural activity in this region. A significant decrease in rainfall amount is observed over north and northwest India during the summer (monsoon) season in $2 \times CO_2$ case. In terms of soil moisture distribution, the warmer atmosphere over the Indian sub-continent does not give rise to any substantial change during winter (figure 6c) except that a marginal increase is observed over north and north-central India. During summer, the model-simulated soil moisture shows no change in its distribution pattern over the region (figure 7c) due to doubling of CO_2.

The CO_2-induced warming over the Indian region as simulated by the NCAR CCM is fairly homogeneous over the whole of the continent. The changes of surface air temperature ($2 \times CO_2$ minus control) for winter and summer seasons as inferred from NCAR CCM simulation are depicted in figure 8. Due to the doubling of CO_2,

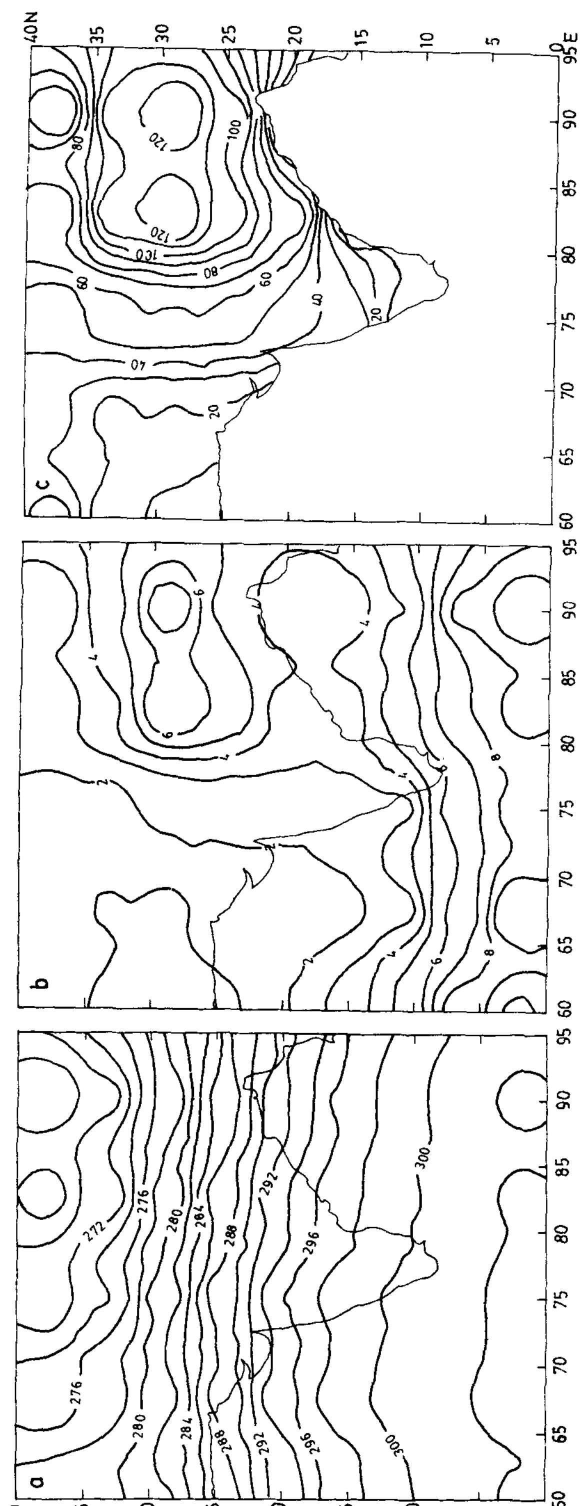

Figure 6. Winter-time distributions of **(a)** temperature (*K*), **(b)** rainfall (mm/day) and **(c)** soil moisture (mm) for doubled CO_2 atmosphere over the Indian sub-continent.

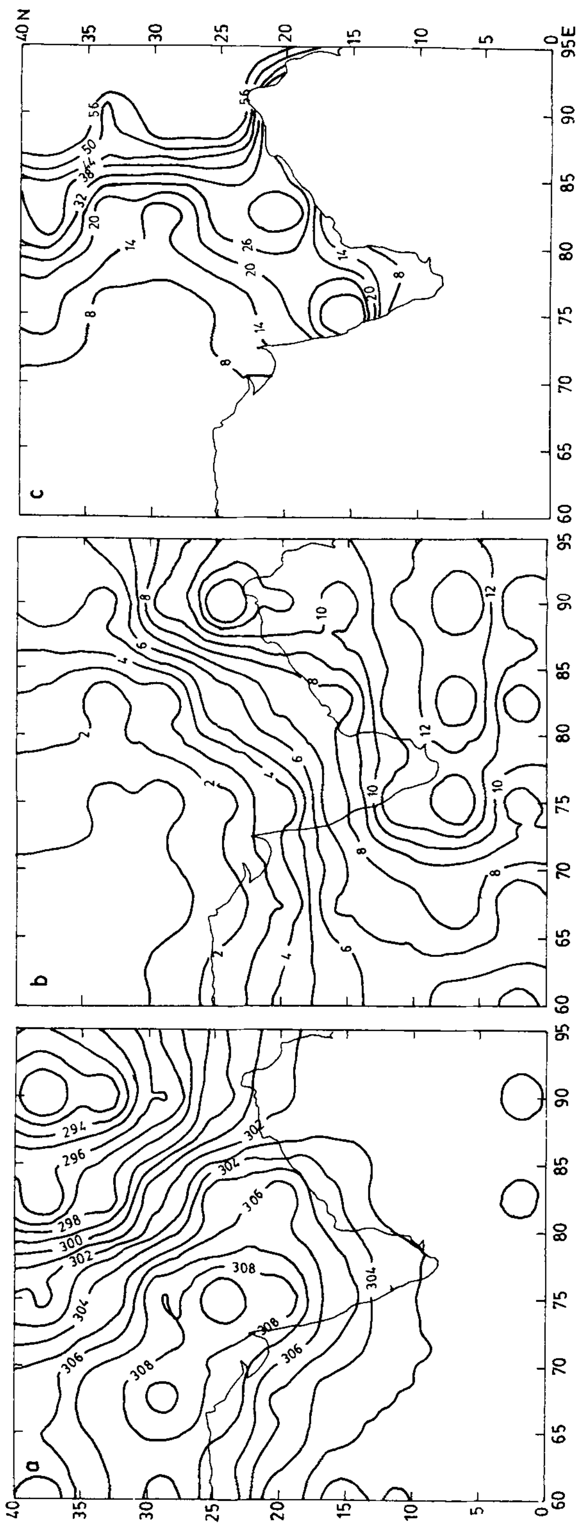

Figure 7. Summer-time distributions of (**a**) temperature (*K*), (**b**) rainfall (mm/day) and (**c**) soil moisture for doubled CO_2 atmosphere over the Indian sub-continent.

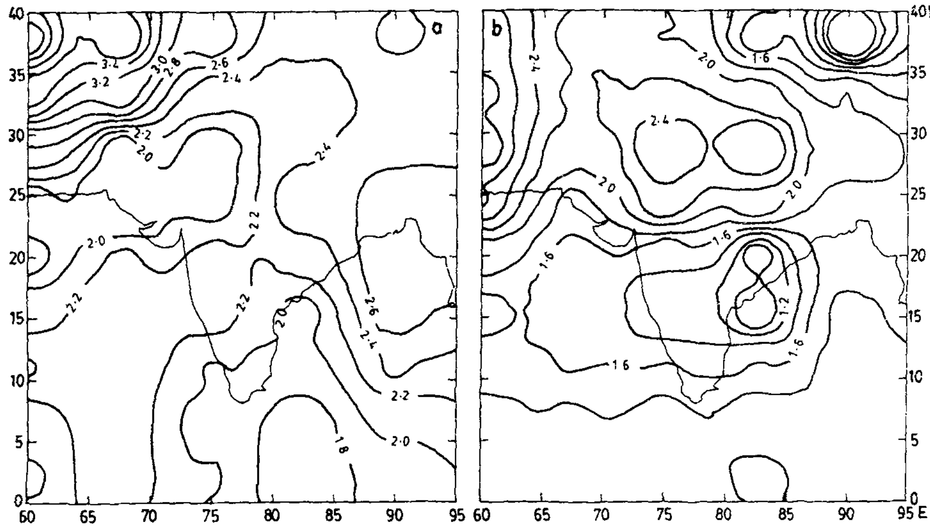

Figure 8. Changes in temperature distribution due to doubling of CO_2 for winter (**a**) and summer (**b**) over the Indian sub-continent.

the increase in surface air temperature during winter, ranges from 1·8°C to 3·4°C over the Indian sub-continent and adjacent seas. The minimum warming (1·8°C) takes place over the Indian ocean, whereas the maximum warming (3·4°C) is located over adjoining Pakistan. In general, the increase in temperature due to doubling of CO_2 in winter is found to be less near the warmer equatorial ocean and more pronounced over the northern tropical latitudes. The model-simulated temperature increase during summer, as a result of doubling in CO_2, varies from 1·0 to 2·4°C over the Indian sub-continent. This increase in temperature is least (about 1°C) along the east coast of India while over the north India pronounced warming (2.6°C) takes place. In general, the model-simulated CO_2-induced warming is less pronounced along the coastal regions of India and more significant over the relatively warmer continental regions (north India).

The changes in rate of daily precipitation during the winter and summer seasons over the Indian sub-continent due to CO_2 increase are depicted in figure 9. In general, the model simulation exhibits an increase in precipitation in both the seasons due to CO_2-induced warming. A marginal decrease in precipitation over the peninsular India (Kerala coast) and over the central Bay of Bengal is observed during winter. An important feature predicted by the model is a substantial enhancement in winter precipitation over the northeast India in a warmer atmosphere. During summer, the model simulation reveals a considerable enhancement in precipitation over the central and southern peninsular India and the adjoining Bay of Bengal. A marginal decrease in precipitation is observed over north and northwest India. A significant increase in rainfall activity could also take place over the northeast India due to CO_2-induced warming.

Precipitation and temperature changes over the continent due to doubling of CO_2 as revealed by model simulation are also reflected in the soil moisture change from control run to 2 × CO_2 case (figure 10). Increased precipitation over the north central India during winter should lead to an increase in soil moisture in a warmer atmosphere.

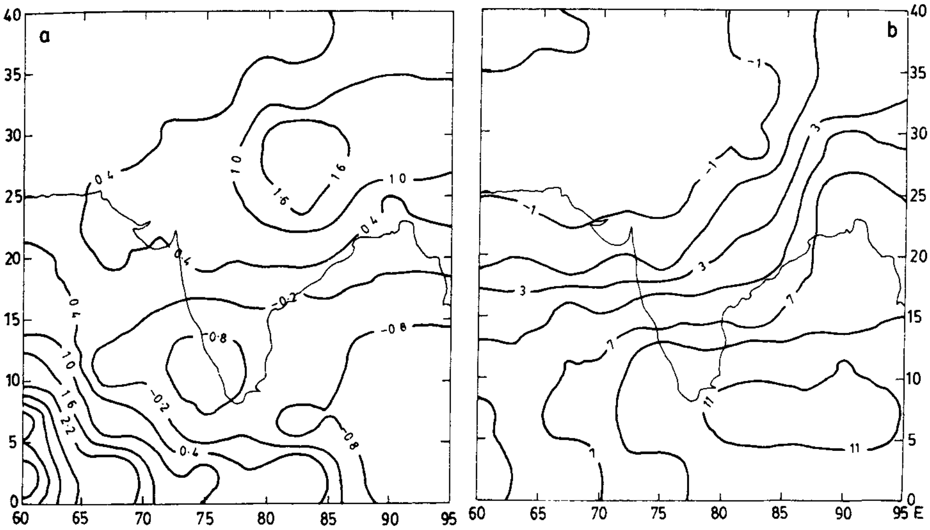

Figure 9. Changes in rainfall distribution (mm/day) due to doubling of CO_2 for winter (**a**) and summer (**b**) over the Indian sub-continent.

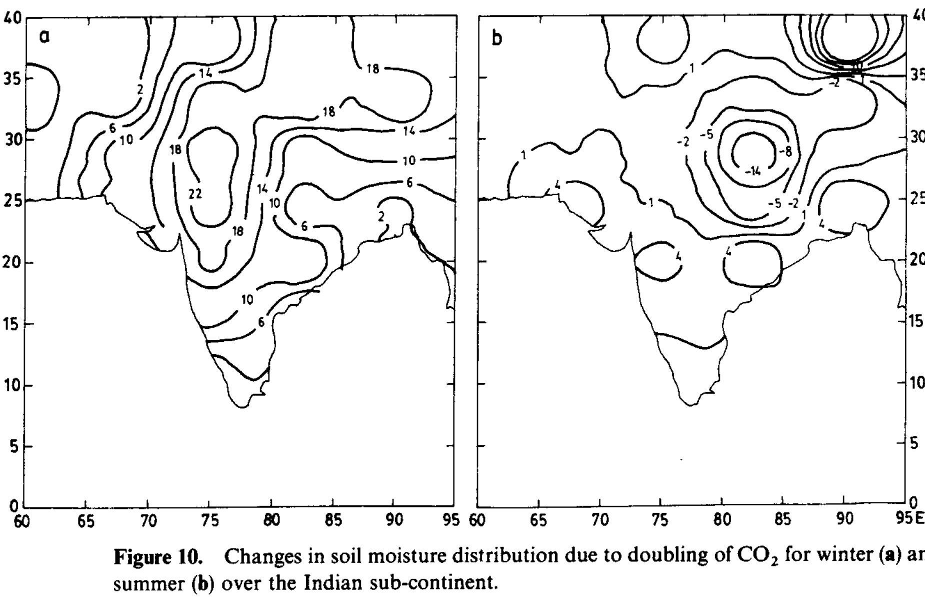

Figure 10. Changes in soil moisture distribution due to doubling of CO_2 for winter (**a**) and summer (**b**) over the Indian sub-continent.

The model results indicate that the central plains of India could be relatively dry compared to the present-day situation during summer in a warmer atmosphere.

To arrive at definite conclusions on the projected changes in soil moisture as well as in temperature and precipitation, a test for statistical significance in the ensemble averages over the region is desired. However, in view of the fact that we had access only to the final 3-year grid point seasonal averages of the three parameters (temperature, rainfall and soil moisture) for $1 \times CO_2$ and $2 \times CO_2$ model runs, we

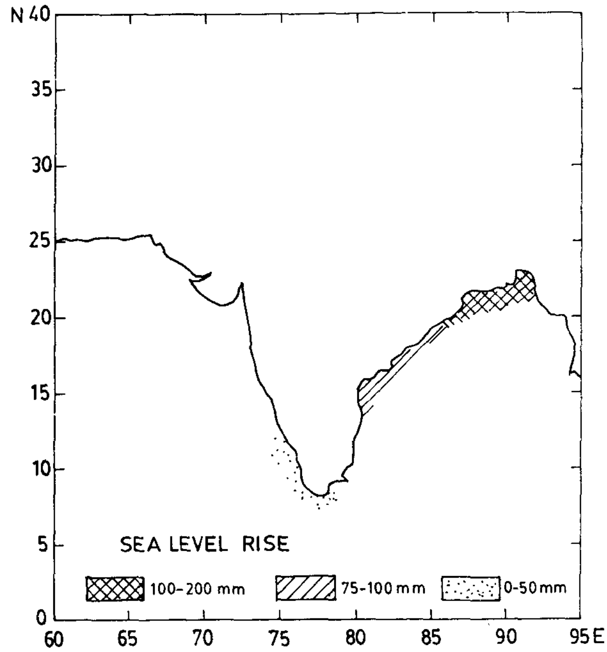

Figure 11. Projected sea level changes (mm) due to doubling of CO_2 by the year 2030 AD along the Indian coastline.

were unable to perform these tests. It may, however, be worth mentioning here that a study on the statistical significance of changes in soil moisture due to doubling of CO_2 as inferred from NCAR CCM experiments has revealed that the regional soil moisture change over 75% of the North American continent is significant at 5% level (Kellogg and Zong-ci Zhao 1988).

The temperature rise predicted by the NCAR CCM (due to doubling of CO_2) over the study area has been used by us in a upwelling diffusion-ocean model (Wigley and Raper 1987) to estimate the thermal expansion of ocean (sea level rise). The estimates of sea level change (expansion of surface waters) in response to the greenhouse warming thus obtained are those expected by the year 2030 AD. For this purpose, we inferred mean grid-point temperature change along the Indian coastline based on the temperature changes for winter and summer seasons as inferred from NCAR CCM. Our computations on the thermal expansion of seawater as a result of temperature increase reveal that an annual mean sea level rise of 150 to 200 mm is expected along the West Bengal and Bangladesh coast, while along the Andhra coast it is expected to be 75 to 100 mm. Only a marginal rise (50 mm) in sea level is expected along the Kerala coast. No significant change is expected over much of the Maharashtra and Gujarat coastline.

5. Conclusions

In this paper, we have presented a climate scenario for the Indian sub-continent expected by the year 2030 AD when the equivalent CO_2 is likely to be doubled from its present day's concentration. This scenario, based on NCAR CCM simulation, is a very broad picture of what the changed climate might be like and should not be considered as a confident forecast. We have had no access to the model-generated data on changes in wind field due to global warming and this is one parameter which needs to be closely looked into in view of the typical monsoon circulation over the Indian sub-continent. Nonetheless, based on a preliminary examination of the model outputs, we may speculate that excessive rainfall could be expected in northeast India as a consequence of global warming. A temperature increase may have serious consequences for the northwest semi-arid regions of the Indian sub-continent. Lowlying coastal regions along the east coast of India could suffer more erosion, salt intrusion and a greater risk of flooding. More elaborate studies based on model output statistics of several other state-of the-art GCMs are currently in progress and it is expected that it would be possible, in the near future, to provide better future projections of regional warming over the Indian sub-continent and associated changes in wind, precipitation, soil moisture and sea level with a higher degree of confidence.

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