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Effect of anthropogenic radiative forcings in the simulation of long-term trend and variability in monsoon climate

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Abstract

Indian Summer Monsoon plays an important role in many of socio-economic activities in the Indian Subcontinent. Water resources are most susceptible to changes in monsoon climate. An accurate and reliable portrayal of change in monsoon climate due to climate change is therefore very important in the perspective of impact of climate change on water resources. The ability of current generation of global climate models, in their long term simulations, to replicate the observed atmospheric behavior on a wide range of spatial and time scales provides support in applying these models to the regional climate change projections induced by anthropogenic radiative forcings. The ability of a coupled atmosphere ocean climate model (ECHAM3 + LSG) at T21 resolution to simulate the trends and interannual variability in area-averaged annual mean surface air temperature and summer monsoon precipitation over Indian subcontinent in three different numerical experiments viz.; control, GHG and GHG plus aerosol is examined. The model has superior skill in reproducing the observed trend and interannual variability in area-averaged annual mean surface air temperature and interannual variability (in terms of standard deviation) of summer monsoon rainfall over Indian subcontinent during the past century in GHG plus aerosol experiment. The model's inability to simulate the observed trend in monsoon rainfall over the area of interest realistically, in all the three experiments, is a reflection of the sensitivity of simulated rainfall to mesoscale forcings such as monsoon trough, effect of complex orography not resolved at a resolution and deficiencies of parameterization scheme for convection and land surface processes.

INTRODUCTION

A significant increase in the atmospheric concentration of several greenhouse gases and aerosols have been observed due to anthropogenic activities since the beginning of industrial era. The ongoing increase of these gases and aerosols is of considerable concern because of their radiative effects, which may change the pattern of natural climatological cycles. Temperature of air at the Earth's surface has risen during the past century (Hansen *et al.*, 1996). The agricultural and industrial productivity is highly dependent on climate and its change. The change in climate may adversely affect the socio-economic sector of human dimension. To mitigate the impact of climate change, the policy makers require the information about the change on regional or country scale. Therefore it is important to assess the regional climate change likely to occur in future, with some confidence and accuracy so that the social and economic consequences expected due to this change may properly be judged and appropriate policy options may be formulated on national scales to combat the impact of greenhouse gas-induced climate change.

Over the past decades, a hierarchy of climate models has been developed to study the effects of increasing greenhouse gas concentration in the atmosphere on the earth's climate. The current state-of-the-art general circulation models (GCM's) incorporate the essential dynamics and thermodynamics of the atmosphere and are considered the best available tools for the assessment of likely climatic changes expected due to the enhanced greenhouse effect. Confidence in climate models depends partly upon their ability to simulate the current climate and recent climatic trends, and partly upon the realistic representation of the physical processes that are important within the climate system. In the present study we examine the ability of a coupled Atmosphere-Ocean General Circulation Model (A-OGCM) in simulating the past climate change, specially the trends in temperature and precipitation over Indian sub-continent in three different numerical experiments. The projection of climate change over the area of interest by the model is also examined. The study aims to understand better the nature of radiative forcing in representing the past climatic trend over Indian sub-continent. The ability to replicate the interannual variability of temperature and precipitation over Indian sub-continent by the model is also examined.

The remainder of the paper is organized as follows. The next section describes the atmosphere and ocean general circulation model used in the study. Thereafter a brief description of the numerical experiments performed with the model and specific region for which detailed data analysis has been conducted is presented. The subsequent section deals with the analysis and interpretation of the results. Finally conclusion of the study with some suggestions for future work is present

THE MODEL

The present study is based on the analysis of data generated in numerical experiments performed with the so-called ECHAM3 model coupled to an ocean model 'LSG'. ECHAM3 is the third generation General Circulation Model (GCM) used for global climate modeling investigations in Germany. The prognostic variables include vorticity, divergence, temperature, log surface pressure, water vapor and cloud water. The model has 19 layers in the vertical hybrid co-ordinate system. The integration is performed following semi-implicit scheme with leap frog time filter at every 40-min intervals. The physical parameterization schemes used in ECHAM3 at T21 resolution have been developed and validated (Roeckner *et al*., 1992; Glecker *et al*., 1994).

The parameterization of subgrid-scale physical processes is formulated in a simplified parametric form. The vertical turbulent transfer of momentum, heat, water vapor and cloud water is based upon the Monin-Obukhov similarity theory for the surface layer, and the eddy diffusivity approach above the surface layer. The parameterization of cumulus convection is based on the concept of mass flux and comprises the effect of deep, shallow as well as mid-level convection on the heat, water vapor and momentum budgets (Tiedtke, 1989). Subgrid-scale condensation and cloud formation is taken into account by specifying appropriate thresholds for relative humidity, depending on altitude and static stability. The land surface scheme considers the heat and water budgets in the soil, snow cover and land, and the heat budget of permanent land and sea ice (Dumenil and Todini, 1992). For further details on the ECHAM3 model, the reader is referred to Deutsches Klimarechenzentrum GmbH Technical Report No. 6 (DKRZ, 1994).

The ocean general circulation model (Maier-Reimer *et al*., 1997) is based on a numerical formulation of the primitive equations appropriate for large-scale geostrophic (LSG) motion. The nonlinear advection of momentum is neglected and fast gravity waves are strongly damped by an implicit time integration scheme using a time step of 30 days. A small explicit horizontal diffusion of 200 m/s is introduced to counteract the inherent tendency for mode splitting in the Arakawa E-grid (Arakawa and Lamb, 1977) used in horizontal discretization scheme. Vertical convective mixing is applied whenever the statification becomes unstable. Sea ice is computed from the ice heat balance and the advection by oceanic currents, using a simplified viscous rheology. The discretization of the ocean model is based on 11 unequally-spaced vertical levels and two overlapping 5.625^0 horizontal grid which are interpolated onto the resolution of the Gaussian grid used in ECHAM3. In the coupled mode, the basic time step of 30 days is reduced to 1 day for the computation of sea ice and the temperature and salinity in the two uppermost ocean layers in order to resolve the rapid response of the upper ocean to the short-term variability of the atmosphere.

THE EXPERIMENT AND REGION OF INTEREST

The data generated by the climate model (ECHAM3 + LSG) in three different experiments have been used to investigate past, present and future trends and interannual variability in the two key climate parameters namely temperature and precipitation over Indian subcontinent. These experiments are as the Control experiment, the GHG experiment and GHG plus Aerosol experiment. In the control experiment (hereafter abbreviated as experiment ‘C’), the control reference atmosphere has been simulated with the coupled climate model over a period from the year 1880 to the year 1989 with constant atmospheric CO_2 concentration. The GHG experiment (hereafter abbreviated as experiment ‘G’) included the radiative forcing of observed atmospheric equivalent CO_2 (CO_2 and other greenhouse gases) concentrations from the period 1880-1989 and the projected equivalent CO_2 concentrations for the period 1990-2049. The projected CO_2 concentration is based on Business-As-Usual scenario of Intergovernmental Panel on Climate Change (IPCC) and represents a 1.3-% per year compound increase of CO_2. In the GHG plus aerosol experiment (hereafter abbreviated as experiment ‘S’), the effect of both the greenhouse gases (equivalent CO_2) as well as the sulfate aerosols was considered. The anthropogenic sulfate burden information was obtained from Langner and Rodhe’s (1991) calculations and direct radiative forcing was mimicked by a change of the surface albedo following the algorithm developed by Charlson *et al*. (1991).

The geographical region of interest for model data analysis reported herein is Indian subcontinent, confined to the region bounded by 5^oN to 30^oN latitude and 65^oE to 95^oE longitudes.

DATA ANALYSIS AND RESULTS

Various diagnostics have been performed on the data in order to examine the skill of the model in different experiments in simulating the trends and interannual variability in area averaged annual mean temperature and total monsoon precipitation over Indian subcontinent. These include the statistical tests such as Kolmogorov-Smirnov test for frequency distribution, and Wilcoxon rank sum test for the locations of the distributions between the data sets from observed climatology and those simulated by the model over the region of interest. Trend analysis was performed over the data sets and F-test was applied to explore whether the long-term trend in these parameters is significant. The observed surface air temperature and rainfall (Parthasarathy *et al*., 1995) time series used here for comparison purposes are of anomalies from long term means of temperature and rainfall monitored at homogeneously spaced meteorological stations over India. For the projection of future trends in these two key climatic parameters, the model output in the experiments G and S from year 1980 to 2049 (70 years) were analyzed. To understand interannual variability of these climatic parameters standard deviations in the data sets are also calculated. In the following discussion in this section, focus is on the surface air temperature, the precipitation and future trends and interannual variability in the temperature and precipitation over the area of interest respectively.

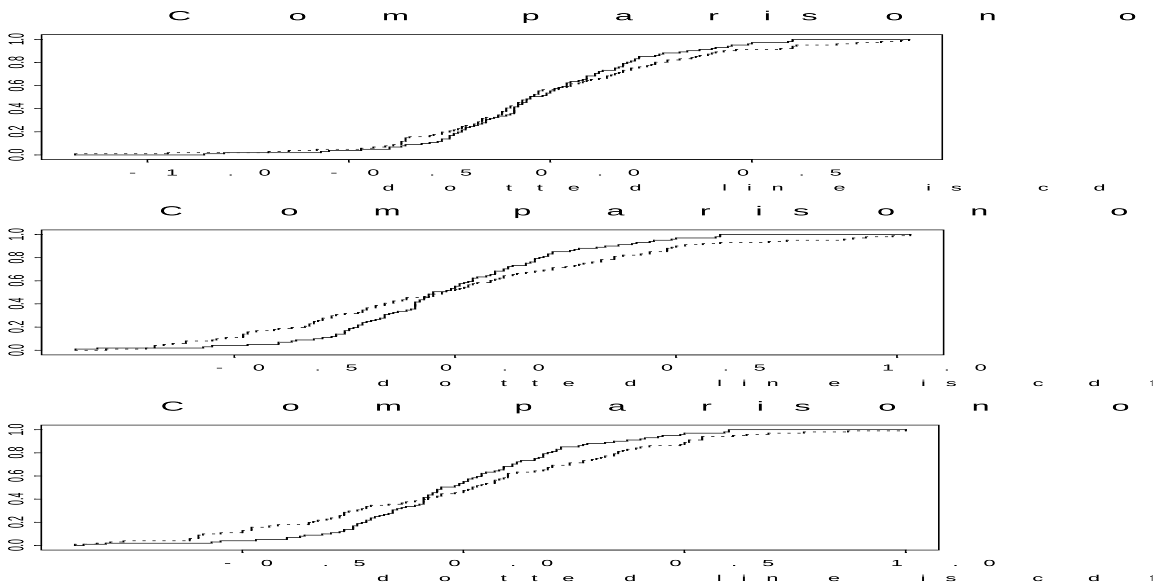

Figure 1. Comparison of cdf's of observed and model simulated average annual temperature over Indian subcontinent.

Surface Air Temperature

For a tropical country like India, the temperature of the air near surface of the ground is an important climatic parameter. To understand the similarity of the distribution of the model generated temperature data for the period year 1880-1980 with that of the observed for the same period, Kolmogorov-Smirnov (K-S) test and Wilcoxon rank sum test has been performed. Albeit K-S test does not find similarity between cumulative frequency distribution (cdf) of the data from model simulation in all three experiments and observed climatology at 10% significance level, Wilcoxon rank sum test shows that the location of the distribution of area-averaged annual mean surface air temperature for the period 1880-1980 from the experiment S and that of observed data for the same period does not differ significantly at 10% level. While the data of area-average annual surface air temperature for the period 1880-1980 from experiment C and G reflect significant difference with that from observed for the same period at 10% level. It is also depicted from Figure 1 that the frequency distribution of data from experiment S is closer to that from observed than other two experiments. This implies that the data from experiment S is representing the frequency distribution better than from other two experiments. It may be due to the better representation of the radiative forcing in the experiment S for the region of interest.

Several studies have reported increasing trend in surface air temperature over Indian subcontinent. The study conducted by Thapliyal and Kulshrestha (1991) reports a slight warming trend of the order of 0.4^{o}C during the last 89 years. Shrivastava et al. (1992) reports a trend of 0.21^{o}C per 100 years in the temperature over India during the recent past. The observed data for annual mean surface air temperature used in this study has a trend of 0.24^{o}C per 100 years averaged over Indian subcontinent, which is significant at 1% level. Table 1 contain the trends and standard deviations in annual mean surface air temperature and summer monsoon rainfall averaged over Indian subcontinent from observed and the model simulated.

Table 1. Trends and Standard Deviations in annual mean surface air temperature and summer monsoon rainfall averaged over Indian subcontinent observed and the model simulated.

Exp.	Trends in Temperature (oC/100 yrs)		Trends in Monsoon Rainfall (mm/day/100 yrs)	
	Period (1880-1980)	Period (1980-2049)	Period (1880-1980)	Period (1980-2049)
Obs	0.24 (0.27)*	-	0.004 (0.67)	-
S	0.25 (0.36)	1.28 (0.46)	-0.40 (0.57)	-0.74 (0.51)
G	0.58 (0.42)	4.84 (1.04)	0.24 (0.50)	2.61 (0.78)
C	0.12(0.40)	-	-0.10 (0.54)	-

* The numbers in brackets are the standard deviations.

The area-averaged annual mean surface air temperature for the period of 1880-1980, simulated by the model in experiment C has a trend of 0.12^{o}C per 100 years. This trend in the temperature is smaller than that in observed. In experiment G, the model simulates a trend in area-averaged annual mean surface air temperature over Indian subcontinent of 0.58^{o}C per 100 years. The trend shown by the model in this experiment, in the temperature is larger than that of observed. This indicates that the radiative forcing considered in this experiment of the model is unrealistically high and leads to overestimation of past temperature trend. The trend in the surface air temperature simulated by the model in experiment S is 0.25^{o}C per 100 years. This trend simulated by the model in experiment S is very much close to that of the observed. It may thus be concluded that the radiative forcing in the experiment S is best among the three different experiments of the model to represent the observed trend in the surface air temperature during the period 1880-1980 over Indian subcontinent.

The observed mean surface air temperature gives standard deviation of_0.27^{0}C, while area-averaged mean surface air temperatures from experiments C, G and S show standard deviation of 0.40, 0.42 and 0.36^{0}C respectively. The standard deviation of the mean surface air temperature from S experiment is closest to that of observed mean surface air temperature among the three experiments. Thus to conclude experiment S of the model best represents the interannual variability of the mean surface air temperature over Indian subcontinent, among the three experiments of the model. From the Figure 2 it is clear that among all three experiments, experiment S shows best replication of past temperature trend and interannual variability in the annual mean surface air temperature averaged over the area of interest.

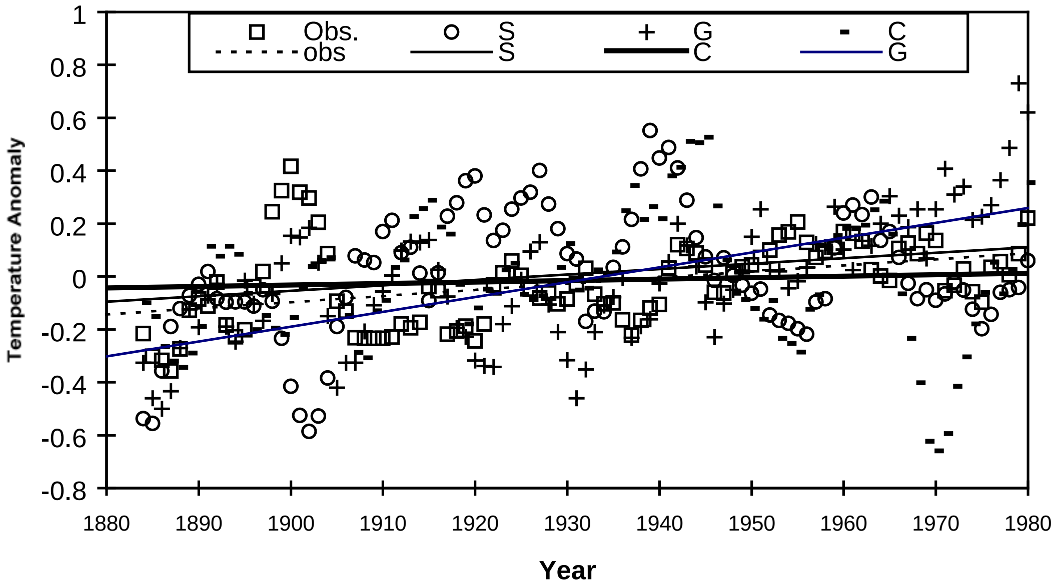

Figure2. Annual mean Temperature of India from Observed and the Model Simulated (5 year running mean).

Precipitation

Considerable amount of work has been reported by several workers on the variability of seasonal and annual rainfall over India during last 100 years. Sarker and Thapliyal (1988) and Thapliyal (1990) studied the long period (1875-1989) annual rainfall over India and did not find any significant trend in rainfall. The analysis of the observed data of summer monsoon rainfall in present study also does not show a significant long-term trend.

K-S test does not find similarity between cdf 's of the data from model simulation in all three experiments and observed time series for summer monsoon rainfall at 10% significance level. Also Wilcoxon rank sum test shows that the location of the distribution of the rainfall for the period 1880-1980 from any of the experiments and that of observed data for the same period does not find similarity significantly at 10% level. From chi square test the model simulated area-averaged monsoon rainfall, in S experiment, is not significantly different with the observed summer monsoon rainfall at 90% of confidence level. While the model simulated area-averaged monsoon rainfall in experiments G and C are significantly different with that of observed at 90% confidence level. The observed monsoon rainfall gives the standard deviation of 0.67 mm/day. The standard deviations in the data sets of the area-averaged monsoon rainfall from the model simulated in experiments S, C and G are 0.57, 0.54 and 0.50 mm/day respectively. This further suggests that the model in GHG plus aerosol experiment in comparison to in other two experiments better simulates the summer monsoon rainfall and year to year variability in the rainfall over Indian subcontinent. For determining decadal trend, running means of annual rainfall have been studied. As would be seen from figure 3, the rainfall of India exhibits fluctuating epochal decreasing and increasing trends during last 100 years. It is clear from the figure 3 that the model in its all the three different experiments also exhibits its epochal decreasing and increasing trend during last 100 years.

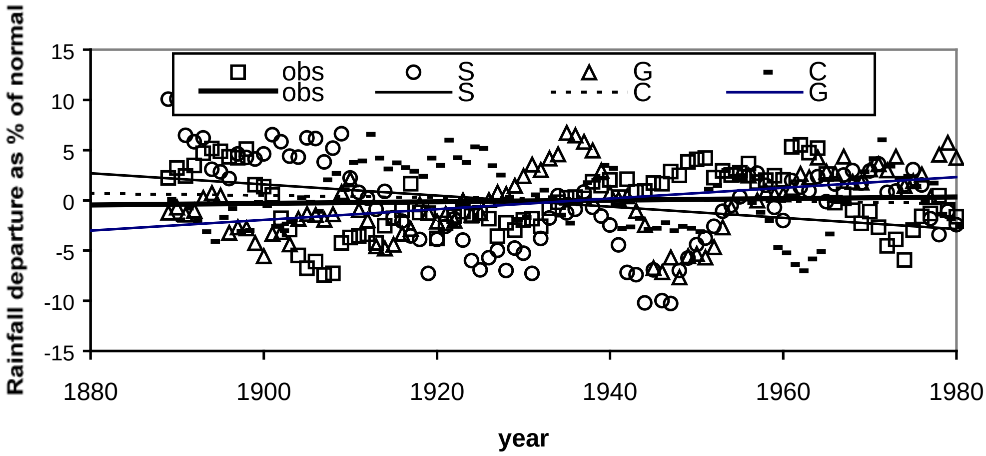

Figure3. Monsoon Rainfall over India from Observed and the Model Simulated (10 year running mean).

The trend in area-averaged monsoon rainfall depicted by the analysis of the model simulated data in experiment S, G and C for the period 1880 to 1980 are -0.40, 0.24 and -0.10 mm/day/100 year respectively. These figures show that none of the model experiments are able to depict the observed trend in summer monsoon rainfall over Indian subcontinent realistically. Study conducted by Lal et al. (1997) also reports the underestimation of total seasonal rainfall by a model. Thus the model in experiment S represents the monsoon rainfall and its interannual variability (in terms of standard deviation) over Indian subcontinent better than the model in other two experiments.

Future Trends and interannual variability in Temperature and Precipitation

The model results, in experiments S and G for the area-averaged mean annual temperature show the trends of 1.28^{o}C and 4.84^{o}C/100 year in next 70 years (1980-2049), respectively. While the trend of 0.39^{o}C/100 year in the surface air temperature (data from 1911 to 1980) is observed. Since the model in experiment G has excessively large radiative forcing, therefore future trend in the temperature projection may be unrealistically high. The model, in GHG plus aerosol experiment projects an increase of nearly 0.9^{o}C/100 year increase in the present increasing trend of surface air temperature. Standard deviations in the data of area-averaged annual mean temperature from the model in experiments S and G for future 70 years (from 1980 to 2049) are 0.46^{0}C and 1.04^{0}C respectively. Observed data for mean annual temperature (from 1911 to 1980) shows standard deviation of 0.25^0C. Therefore the model in its best experiment projects an increase in year to year variability in average annual mean surface air temperature over Indian subcontinent.

The model projects in experiments S and G for the area-averaged monsoon rainfall the trends of -0.74 and 2.61mm/day/100 year in near future 70 years (1980-2049), respectively. While the trend of 0.21mm/day/100 year in summer monsoon rainfall from observed data (data from 1911 to 1980) is found. The model in experiment G excessively huge radiative forcing, therefore projection of future trend in the summer monsoon rainfall is very large. The model, in experiment S projects a decrease in the summer monsoon rainfall. This may be due to decrease in thermal gradient, the driving force of monsoon between land and sea. Standard deviations of the data for summer monsoon rainfall, from the model in and experiments S and G for future 70 years (from 1980 to 2049) are 0.51mm/day and 0.78mm/day respectively. Observed data (from 1911 to 1980) shows standard deviation of 0.68mm/day. Thus, to conclude the model in its best experiment projects a decrease in interannual variability in summer monsoon rainfall over Indian subcontinent.

CONCLUSION

The study suggests that the climate model (ECHAM3 + LSG) simulation, in GHG plus aerosol forcing experiment is superior in portraying the trend in area-averaged annual mean temperature over Indian subcontinent. This experiment also shows better performance in simulating the year to year variability (in terms of standard deviation) in summer monsoon rainfall over Indian subcontinent. The model is unable to realistically reproduce the observed trend in the summer monsoon rainfall over the area of interest in all three experiments. This is due to the fact that simulated precipitation is very sensitive to the meso-scale forcings forcings, as also the deficiencies of parameterization schemes for convection and land surface processes. The parameterization of subgrid-scale physical processes such as boundary layer mixing, convection and surface fluxes needs to be reformulated to more adequately represent their interaction with horizontal resolution for accurate simulation of monsoon climate.

The simulation experiments referred to in here have considered only the direct cooling effect of sulfate aerosols produced by industrial activity. Considerable uncertainty prevails about the indirect effect of sulfate aerosols on tropospheric clouds, which could strongly modulate the monsoon climate. We are still unclear about the implications of localized radiative forcing on the deep convection in the tropics and on Hadley circulation. It has also been suggested that aerosols produced by tropical biomass burning could lead to additional negative radiative forcing. The radiative forcing due to tropospheric ozone increases as a consequence of biomass burning has been found to be of same magnitude but opposite in sign to that due to direct effect of biomass burning aerosols. However, geographical extent of increases in tropospheric ozone is considerably larger than that of aerosols. Precise magnitude as well as the role of these spatially localized potential forcings must be known before a confident prediction of regional changes in climate and its variability could be made.

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