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Regional aspects of global climate change simulations : Validation and assessment of climate response over Indian monsoon region to transient increase of greenhouse gases and sulfate aerosols

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सार - भूमंडलीय जलवायु परिवर्तन के साथ क्षेत्रीय जलवायविक दुष्प्रभाव के सहचारी होने का और उनके मूल्यांकन का अत्यंत महत्व है क्योंकि क्षेत्रीय पैमाने पर कृषि, जलसंसाधन, परिस्थितिकी आदि सभी जलवायविक परिवर्तनों के प्रति अतिसंवेदनशील होते हैं। युग्मित कपल्ड वायुमंडल-महासागर सामान्य परिसंचरण मॉडल (ए.ओ.जी.सी.एम.) के अनुकरण परिदृश्यों का एक क्षेत्र प्रदान करते हैं जिसका उपयोग दुष्प्रभावों के मूल्यांकन और इन दुष्प्रभावों के समाधान के लिए अपनाने के लायक अथवा प्रश्मनात्मक नीतियों को विकसित करने के लिए किया जा सकता है। संभावित दुष्प्रभावों के निर्धारण हेतु निदर्श के प्रक्षेपणों को प्रयुक्त करने से पूर्व, प्रेक्षणों से संबंधित निदर्शों के प्रमाणीकरण तथा जलवायु परिवर्तन के आवेग की संवेदनशीलता को सुव्यवस्थित करना अनिवार्य है। निदर्श से अनुकरित अधिकांशतः जलवायु प्रक्षेपण प्रायः घटिया किस्म के होते हैं क्योंकि दुष्प्रभाव के मूल्यांकन के लिए निदर्श का प्रयोग (जैसे फसल अनुकरण निदर्श अथवा नदी प्रवाह निदर्श आदि) उच्चतर स्थानिक समाधान के लिए किया जाता है। जी.सी.एम. निष्पादन की मात्रा को घटाने की यथोचित नीति अपनाकर इस स्थानिक विसंगति को दूर किया जा सकता है।

इस अध्ययन द्वारा दो ए.ओ.जी.सी.एम. (ECHAM 4/OPYC 3 और HadCM 2) जलवायु परिवर्तन के अनुकरणों की भारत में मानसून जलवायु के अनुकरण और अनुकरित जलवायु के क्षणिक परिवर्तनों की संवेदनशीलता में उनके निष्पादन के लिए ग्रीन हाउस गैसों के संबंध में वायुमंडलीय केन्द्रीकरण और सल्फेट वायुविलयों की जाँच की गई है। इन परिणामों से यह पता चलता है कि भारत में जलवायु की सकल विशिष्टताओं को ये दो मॉडल काफी हद तक सही ढंग से अनुकरित करते हैं। तथापि माध्य अभिलक्षणों के अनुकरण वलीयनों की संवेद्यता और जलवायु परिवर्तन के अनुकरण में पाई गई अन्तः निदर्श विभिन्नताएं के संबंध में सावधानी बरतने की सलाह दी गई है। आगे, इस शोध पत्र में यह भी बताया गया है कि भारत में क्षेत्रीय जलवायु परिवर्तन का परिदृश्य तैयार करने के लिए जी.सी.एम. प्रक्षेपणों के प्रयोग की संभावना का पता लगाने के लिए एक आनुभाविक डाउनस्केलिंग दृष्टिकोंण का उपयोग किया जाता है।

ABSTRACT. The regional climatic impacts associated with global climatic change and their assessment are very important since agriculture, water resources, ecology etc., are all vulnerable to climatic changes on regional scale. Coupled Atmosphere-Ocean general circulation model (AOGCM) simulations provide a range of scenarios, which can be used, for the assessment of impacts and development of adaptive or mitigative strategies. Validation of the models against the observations and establishing the sensitivity to climate change forcing are essential before the model projections are used for assessment of possible impacts. Moreover model simulated climate projections are often of coarse resolution while the models used for impact assessment, (*e.g.* crop simulation models, or river runoff models etc.) operate on a higher spatial resolution. This spatial mismatch can be overcome by adopting an appropriate strategy of downscaling the GCM output.

This study examines two AOGCM (ECHAM4/OPYC3 and HadCM2) climate change simulations for their performance in the simulation of monsoon climate over India and the sensitivity of the simulated monsoon climate to transient changes in the atmospheric concentrations of greenhouse gases and sulfate aerosols. The results show that the two models simulate the gross features of climate over India reasonably well. However the inter-model differences in simulation of mean characteristics, sensitivity to forcing and in the simulation of climate change suggest need for caution. Further an empirical downscaling approach is used to assess the possibility of using GCM projections for preparation of regional climate change scenario for India.

Key words – Climate models, Climate change, Regional climatic scenario, Downscaling, Monsoon change, Climate sensitivity.

1. Introduction

The regional climatic impacts associated with global climatic change and their assessment are gaining increasing importance. This is because the agriculture, water resources, ecology etc., are vulnerable to climatic changes on regional scale. Though general circulation models (GCMs) have been successful in realistic simulation of the global climate and observed climate change, significant differences come to the fore when examined on sub-continental regions with few grid points.

The three-dimensional climate models involve comprehensive coupling of atmospheric general circulation models with ocean general circulation models,including sea ice models, and models of land-surface processes. While even the most complex models are prone to substantial errors in their simulations on regional scale, such errors by no means make a given model totally unusable for regional applications. Regional validations can be used to identify and quantify the biases in the simulations, which can possibly help in deriving correction factors. In addition to regional validation, assessment of the sensitivity of the model (with reference to regional climate) to various forcings can help in establishing confidence in the model projections for assessment of impacts and other applications.

The impact assessment models (*e.g.* crop simulation models, or river runoff models etc.) operate on a higher spatial resolution (~40 km; Gallaini and Filippini 1985). Derivation of regional climatic information at such high spatial resolution from the coarse-resolution GCM products is achieved by 'downscaling'. This is done either through dynamical methods, *e.g.*, regional models nested with GCMs (Giorgi, 1990; Giorgi and Mearns, 1991) and 'time-slice' methods (Cubasch *et al*., 1996; 1995a) or through empirical downscaling techniques (Karl *et al*., 1990; Wilks, 1989; Wilby *et al*., 1998).

In the present study, climate change simulations of two models are used to develop climate change scenario over India through assessment of sensitivity to transient forcings and empirical downscaling.

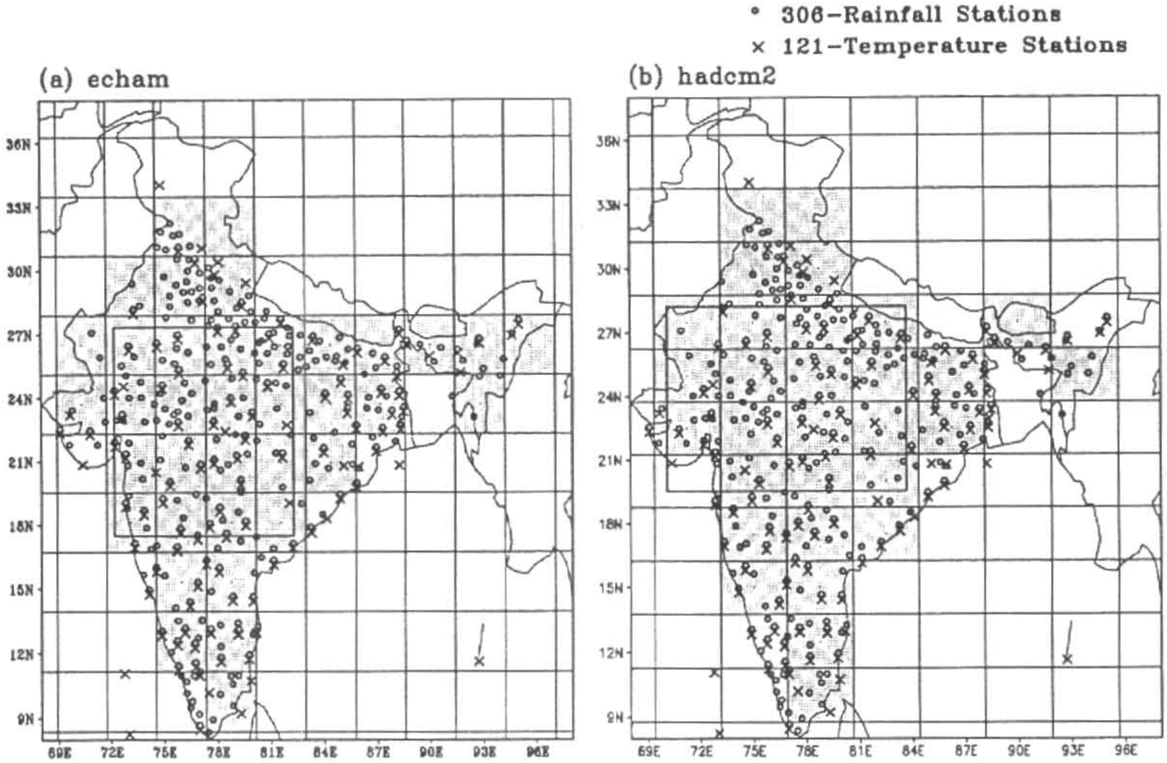
2. Data

2.1. *The AOGCMs and the climate change simulations used in this study*

The models chosen for this study are the ECHAM4/OPYC3 of Deutsches Klimarechenzentrum (DKRZ) and HadCM2 of Hadley Centre for Climate Prediction and Research (HCCPR). ECHAM4 is a 19-level spectral GCM with a resolution of T42 (~ 2.8° in lat. long.). A detailed account of the model specifications has been given by Cubasch *et al*. (1996). HadCM2 is a grid point GCM with horizontal resolution of 3.75 longitude and 2.5° latitude and 19-levels in the vertical, Johns *et al*. (1997) gives full details of the model. A layout of model grids over the monsoon region is shown in Fig. 1 for both models, with shaded area representing the land grid points of present interest. Output data of three experiments performed using these models at the respective centers as part of IPCC climate change simulations have been obtained from IPCC Data Distribution Centre (http://www.ipccddc.cru.uea.ac.uk/). For ECHAM4 a control (C) run in which the atmospheric forcing is kept constant, has been performed over a period over 1000 years in length. The concentrations of CO_2, CH_4 and N_2O are fixed at the observed 1990 levels as given by (IPCC'90), and the concentrations of the industrial gases (CFC's and others) are set to zero, while ozone and aerosols are prescribed as climatological distributions. After a 100-year spin up, the model was run, with constant flux adjustment, for another 300 years. The climatology constructed from this 300-year (C) run serves as a reference for the time-dependent forcing experiments. The transient experiments are initialized at year 100 of control. In HadCM2 simulations, the control (C) run is initialized from the end of the spin up (510 years). The two anomaly runs are initialized at 10th year of control. In the greenhouse (G) experiments of both models the greenhouse gas forcing is increased gradually to represent the observed changes in forcing due to all the greenhouse gases from 1860 to 1990. From 1990 to 2099 it uses a rate of 1% / year compounded increase in concentrations (a rather larger forcing scenario than is represented by the IS92a emissions scenario; Kattenberg *et al*., 1996). Another simulation includes the effects of the sulfate aerosols (GS) in addition to the greenhouse gas forcing. The forcing due to sulfate aerosol includes the direct radiative effect of historic sulfate aerosol concentrations during 1860-1990 and a scenario of sulfate aerosol concentrations during 1990-2099 derived from the sulfur emissions in the IS92a scenario. This anomaly run (GS) for ECHAM4 is available for the period 1860-2049.

2.2. *Observational data sets*

Historical climatic data used for model validation consist of the rainfall data for 120 years (1871-1990) at 306 raingauge stations in the plains (Parthasarathy *et al*., 1994) and mean surface air temperatures data for 90 years (1901-1990) at 121 stations (Rupa Kumar *et al*., 1994). The spatial distribution of the station network is shown in



Figs.1 (a&b). The layout of two GCM grids over India and the network of stations with observational data. (a) ECHAM4 (b) HadCM2. GCM land grids are shaded and the box indicates the study area for which downscaling is done

Fig. 1. The rainfall and temperature data have been gridded onto resolution of ECHAM4 and HadCM2 grids by using an inverse square distance kernel with search radius limited to 2.5°, similar to a method proposed by Cressman (1959). Observed gridded data are used for validation and downscaling analysis.

3. Regional validation of simulated climate over India

Model evaluation or validation involves assessment of model's ability to simulate the climate of the present and the past. The assessment further guides the interpretation and use of the model projections. Model evaluation can be done either on the basis of a study of the degree to which the model is physically based and the degree of complexity with which the various processes and interactions have been parameterized, or it can be based on quantification of the model errors and assessment of causes of errors. In the present study, the efficiency of the two models ECHAM4 and HadCM2 in simulating the mean seasonal climate and its variability over the monsoon region is examined. Monthly rainfall and temperature, which are end results of all the physical processes, have been used to characterize the model simulations. Correlation and RMS error are some of the effective tools generally used for model evaluation. However the climate change simulations used in the present study correspond to a nominal time scale *i.e.*, the simulated climate approximately represents the period spanning 1860-2099 but the individual model-years do not correspond to any specific years or events in this period. Therefore, the evaluation is based on comparison of statistical characteristics over different sub-periods. Further for analysis in the spatial domain, the Principal Component Analysis (PCA) is used to evaluate models' ability to reproduce the dominant modes of variability. These tools are also used to assess the sensitivity to transient forcing.

3.1. *Regional climatology in GCM simulations*

The simulation of climate over Indian region using ECHAM3+LSG (Lal *et al.*, 1994; 1995) is reported to be

TABLE 1

Characteristics of observed and simulated seasonal and annual total rainfall and mean temperatures for the two models ECHAM4 and HadCM2

Long-term averages

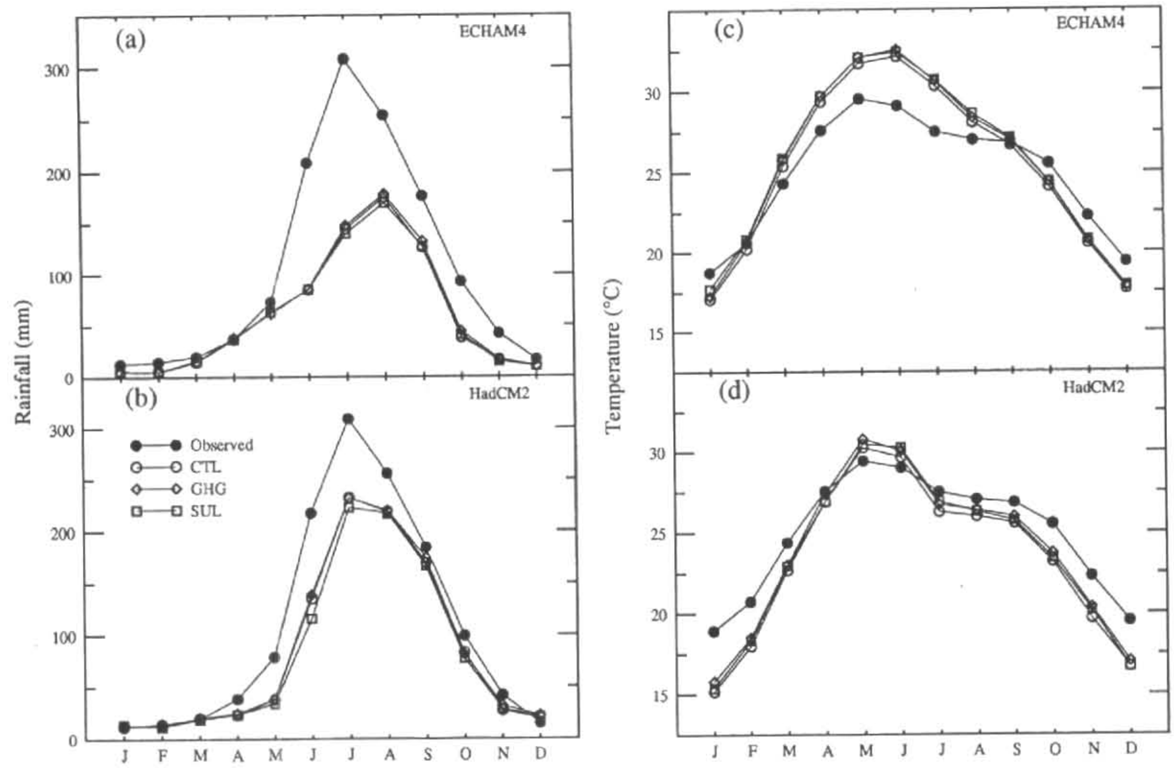
	Rainfall (mm)					Mean Temperature (°C)				
ECHAM4	DJF	MAM	JJAS	ON	Annual	DJF	MAM	JJAS	ON	Annual
Observed (E)	43.00	129.70	948.00	135.30	1256.10	19.60	27.10	27.60	23.90	24.90
CTL	20.40	114.30	531.90	54.70	721.40	18.30	28.80	29.30	22.30	25.20
GHG	19.00	114.30	545.10	61.10	739.70	18.60	29.30	29.60	22.60	25.60
SUL	20.30	115.00	522.90	55.60	714.00	18.90	29.30	29.70	22.50	25.70
HadCM2										
Observed(H)	40.80	136.80	966.90	140.50	1285.10	19.70	27.10	27.60	23.90	24.90
CTL	45.00	81.20	755.50	109.90	991.50	16.60	26.50	26.90	21.40	23.30
GHG	47.30	83.00	764.90	112.50	1007.70	17.20	27.20	27.40	22.10	23.90
SUL	45.60	76.30	722.20	105.40	949.50	16.80	26.80	27.40	21.80	23.70

Standard Deviation

	Rainfall (mm)					Mean Temperature (°C)				
ECHAM4	DJF	MAM	JJAS	ON	Annual	DJF	MAM	JJAS	ON	Annual
Observed (E)	15.70	25.50	88.90	34.60	105.70	0.39	0.48	0.26	0.42	0.24
CTL	14.70	24.00	77.80	19.10	87.50	0.68	0.54	0.68	0.88	0.42
GHG	12.10	18.40	87.20	23.60	93.80	0.83	0.55	0.78	0.97	0.40
SUL	15.30	20.60	98.50	22.70	103.40	0.98	0.60	0.98	1.07	0.49
HadCM2										
Observed(H)	14.80	27.10	86.20	37.10	105.60	0.39	0.46	0.25	0.41	0.24
CTL	13.80	32.20	71.10	32.90	93.00	0.61	0.58	0.75	0.75	0.46
GHG	16.30	34.00	88.30	38.00	115.80	0.76	0.71	0.94	1.01	0.60
SUL	19.50	31.10	80.30	38.30	106.20	0.64	0.63	0.68	0.84	0.39

Linear trend

	Rainfall (% of mean / 100 years)					Mean Temperature (°C / 100 years)				
ECHAM4	DJF	MAM	JJAS	ON	Annual	DJF	MAM	JJAS	ON	Annual
Observed (E)	0.92	3.67	1.59	9.22	2.54	0.69	0.37	0.12	0.61	0.42
CTL	25.20	5.00	1.27	14.11	3.54	-0.50	0.01	-0.08	-0.22	-0.19
GHG	-27.94	9.03	11.93	9.53	10.22	0.35	0.94	0.16	0.70	0.49
SUL	27.88	0.30	5.69	18.66	6.45	0.04	0.26	0.80	1.42	0.54
HadCM2										
Observed(H)	0.46	3.67	1.31	8.01	2.21	0.73	0.39	0.13	0.62	0.43
CTL	1.82	-0.95	-2.15	-10.72	-2.88	0.12	0.14	0.17	0.39	0.19
GHG	-4.94	-6.57	-1.85	-11.10	-3.45	1.49	1.03	1.39	1.94	1.41
SUL	-11.68	-1.99	-4.41	-8.91	-5.05	0.44	0.31	0.48	0.29	0.39

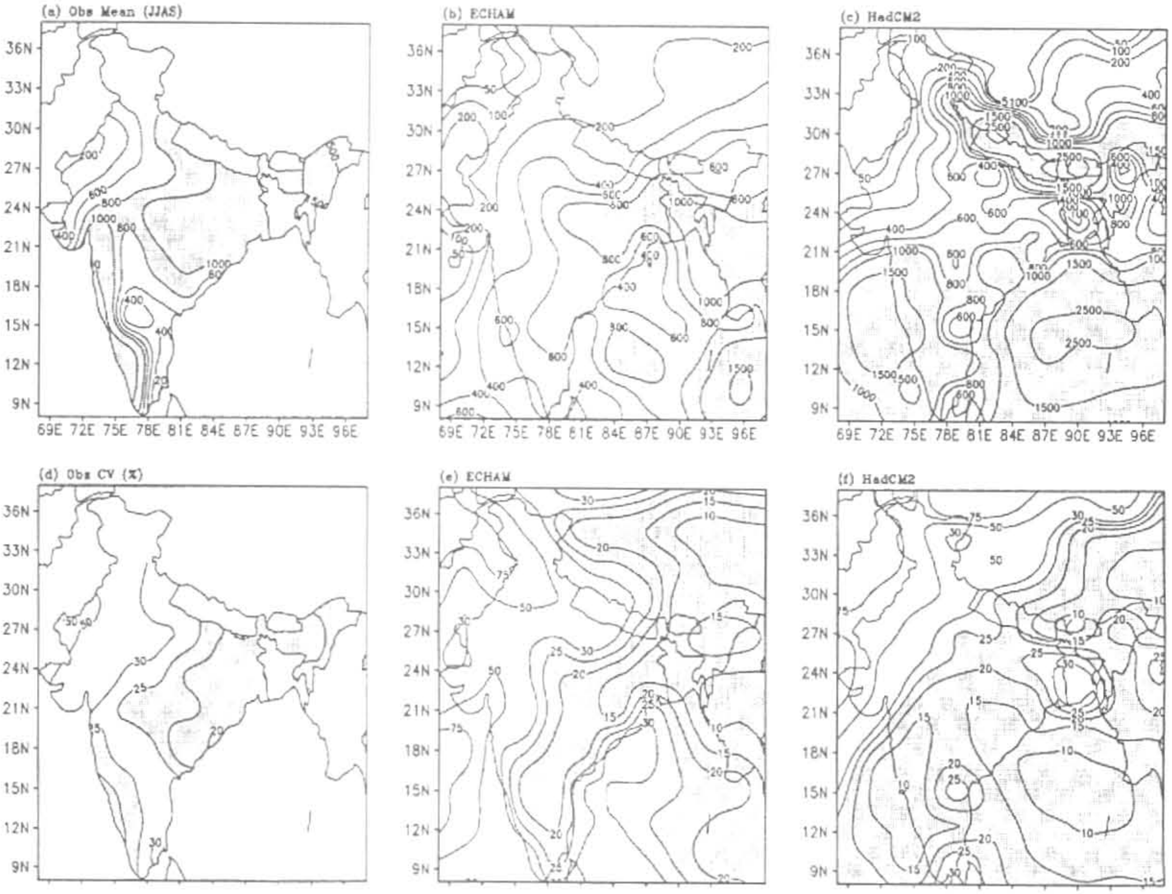


Figs.2(a-d). Annual cycle of monthly rainfall (mm) mean temperature (°C) over India. GCM simulated and observed rainfall (mm) (a) ECHAM4, (b) HadCM2 and mean temperature (°C), (c) ECHAM4 and (d) HadCM2

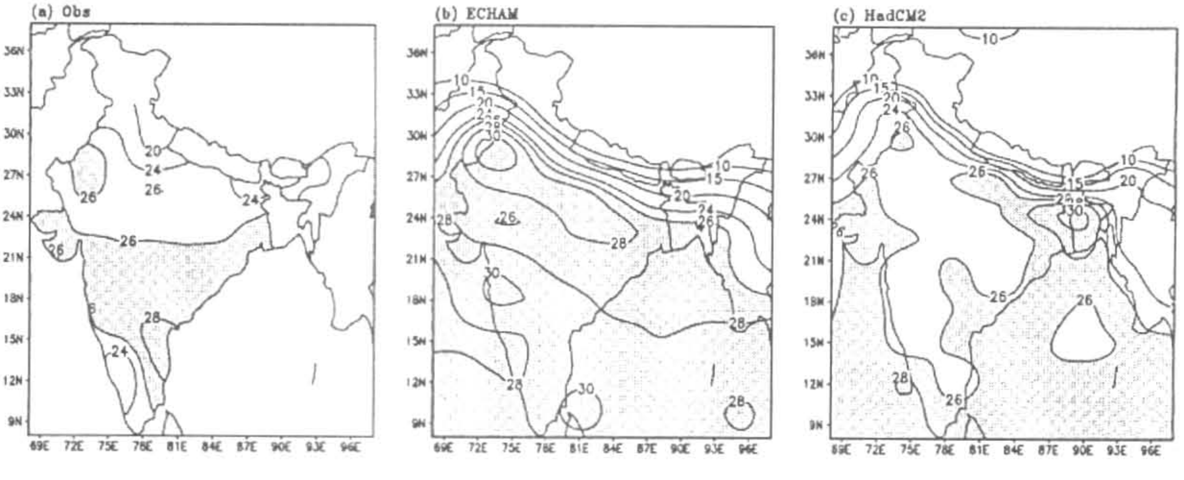
close to the observations, in terms of mean annual near surface temperature climatology and interannual variability of monsoon rainfall. Further the study shows that the model also simulates the observed cooling trend over north and northwest India and enhancement of aridity in semi-arid regions of north India. Using 150-year data for ECHAM4, Dumenil (1998) reported that monsoon rainfall simulated by ECHAM4 was considerably less than that observed. However, the interannual variability of the monsoon and the occurrence for strong and weak monsoons associated with ENSO events are very well simulated. The 150 year control simulation features 31 strong monsoon and 30 weak monsoons, with strong monsoons most likely to be followed by La Nina (15 cases) than by El Nino (2 cases).

To assess the climatology of the two models over India, gridded observational data is used. The AISMR corresponding to 306 stations, averaged over the period of 1871-1990, is 852 mm with an SD of 84 mm. These are computed from the area weighted rainfall series. However the observed gridded rainfall data represent the model resolutions and the mean monsoon works out to 948 mm with a standard deviation of 89 mm for ECHAM4 and 966 mm with a standard deviation of 86 mm for HadCM2 (Table 1).

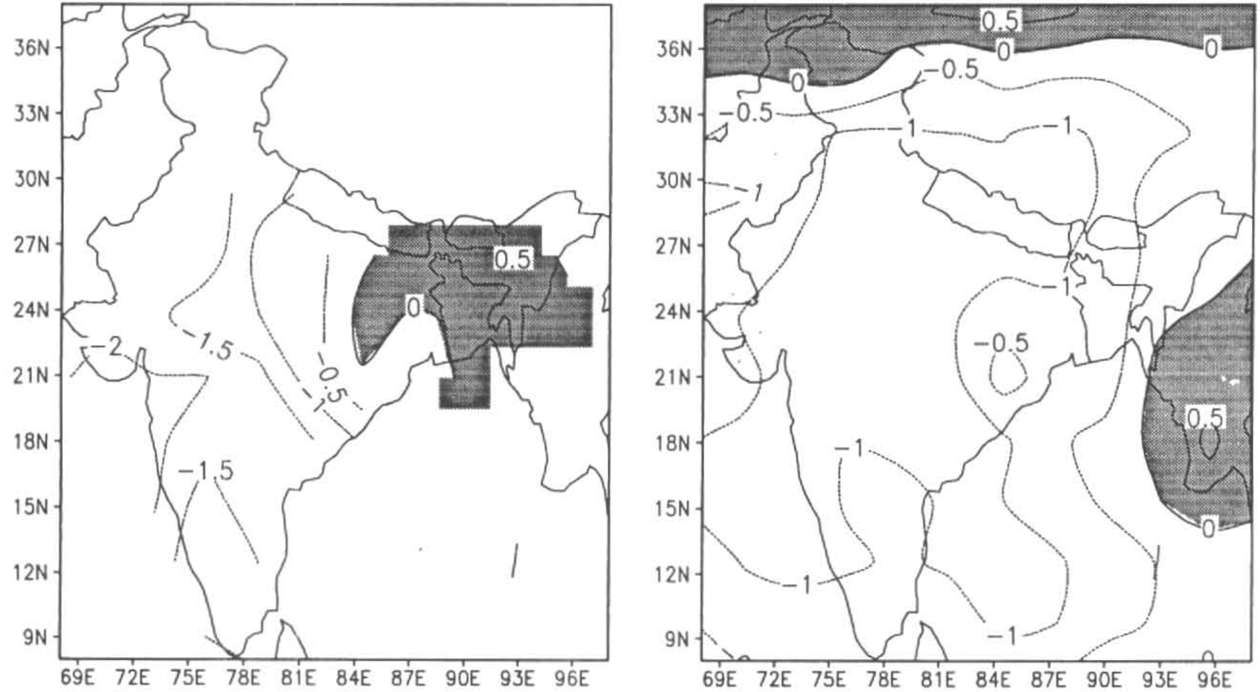
The annual cycles of observed and simulated all-India mean monthly rainfall and temperatures are shown in Fig.2. Spatial averages of the GCM fields are computed for the period corresponding to observational record, *vis* 1871-1990 for rainfall and 1901-1990 for temperatures. Both ECHAM4 and HadCM2 underestimate rainfall especially during the monsoon months (Figs.2 a&b). The annual cycle in the surface air temperatures, typically having the highest temperatures in the pre-monsoon months followed by an abrupt drop during the monsoon months is generally well-represented in both the models (Figs. 2 c&d). On the whole the two models do reproduce the annual cycle of both rainfall and temperature reasonably well. Table 1 summarizes the observed and simulated rainfall mean, standard deviation



Figs.3(a-f). Long-term mean spatial patterns of observed and simulated (C) monsoon rainfall during 1871-1990. Mean monsoon rainfall (mm) (a) Observed, (b) ECHAM4, (c) HadCM2, and coefficient of variation (%), (d) Observed and (e) ECHAM4 (f) HadCM2

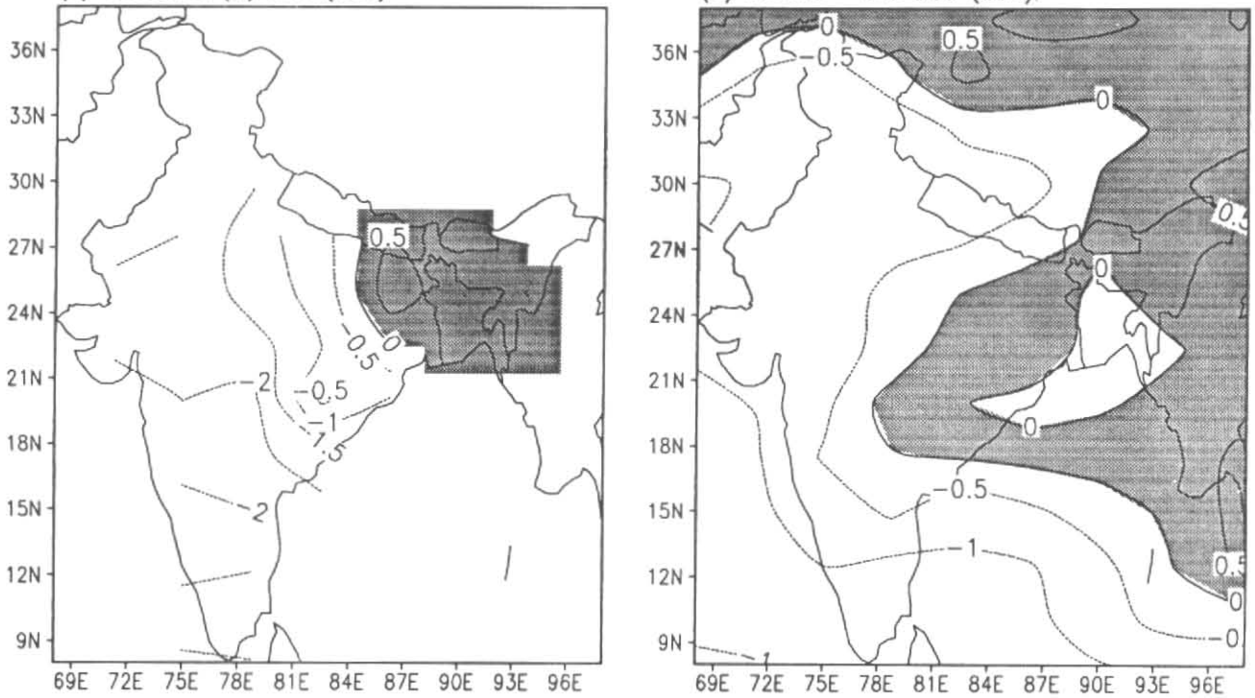


Figs.4(a-c). Long-term mean spatial patterns of observed and simulated (C) mean annual temperature (°C) during 1901- 1990. (a) Observed, (b) ECHAM4 and (c) HadCM2



(a) Observed (E) PC1 (21%)

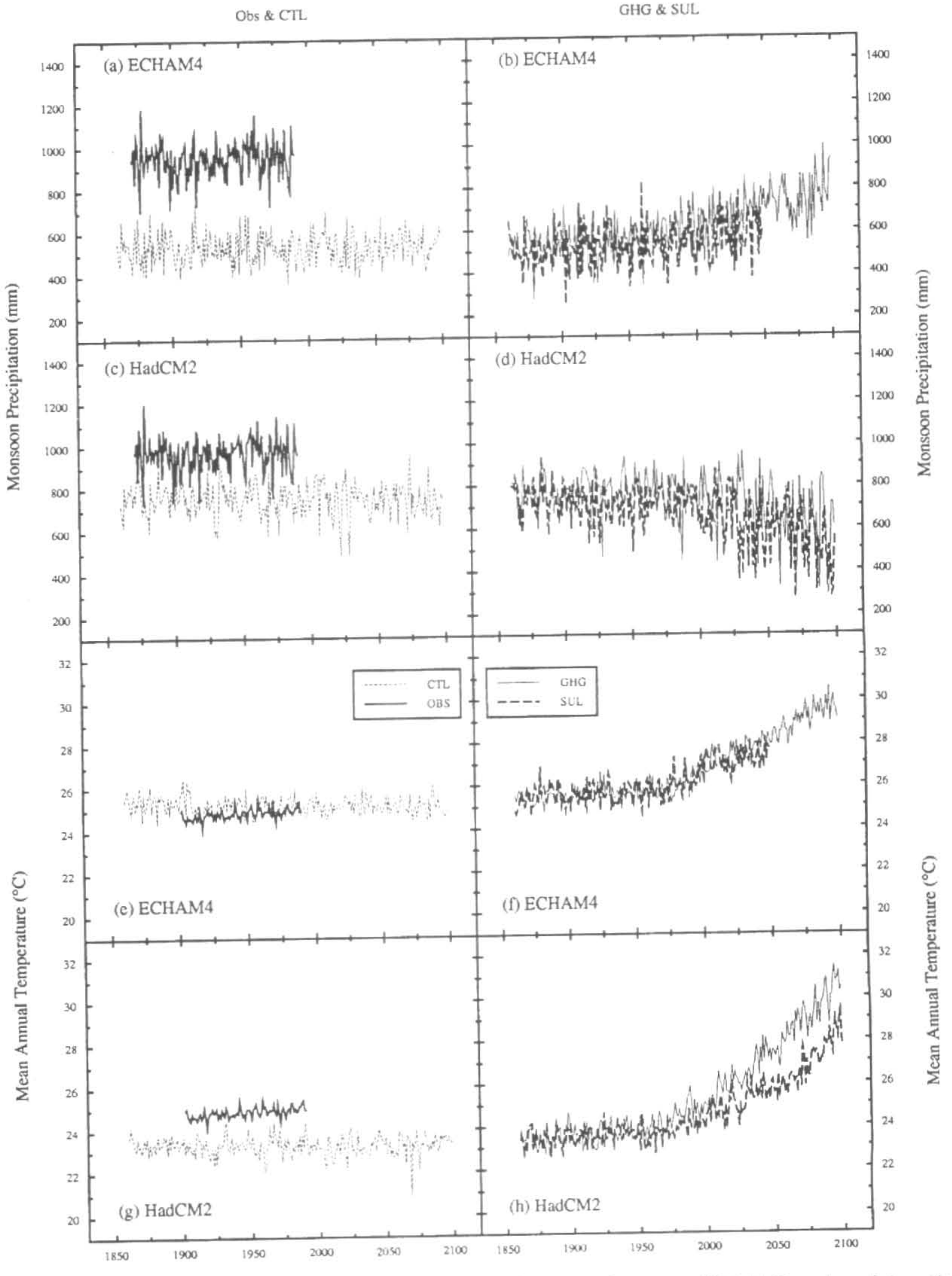
(b) ECHAM - CTL PC1 (15%)



(c) Observed (H) PC1 (22%)

(d) HadCM - CTL PC1 (16%)

Figs. 5(a-d). Principal component analysis of Monsoon rainfall over India : Observed and simulated (C) (a) Observed -ECHAM4 grids, (b) ECHAM4 -CTL, (c) Observed -HadCM2 grids and (d) HadCM2 -CTL



Figs. 6(a-h). Time series of all-India summer monsoon rainfall (mm) (a-d) and mean annual temperature(°C) (e-h). Comparison of observations with model simulations, Monsoon rainfall in ECHAM4 (a) Obs & C, (b) G & GS, and in HadCM2, (c) Obs & C, (d) G & GS. Mean annual temperature in ECHAM4, (e) Obs & C, (f) G & GS and in HadCM2, (g) Obs &C and (h) G & GS and linear trends for four seasons and annual. The mean monsoon rainfall is less than the observations in all the three simulations of both the models. However the standard deviation in monsoon rainfall of (G) simulation by both models compares reasonably well with the observations. The linear trend in monsoon rainfall expressed as % of mean/100 years is also indicated in Table 1. Observations indicate small increasing trends and the ECHAM4 simulations also show increasing trends while the HadCM2 simulations show small negative trend. ECHAM4 simulates a warmer climate (by about 1°C in mean annual temperature) over India while HadCM2 simulates cooler climate. Simulated temperatures of both the models have higher variability compared to the observations. The observations indicate a warming of 0.42°C/100 years in the mean annual temperature with highest trend in DJF season (0.73°C/100 years). Trends in mean annual temperature of sulfate simulation (GS) of both models are comparable with observations. Johns *et al.* (1997) have shown that the (GS) simulation of HadCM2 captures the observed signal of temperature change better then the (G) and (C) simulations, based on the global decadal anomaly pattern correlation between the two experiments and observations, Over the Indian region the simulated trends seem to show some agreement with observations.

3.2. *Spatial patterns of monsoon rainfall and variability*

The spatial patterns of the monsoon rainfall and its coefficient of variation are shown in Fig.3. Both the models capture the gross features of the monsoon in terms of low rainfall amount coupled with high variability over Rajasthan compared to other parts of India. However, some of the finer details of regional significance, are completely missed in both the models. For instance, ECHAM4 (Fig. 3b) fails to reproduce the rainfall minimum in the rain shadow region over eastern peninsula. On the other hand HadCM2 (Fig. 3c) seems to underestimate the rainfall over the Indo - Gangetic plains. Though HadCM2 does well in simulating the region of rainfall minimum over southeastern peninsula, there is a general overestimation of rainfall in and around peninsula as well as over the Himalayan region.

3.3. *Mean annual temperatures*

The comparison of simulated mean annual temperatures with observations (Fig. 4) shows that the ECHAM4 (Fig. 4b) has a warmer climate compared to observations (Fig. 4a) while HadCM2 (Fig. 4c) has a cooler than observed climate over the Indian region. This fact is evident from Table 1, where ECHAM4 simulated temperatures are warmer than observed in all the seasons and HadCM2 simulated temperatures are cooler than observed in all the seasons. It is observed that both the models capture the continental warming during the summer season and simulate the highest temperatures over northwest India.

3.4. *Dominant modes of monsoon variability*

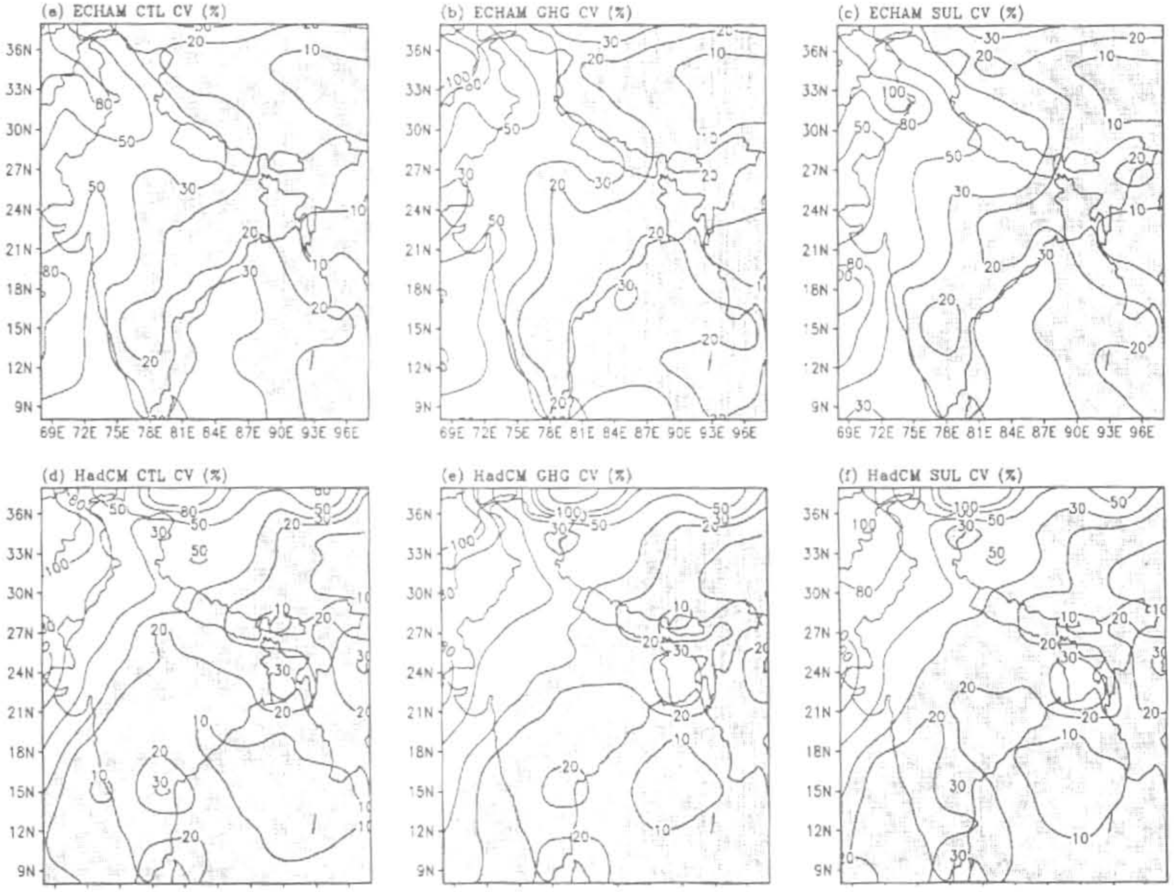
One of the major manifestations of spatio-temporal variations in monsoon rainfall is the occurrence of large scale flood and drought conditions over India involving spatially coherent rainfall anomalies over a large area. PCA applied to monsoon rainfall (Pant and Rupa Kumar, 1997) indicates that the most dominant principal component representing an east-west dipole involving the anti-correlation of monsoon rainfall over northeast India with the rest of India Figs. 5(a, c). This pattern represents a typical drought/flood year over India, when northeast India features conditions opposite to those seen over rest of the country.

Similar analysis is carried out using the model simulated monsoon rainfall in the control simulation for a fixed common period of 1871-1990 (Fig. 5). The first principal component pattern resembles the observed dipole structure suggesting that the models are capable of simulating patterns that dominate the observed interannual variability. HadCM2 (Fig. 5d) seems relatively closer to the observations, while the dipole in ECHAM4 (Fig. 5b) is rather weak.

Thus from the above discussion it can be understood that the two models capture the gross characteristics of climate over the monsoon region in terms of the mean annual cycle and the dominant modes of variability. However ECHAM4 simulates a warmer than the observed climate and the simulated monsoon rainfall is less than the observed. Further it fails to capture some of the finer spatial details like the rainfall maximum along the west coast of India and rain-shadow area eastern part of Indian peninsula. HadCM2 simulated monsoon rainfall pattern resembles the observations very well, especially over the Indian peninsula. Further it produces an overestimation of rainfall over the Himalayas and eastern peninsula.

4. Sensitivity of the climate over India to transient increase in greenhouse gases and sulfate aerosols

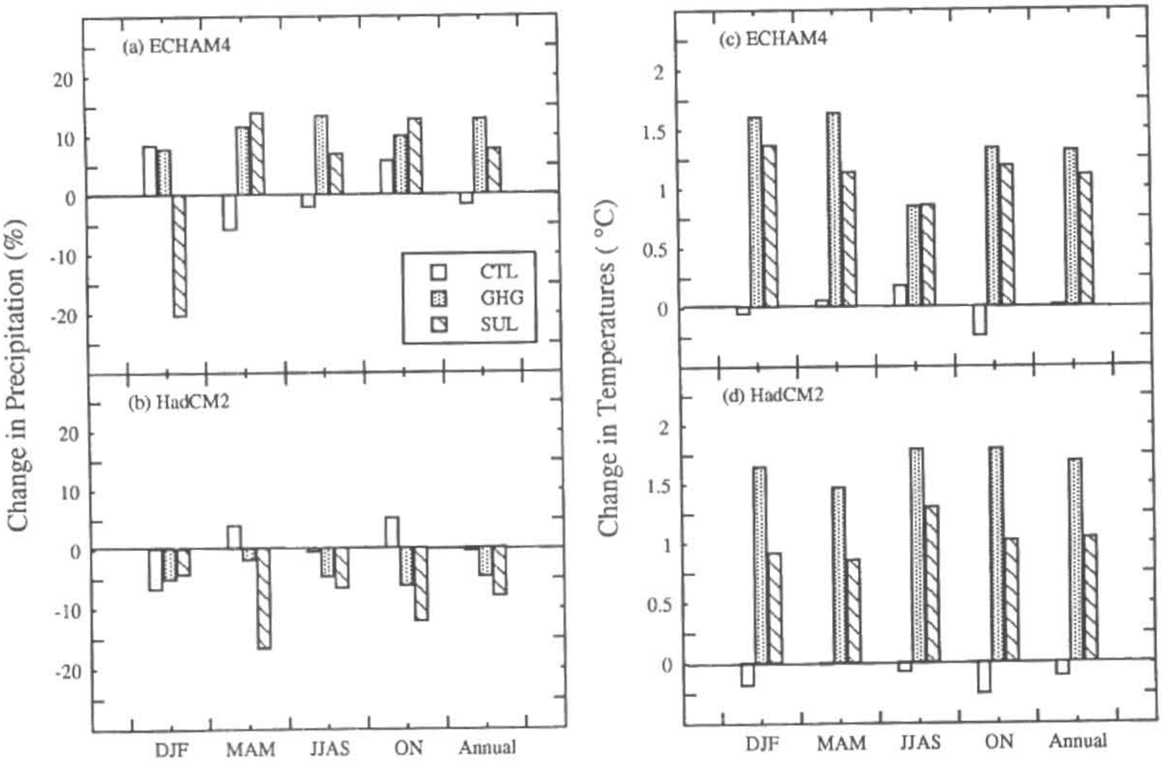
The time series of observed and simulated all-India mean monsoon rainfall and mean annual temperature based on an arithmetic mean of land grid points over India are shown in Fig. 6. The time series of monsoon rainfall indicates that the simulated rainfall is lower compared to



Figs.7(a-f). Sensitivity of variability in monsoon rainfall to transient forcing (G and GS experiments) relative to control (C).Coefficient of variation in monsoon rainfall in ECHAM4 (a) C, (b) G, (c) GS and in HadCM2 and (d) C (e) G and (f) GS

observations Figs. 6(a, c). On the other hand, in terms of the mean annual temperatures ECHAM4 simulates a warmer mean climate and HadCM2 simulates a cooler climate compared to the observations Figs. 6(e,g). To assess the model sensitivity to the greenhouse gas forcing, it is compared with the control simulation. During the period 1871-1990 the monsoon rainfall in the control run as well as in the two experiments is less than the observations while the variability in the experiments compare better with observations (Table 1). Relative to the control run (C), the greenhouse run (G) has a higher rainfall and also higher variability in both the models (Table 1). In the sulfate run (GS), on inclusion of sulfate aerosols in addition to greenhouse gases the monsoon rainfall is reduced relative to the greenhouse run (G) and is also less than the rainfall in the control run (C). The two greenhouse simulations, ECHAM(G) and the HadCM2(G) indicate opposing scenarios of monsoon rainfall for the future Figs. 6(b,d). This is also seen in the (GS) simulation of both the models. However the effect of sulfate aerosols show a reduction in rate of rainfall increase, which will be discussed in the next section.

The sensitivity to transient forcing relative to control (G-C) suggest warming over India (by a maximum of 0.6°C in HadCM2) (not shown) coupled with an increase in the monsoon rainfall (by maximum of 5% in HadCM2). The reduction in rainfall enhancement due to inclusion of aerosols is also clear in both models and is more pronounced in HadCM2 simulation. The spatial pattern of variability in monsoon rainfall (Figs. 7a-f) seems to be insensitive to changes the forcing. This indicates that the basic character of the monsoon is unchanged while there might be changes in the total rainfall amount. This fact is also evident from the PC 1 (not shown) pattern, which is same in the three experiments.



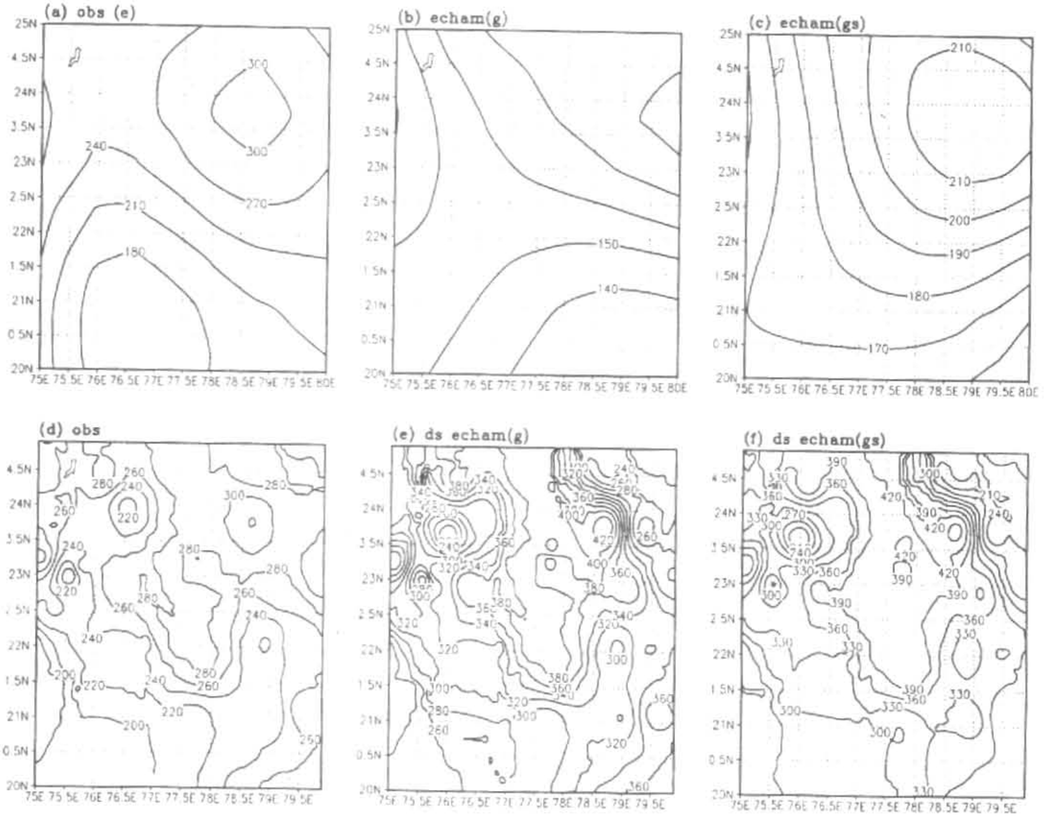
Figs. 8(a-d). Simulated climate change over India during 1980-2039 (relative to 1919,79) in two models. Rainfall (mm) (a) ECHAM4, (b) HadCM2 and Mean Temperature(°C), (c) ECHAM4 and (d) HadCM2

5. Future climatic scenario for India under continued transient forcings

This inter-model disagreement makes it difficult to choose a common baseline climate and define climate change signal. The all-India scenarios of rainfall and temperature for the period 1980-2039 relative to 1920-1979 are shown in Fig. 8. ECHAM4 suggests an increased monsoon rainfall by 13% (Fig. 8a) while HadCM2 suggests a reduction in monsoon rainfall by 6% (Figs. 8b) in the greenhouse gas (G) simulation, Both GCM's suggest an increase in annual mean temperature by more than 1°C (1.3°C in ECHAM4 and 1.7°C in HadCM2 ; Fig. 8(c-d) respectively). Studies using GCM simulations indicate an increase in winter temperatures by 1-4°C for a doubling of CO_2 concentration (Bhaskaran *et al*., 1995). The (G) simulations of two models indicate that under the influence of a 1 % increase per year in all greenhouse gases the winter temperatures over India might increase by nearly 1.7°C (Fig. 8d), However the (GS) simulations suggest 1°C (HadCM2) to 1.5°C (ECHAM4) increase in the winter temperatures over India.

The above analysis suggests that both the models show warming in all the seasons and in the mean annual temperature due to transient forcing while response of the monsoon rainfall in HadCM2 simulations suggests a scenario that seems to disagree with ECHAM4 simulations. Decrease of summer (JJA) rainfall (with transient increase in the forcings), in the HadCM2 simulations is seen over entire south Asian region (Hulme *et al.*, 1999). The mean annual cycle (not shown) of rainfall and temperatures is seen to undergo changes in the scale alone and the amplitude of the cycle remains unchanged.

Direct use of these model scenarios on regional scale for studying the impacts is difficult since the GCM's do not capture the finer details of spatial variations. Since some of the large scale features are well captured by the GCMs, (*e.g.* PC 1) an attempt is made to empirically downscale the monsoon rainfall to translate the model generated climate change information to a regional scale.



Figs. 9(a-f). Standard deviation of monsoon rainfall over central India during 1871-1990. Comparison of observations with ECHAM4 simulations and the downscaled monsoon rainfall. (a) Observed -ECHAM grids, (b) ECHAM4(G), (c) ECHAM4(GS), (d) Observed station data, (e) downscaled (G) and (f) downscaled (GS)

6. Downscaling methodology

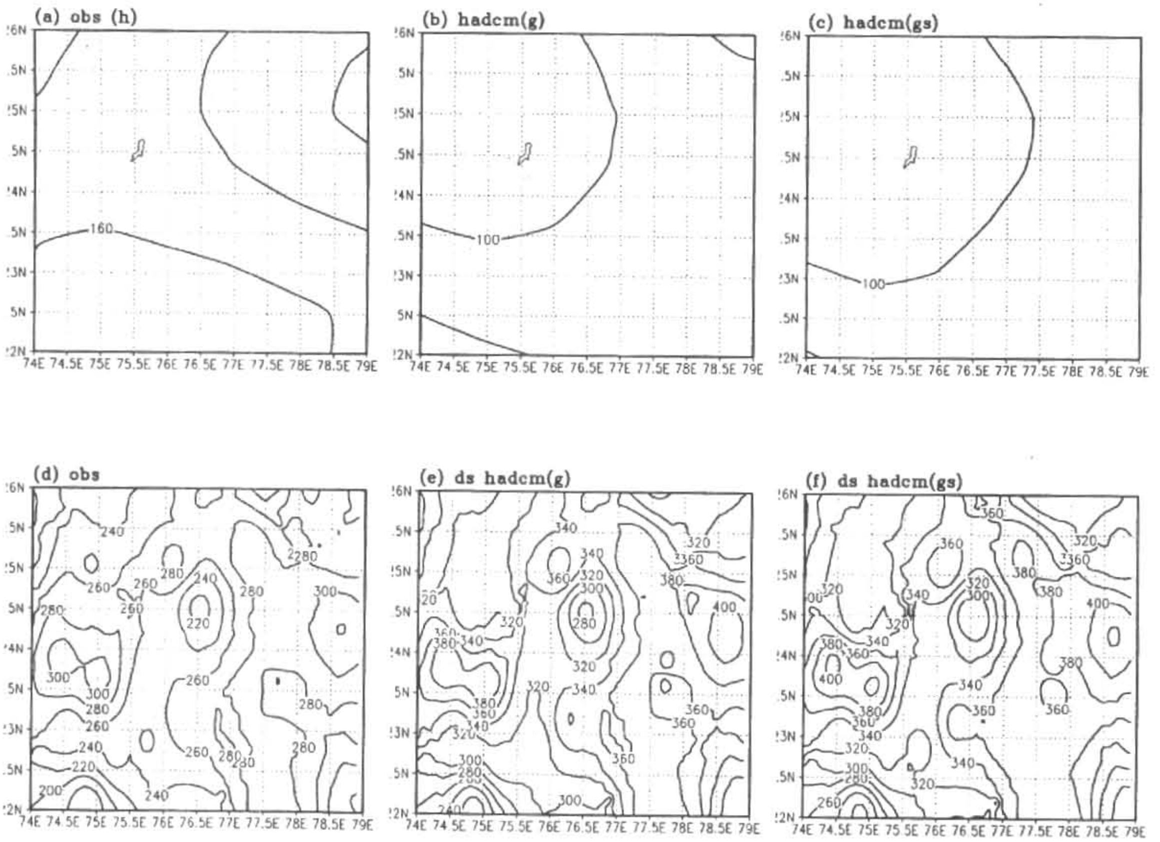
6.1. *Review of Empirical downscaling approaches*

Empirical downscaling approach is similar to the perfect prog. (PP) method or model output statistics (MOS) approach used in numerical weather forecasting, based on multiple regression exploiting the correlation between the predictand and the predictors. A review of such methods is given in Giorgi and Mearns (1991) covering the early works of Kim *et al*. (1984) and its advanced version by Wilks (1989). Karl *et al.* (1990) give a more sophisticated strategy-Climatological Projection of Model output Statistics (CPMS). It involves extensive use of free atmosphere variables (RPCs) as predictors. CCA is used to develop simultaneous relationship between a linear combination of predictors, the canonical variables and the predictands (surface observations). Important canonical variables are regressed to each of the surface based observations through inflated regression.

More recently fuzzy clustering (Bardossy and Plate, 1992), empirical transfer functions (Winkler *et al*., 1997), artificial neural networks (ANN) (Hewitson and Crane 1992), weather generators,(Wilks 1989; 1992; Wilby *et al*., 1998), etc are used for downscaling. Wilby *et al*. (1998) brings out an exhaustive account of comparison of all the empirical downscaling techniques and their performance.

6.2. *Application of a empirical downscaling technique over India for preparation of scenario*

The GCM simulations are firstly corrected for the biases, by applying the difference of mean to correct the



Figs. 10(a-f). Standard deviation of monsoon rainfall over central India during 1871-1990. Comparison of observations with HadCM2 simulations and the downscaled monsoon rainfall. (a) Observed -HadCM2 grids, (b) HadCM2(G), (c) HadCM2(GS), (d) Observed station data, (e) downscaled (G) and (f) downscaled (GS)

bias in mean and by ratio of the variance to correct for bias in the variance. Downscaling is done using these corrected data. In this study the development of climate change scenario on a regional scale is done through empirical downscaling technique in thee steps.

STEP 1. Firstly, across-scale empirical relationship is established in the historic data. There are several approaches but the most common one uses the dominant modes of variability in the large scale fields as the independent variable with the station or local climate variable as dependent.

STEP 2. The empirical relations developed in step 1 are applied to the model simulations. This approach assumes the model simulations to be comparable to the observations, or any systematic bias is eliminated using suitable corrections.

STEP 3. In this step the large scale predictor fields are derived from the changed climate, and are used to evolve local climate information. Assumption that the empiricism remains unchanged in the changed climate, is unrealistic. However this study aims at using the downscaling technique as a means to translate the GCM generated information, which is usually not interpretable on local scales.

Large scale monsoon rainfall (at grid points) is used as predictor to derive the monsoon rainfall at various stations in the central India. An area bounded by 73.1250 -81.5625°E and 18.1390 - 26.5108°N is the ECHAM4 domain with 16 grid points, and 71.2500 - 82.5000°E and 20.0000 - 27.5000°N is the HadCM2 domain with 15 grid points in the region. These two regions are marked in Fig. 1. ECHAM4 grid has 38 stations with rainfall data.

Similarly HadCM2 grid has 44 rainfall stations. Firstly large scale observed rainfall is subjected to PCA to obtain the most dominant modes. The use of PC scores as predictors prevents the bias due to possible coherence among the predictors, besides reducing the dimension. In the second step the scores of the dominant modes (PC's 96-98% of variance explained) are used as predictors to estimate the stations rainfall. The multiple correlation that can be achieved is fixed at 0.9 and no variable is forced either into or out of the regression. The empirical model so obtained is used with the independent variables of the GCM generated large scale rainfall corresponding to the comparable time span. In this case ECHAM4 and HadCM2 (G) and (GS) simulation corresponding to 1860-1990 are used. In this study the validation is not done on an independent data set, since the aim of this approach is not that of forecasting, and more over the simulated climate corresponds to a nominal time scale. The downscaling is aimed at reproducing the climatic characteristics of a sub-grid scale region. Further the same scheme is used to derive the possible gross changes in the mean climate of the region as suggested by the GCM simulations.

Analysis of results is confined to the variability in monsoon rainfall. Figs. (9 &10) show the SD in monsoon rainfall in a small region over central India. The coarse resolution observations (Fig. 9a) and GCM simulations Figs. 9(b&c) indicate the presence of a region of high SD in the northeast, with relatively lesser variability in southwest. However the observations in this region are computed from the 38 stations. The pattern of variability indicate similar increase in SD from southwest to northeast (Fig. 9d). There are three distinct pockets of high variability in monsoon rainfall between 23-25°N (representing orographic features). The downscaling of the (G) and (GS) simulations also show the occurrence of this feature and gives a pattern. Figs. 9(e&f) that is comparable to the observations. Similarly in Fig. 10 downscaling results from HadCM2 show patterns of variability which not only compare better with the observations, but also indicate the influence of regional factors like topography which are not accounted for in the GCM.

The above discussion suggests that the method of empirical downscaling used in this study results in translating the GCM product that is better comparable with the observations, than the GCM product itself.

Changes in the variability of monsoon rainfall superimposed on a higher mean state like that of ECHAM4 or a lower mean state like in HadCM2 simulations can lead to changes in the local climate leading to increased frequency of extremes like floods and droughts. The uncertainties pertaining to changes in the mean state of scenarios of these two models calls for caution.

7. Discussion and conclusions

(a) The two models capture the gross characteristics of climate over the monsoon region in terms of the mean annual cycle and the dominant modes of variability. However ECHAM4 simulates a warmer than observed climate and the monsoon rainfall is less than the observed, with poor representation of finer spatial details like the rainfall minima over the Indian peninsula. Though HadCM2 simulated monsoon rainfall pattern resembles the observations, it produces an overestimation of rainfall over the Himalayas and the eastern peninsula. The dominant modes of variability are captured well by both the models.

(b) Inter-experiment comparison of means and the CV clearly indicate the increase in rainfall in the G experiment relative to the control experiment (C). Further the dampening of this sensitivity due to inclusion of aerosols (GS-C) suggest strong sensitivity even on regional scale. Both the models show increase of rainfall only over land (particularly NW India) and decrease over the oceans (particularly over Arabian sea) in the (G-C and GS-C) case.

(c) The two models show warming in the mean annual temperature due to transient forcing while response of the monsoon rainfall in HadCM2 simulations suggests a scenario that seems to disagree with ECHAM4 simulations. The decrease of rainfall in HadCM2 simulations is seen in other regions also (Hulme *et al.*, 1999). The mean annual cycle of rainfall and temperatures are seen to undergo changes in the scale alone and the amplitude of the cycle remains unchanged.

Assessment of the causal mechanisms for this higher sensitivity, inter-model disagreement are beyond the scope of the present study. Direct use of these model scenarios on regional scale for studying the impacts is difficult since the GCM's do not capture the finer details of spatial variations. Since some of the large scale features are well captured by the GCMs (*e.g.* PC1), an attempt is made to empirically downscale the rainfall, to assess the possibility of use of these simulations for development of climate change scenario on regional scale. The empirical exercise suggests that the downscaling approach reproduces the observed climate on local scale. Applied to the GCM generated fields it translates the climate change information to local scale. The method needs to be tested for a relatively inhomogeneous region, like peninsular India, with western ghats, the semi-arid region etc., where the regional geographical features have a strong bearing on the monsoon rainfall and where the GCM's fail to capture those aspects. Apart from rainfall, downscaling of temperature is also necessary for in regional climate change studies. Several studies seek the signal for variability in surface meteorological parameter, in the free atmosphere. This work is planned for a subsequent paper.

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References

Bardossy, A., and Plate, E. J., 1992, "Space time model for daily rainfall using atmospheric circulation patterns". *Water Resour. Res.*, **28**, 1247-1259.

Bhaskaran, B., Mitchell, J. F. B., Lavery, J. R., and Lal, M., 1995, "Climatic response of Indian subcontinent to doubled CO_2 concentrations". *Int. Journ. Climatol.*, **15**, 873-892.

Cressman, G. P., 1959, "An operational objective analysis scheme". *Mon. Wea. Rev.*, **87**, 329-340.

Cubasch, U., Von Stortch, H., Waszkewitz, J., Zorita, E., 1996, "Estimates of climate change in southern Europe derived from dynamical climate model output". *Clim. Res.*, **7**, 129-149.

Cubasch, U., Waszkewitz, J., Hegerl, G., Perlwitz, J., 1995a, "Regional climate changes as simulated in time-slice experiments. *Climatic Change,* **31**, 273- 304.

Dumenil, Lydia,1998, "Portrayal of the Indian Summer Monsoon in the Land-Ocean- Atmosphere system of a coupled GCM", *Report No. 271., Max-Planck - Institute fiir meteorologie,* Hanburg.

Galliani, G. and Filippini, F., 1985, "Climatic clusters in a small area", *J. Climatol.,* **5**, 487- 501.

Giorgi, F., 1990, "On the simulation of regional climate using a limited area model nested in general circulation model", *J. Climate,* **3**, 941-963.

Giorgi, F. and Mearns, L., 1991, "Approaches to the simulation of regional climate change", A review. *Rev. of Geophys.*, **29**, 191-216.

Hewitson, B. C., and Crane, R. G., 1992, "Regional climate in GISS global circulation model: Synoptic-scale circulation". *J. Climate,* **5**, 1002-1011.

Hulme, M., Mitchell, J. and *et. al.*, 1999, "Climate change scenarios for global impacts studies". *Global Enviromental Change,* **9**, S3-S19.

IPCC, 1990, Scientific Assessment of climate change, Eds. J.T. Houghton, G.J. Jemkins and J.J. Ephraums, Cambridge University Press, 365 p.

Johns,T.C. and Carnell,R.E., *et al*, 1997, "Global and regional variability in a coupled AOGCM". *Climate Dynamics,* **13**, 303-323.

Karl, T. R., Wang, W. C., Schlesinger, M. E., Knight, R. W. and Portman, D., 1990, "A method of relating general circulation model simulated climate to the observed local climate, Part I: Seasonal Statistics", *J. Climate,* **3**, 1053-1079.

Kattenberg, A., Giorgi, F., Grass, H., Meehl, G. A., Mitchell, J, F. B. *et al.*, 1996, "Climate models- Projection of future climate. In *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the second assessment report of Intergovernmental Panel on Climate Change, ed. by .J. T. Houghton et al. 285-357.* Cambridge Univ. Press, New York.

Kim, J. W., Chang, J. T., Baker, N. L., Wilks, D. S. and Gates, W. L, 1984, "The statistical problem of climate inversion: Determination of relationship between local and large scale climate", *Mon. Wea. Rev.,* **112**, 2069-2077.

Lal, M., Cubasch, U., Voss, R. and Waszkewitz, J., 1995, "Effect of transient increase in greenhouse gases and sulfate aerosols on monsoon climate", *Current Science.* **69**, 752-763.

Lal, M., Cubasch, U. and Santer, B. D., 1994, "Effect of global warming on Indian monsoon simulated with a coupled ocean-atmosphere general circulation model", *Current Science.* **66**, 430-438.

Pant, G. B. and Rupa Kumar, K., 1997, "Climates of South Asia. John Wiley Sons", Chichester, UK, 320 pp.

Parthasarathy, B., Mukut, A.A., and Kothawale, D.R., 1994, All India Monthly and seasonal rainfall series : 1871-1993, *Theor. Appl. Climatol*, **49**, 217-224

Rupa Kumar, K., Krishna Kumar K. and Pant, G. B., 1994, "Diurnal asymmetry of surface temperature trends over India", *Geophys. Res. Lett.*, **21**, 677-680.

Winkler, J. A., Palutikof, J. P., Andersen, J. A., and Goodness, C. M., 1997, "The simulation of daily temperature series from GCM output.-Part II: Sensitivity analysis of empirical transfer function methodology", *J. Climate*, **10**, 2514- 2532.

Wilks, D. S., 1992, "Adapting stochastic weather generation algorithms for climate change studies", *Climatic Change*, **22**, 67-84.

Wilks, D. S., 1989, "Statistical specification of local weather elements from large- scale information", *Theor. Appl. Climatol.*, **40**, 119-134.

Wilby, R. L., Wigley, T. M. L., Conway, D., Jones, P. D., Hewitson, B. C., Main, J. and Wilks, D. S., 1998, "Statistical downscaling of general circulation model output: A comparison of methods", *Water Resour. Res.*, **34**, 2995-3008.