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Simulation of Present-Day Climate Over the Indian Subcontinent by General Circulation Models

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ABSTRACT

There continues to be some improvement in the ability of general circulation models to simulate the present-day climate on large scales although further improvements in the model resolution and parameterization of physical processes are still needed for the realistic simulation of regional climates. Quantitative assessment of the magnitude of climate change on a regional scale and its implications are essential for understanding, planning and management of resources at national/regional levels. In developing countries like India, where the economy is largely regulated by variability in summer monsoon rainfall, the consideration of measures for reducing the impacts of global change should begin as soon as possible, particularly with regard to floods and droughts, cyclone disaster preparedness, hydrological planning in semi-arid regions and coastal zone management issues. With this in view, we examine here the skill of a range of global climate models in simulating the regional climatology of the Indian subcontinent. This is a necessary first step in preparing climate change scenarios for the region.

The simulation of the current broad scale patterns of mean sea level pressure, temperature and precipitation over the northern hemisphere and over the Indian subcontinent in particular are assessed for a broad range of global climate modelling experiments. The experiments included both slab ocean and coupled ocean experiments. Five experiments are identified as having a fairly realistic simulation and may be considered acceptable for use in regional climate change assessments. All of these are of relatively high resolution and use a Q-flux correction (in the slab ocean experiments) or a flux correction (in the coupled ocean experiments). A further four experiments, with somewhat poorer regional climate simulations, are acceptable but only to a moderate degree of confidence. However, some six experiments have such marked deficiencies in their simulation of present-

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day regional climatology that we consider them unacceptable for regional climate change assessment.

(Key Words: Global climate models, Control experiments, Regional climates, Indian subcontinent, Monsoon)

1. INTRODUCTION

Since the beginning of the industrial era, atmospheric concentrations of carbon dioxide and several other greenhouse gases have been increasing due to anthropogenic activities. The ongoing increase in these gases is of considerable concern because their radiative effects will increase the temperature of the earth's surface and change climatic patterns. The state-of-the-art general irculation models (GCMs) incorporate the essential dynamics and thermodynamics of the atmosphere and are considered the best available tools for the assessment of the likely climate changes expected due to the enhanced greenhouse effect. The relative performance of many climate models at the global scale has been assessed (Cess *et al.*, 1993; Gates et al., 1993 among others) and considerable improvements in their performance have been noted in recent years (IPCC, 1990; 1992; 1996).

The impacts of climate change may be felt more severely in developing countries such as India whose economy largely depends on agriculture and is already under stress due to current population increase and associated demand for energy, fresh water and food. It is, therefore, important that we assess the regional climate change likely to occur in the future over the Indian subcontinent with some confidence and accuracy, so that the social and economic consequences expected due to this change may properly be judged allowing appropriate policy options to be formulated on national and regional scales. Lal & Bhaskaran (1993), Lal *et al.* (1994), Chakraborty & Lal (1994) and Bhaskaran *et al.* (1995) have analysed the simulations of present and future climate generated by a few GCMs over the Indian subcontinent. However, these studies which use some of the experiments we will consider here, do not compare experiments.

Before analysing climate change simulations, it is essential to ensure that the experiments to be used give an adequate simulation of the observed climatological features over the Indian subcontinent. We examine the relative performance of a range of GCMs varying in vertical and horizontal resolutions, physical parameterizations, convection schemes and ocean representation from various modelling groups of the world in simulating the present-day climate over the northern hemisphere and, more particularly, over the Indian subcontinent. Our aim is to identify how well the present climate models are able to simulate the present-day observed climatological features over the Indian subcontinent in their control runs. Depending on our analyses, we would like to select some of the models which show reasonable skill in simulating observed climatology over the study region. These models should provide the future greenhouse-induced climate changes over the Indian subcontinent with greater reliability. We would like to stress here that a model performing well over the region of interest may exhibit poor skill over other regions and a good performance in control simulation by a model does not necessarily mean that the projections of future climate by that particular model are completely reliable.

2. THE MODELS, REGION OF STUDY, SPECIFIC FIELDS AND OBSERVATIONS

2.1 The Models Used

The simulated climate data used for this study are obtained from the reference control runs of different versions of the GCMs from Geophysical Fluid Dynamics Laboratory (experiments named as GFDL, GFDLQ, GFDLCand GFDLH),USA; National Center for Atmospheric Research (experiments named as NCAR and NCARC), USA; Oregon State University (experiment named as OSU),USA; Godard Institute of Space Studies (experiment named as GISS),USA; United Kingdom Meteorological Office (experiments named as UKMO, UKMOH and UKMOC), UK; Max-Planck-Institute for Meteorology (experiments named as DKRZO and DKRZL), Germany; Commonwealth Scientific and Industrial Research Organisation (experiments named as CSIRO4 and CSIRO9), Australia; Bureau of Meteorology Research Centre (experiment named as BMRC), Australia and Canadian Climate Centre (experiment named as CCC), Canada. A brief reference on these models and experiments is listed in Table 1.

The models have many differences as regards their vertical and horizontal resolutions, convection and other parameterization schemes, surface topography and ocean representation. The list of experiments includes both slab ocean experiments (where the atmospheric

Table 1. A brief description of the models used in our intercomparison study.

Classification	Experiment Acronym	Horizontal Resolution (Number of Waves or Lat. x Long.)	Reference
Without Flux Correction Experiments	GFDL	R 15	Manabe & Wetherald (1987)
	NCAR	R 15	Oglesby & Saltzman (1990)
	NCARC	R 15	Washington & Meehl (1989)
	OSU	4^ox5^o	Schlesinger & Zhao (1989)
Low Resolution Flux Corrected Experiments	GISS	8^ox10^o	Hansen et al. (1984)
	GFDLQ	R 15	Manabe & Wetherald (1987)
	GFDLC	R 15	Manabe et al. (1991)
	UKMO	5^ox7.5^o	Wilson & Mitchell (1987)
Medium Resolution Flux Corrected Experiments	DKRZO	T 21	Lunkeit et al. (1994)
	DKRZL	T 21	Cubasch et al. (1992)
	CSIRO4	R 21	Gordon et al. (1992)
	CSIRO9	R 21	McGregor et al. (1993)
	BMRC	R 21	Colman et al. (1994)
High Resolution Flux Corrected Experiments	CCC	T 32	McFarlane et al. (1992)
	GFDLH	R 30	Houghton et al. (1990)
	UKMOH	2.5^ox3.75^o	Senior (1993)
	UKMOC	2.5^ox3.75^o	Murphy (1995)

model interacts with an ocean model which represents only the surface mixed layer of the ocean and has inferred oceanic transports),and coupled ocean experiments (where a full ocean model is coupled to the atmospheric model). Most models use a correction procedure which keeps sea surface temperature in the control run close to that observed (In the slab ocean experiments the "Q-flux correction" makes up for the absence of ocean currents, whereas in the full ocean experiments the "flux correction" allows for coupling errors leading to climate drift). For analytical purposes, we have grouped the model experiments into four categories and represented them by different symbols in relevant illustrations. The grouping was chosen to best demonstrate differences in simulation performance. The first group contains those slab ocean experiments which do not use a "Q-flux correction" (GFDL, NCAR and OSU) and the coupled atmosphere-ocean model experiment that does not use a flux correction (NCARC). We term this group as"non-flux corrected experiments". The remaining experiments are grouped according to horizontal resolution: low (GISS, GFDLQ, GFDLC and UKMO), medium (DKRZO, DKRZL, CSIRO4, CSIRO9 and BMRC) and high (CCC, GFDLH, UKMOH and UKMOC). Of the experiments in these three groups, GFDLC, DKRZO, DKRZL and UKMOC are coupled model experiments and the rest use a slab ocean model.

2.2 Region of Study

The geographic region of interest considered in this paper is the monsoon area bounded by latitudes 1.6°N to 33.5°N and longitudes 61.9°E to 95.6°E (Indian subcontinent and adjoining Seas). For all validation purposes, we have analysed the data for winter (December, January and February: DJF) and summer (June, July and August: JJA) seasons. The summer months are regarded as the peak period for southwest monsoon activity and contribute about 55% of the observed total annual rainfall averaged over the subcontinent. The winter period is the dry season over the study region. We begin by analysing the model performances over the northern hemisphere as a whole, as we feel it would be inappropriate to place reliance on a model with a good control performance over India, if it simulates hemispheric climate poorly.

2.3 Specific Fields of Study

The primary climatic elements considered in this study from among the model-generated data sets are mean sea level (MSL) pressure, surface air temperature and precipitation. Boer et al. (1992) have described the importance of the MSL pressure as a sensitive indicator of the dynamical and thermodynamical behaviour of general circulation models. The MSL pressure and precipitation data generated by the models can be used readily for comparison purposes with the observed fields. However, the simulated temperature data are directly comparable with screen height temperature (2 metres above ground) only in the BMRC, CSIRO9, DKRZO, DKRZL and GISS model experiments. For all other models, the simulated temperature of the earth's surface was used for comparison. The use of both surface and near-surface temperature data complicates the comparison between models and the climatological temperature data sets and special care needs to be taken before concluding that simulation of surface temperature is poor in a model.

There are some fields representing the state of the free atmosphere which could be used to discriminate the performances of various models, but they have limited direct relevance to impact studies and, to some extent, they can be represented by the selected fields. The fields considered here are chosen for impact assessment purposes and are limited by data availability. The model simulated winds over the Indian subcontinent have not been included in our study because these were available for only a few model, experiments (and, in any case, the MSL pressure pattern is indicative of the pattern of winds).

2.4 Observed Climatological Data

For all comparison purposes in this study, the MSL pressure climatology is based on the data sets for the period 1985-1990 analysed and compiled by the European Centre for Medium Range Weather Forecasts (ECMWF, 1993). It should be kept in mind that, due to the natural climatic variability, different epochs in the observational records will have different mean climates, and that a six year period is very short for preparing a reference climatology. However, Whetton et al. (1995) found that differences over the Southern Hemisphere between the ECMWF climatology and a 10-year climatology from an independent source were very small compared to the differences between the results of current models and either climatology. Furthermore, it should be noted that mean sea level pressure data is a rather questionable concept in the vicinity of high altitude areas such as those occurring in part of the region considered here.

The observed surface temperature and precipitation climatology used in this study is based on the data sets compiled by Legates and Willmott (1990a & b). Over the oceans and at higher altitudes, precipitation estimates are less reliable due to the sparsity of observations and practical complexity in the measurement procedures. Temperature, unlike precipitation, is mainly dependent on altitude, latitude and season. However, temperature estimates are also less realistic over the mountainous and oceanic regions.

3. COMPARISON OF MODEL SIMULATIONS WITH OBSERVED HEMISPHERIC CLIMATOLOGY

As our region of interest is the tropical Indian subcontinent in the northern hemisphere, we shall focus on only the climatology of the northern hemisphere when examining the model performances on the hemispheric scale. In doing so, we recognise that the models may perform rather differently over the southern hemisphere where many factors which determine climate vary greatly from the northern hemisphere. An analysis of the southern hemisphere performance of some of the models used here may be found in Whetton *et al.* (1995).

3.1 Mean Sea Level Pressure

To assess model performance quantitatively, we have calculated spatial pattern correlation coefficients and root mean square (RMS) errors between the model-simulated and the observed MSL pressure data over the northern hemisphere for winter and summer. The approach for calculating the spatial pattern correlation coefficient and root mean square error between the observed and model simulated fields is similar to what described in Wigley and Santer (1990). The pattern correlation coefficient (r) gives a measure of similarity of the pattern structure of the observed and simulated fields throughout the region whereas the RMS error (e) gives an overall measure of the absolute error in simulating the field over the region. The calculations involve interpolation of the model-simulated and observed data to a common grid specification with a cubic spline fit and uses a weighting function to compensate the shrinking effect for the area of the grid boxes from equator to north pole. Figure 1 (a & b) illustrates the pattern correlations and RMS errors between model-simulated and observed mean sea level pressure data for the northern hemisphere during the two seasons.

During winter, the DKRZO model experiment demonstrates the best performance with r = 0.91. The UKMOH, UKMOC, CCC and BMRC model experiments perform well (0.85 < r < 0.90). The GFDLQ, GFDLC and GFDLH model experiments have pattern correlations almost as high (r > 0.80), though, the RMS errors in the model-simulated and observed pressure fields in these cases are rather high (e > 7.0 hPa) with respect to the best performing models. This is largely due to the fact that these experiments have a global pressure bias of about 6 hPa (this also affects the GFDL experiment). The GFDL, NCAR, NCARC, UKMO and

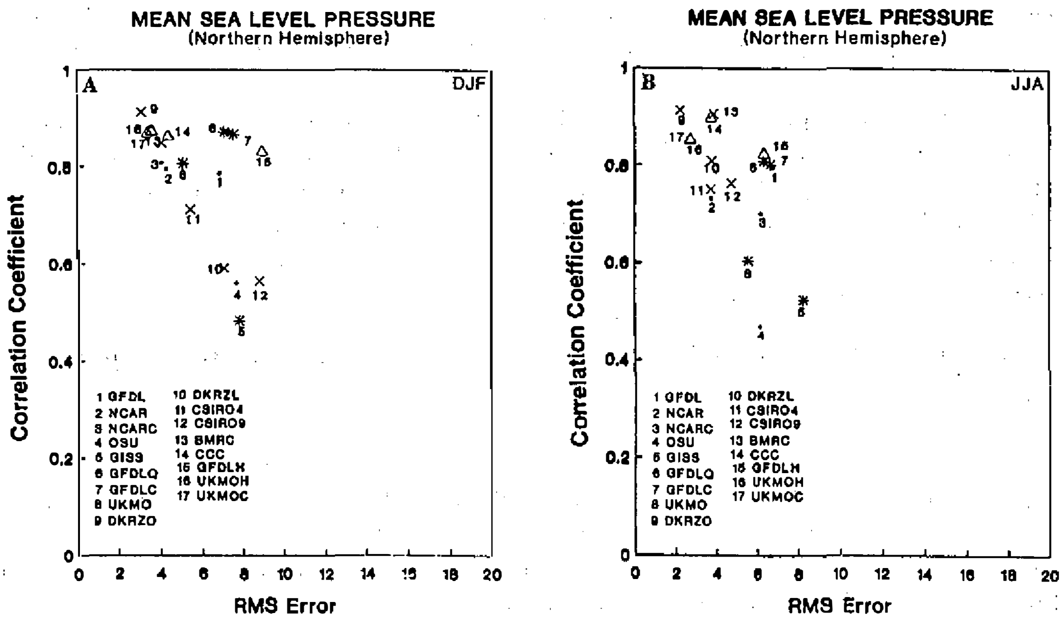


Fig. 1. The pattern correlation coefficients and RMS errors between the observed and model-simulated mean sea level pressure fields over the Northern Hemisphere. The non-flux corrective model results are marked in this and all other relevant figures as '■', the low resolution flux corrective model results are marked as '✳' the medium resolution flux corrective model results are marked as '×' and the high resolution flux corrective model results are marked as 'Δ'.

CSIRO9 model experiments have poorer pattern correlations (r > 0.70). The lowest correlation coefficient is obtained by GISS model (r = 0.48) while DKRZL, OSU and CSIRO4 model experiments also do not perform well (r < 0.60).

In summer (JJA), the DKRZO model simulation has, again, the highest correlation coefficient (r > 0.91) followed by good simulation performances in UKMOH, UKMOC, CCC and BMRC model .experiments (r > 0.85). All the GFDL model experiments perform well (r > 0.80), although they show a higher RMS error due to the inherent global pressure bias (e > 7.0 hPa). The performances of DKRZL, CSIRO9 and CSIRO4 model simulations are substantially improved during JJA months (r > 0.75) compared to DJF. The UKMO model performance is poorer (r = 0.60) and the OSU and GISS model simulations exhibit lower correlation coefficients (r < 0.55) than they had in winter. While the NCARC has a similar pattern correlation value to winter (r > 0.7) the rms error has increased (e > 6.0 hPa).

It can be readily judged from Figure 1 that all the high resolution flux-corrected models perform well (r > 0.80) in simulating the observed climatological MSL pressure over the northern hemisphere during both seasons. The medium resolution flux-corrected models do well in summer (r > 0.75), but do not perform well in winter. Except OSU and GISS models, non-flux-corrected and low resolution flux-corrected models also perform well in their simulations for both seasons (r < 0.60). As examples, we present MSL pressure maps of the DKRZOand GISS model experiments (which performed well and poorly respectively in the statistical testing) for JJA and DJF months along with the observed pressure patterns in Figure 2. The DKRZO model experiment demonstrates a substantial skill in simulating the low pressure over the north Atlantic and high pressure systems over north America and Siberia during winter. In summer also, the highs over the Pacific and Atlantic oceans are simulated realistically by this model. On the other hand, the GISS model simulation identifies the location of high and low pressures but shows significant variation from observations in their intensity during both the seasons.

Although, there is considerable variation in the performance of the models (and the GISS and OSUexperiments are notably poorer than the rest), all the simulations show the major features of the northern hemisphere circulations and can be considered acceptable.

3.2 Surface Air Temperature

The hemispheric surface temperature data sets were analysed following a similar approach as used to examine the MSL pressure patterns. The models are able to represent the strong gradient in surface temperature from equator to pole. As a consequence of this, the pattern correlations are higher for all the models (r > 0.90) except for relatively poorer performance in the NCARC model simulation during the winter season (r = 0.75). This could be attributed to the fact that no flux corrections were applied in the NCARC model integrations. However, the other non-flux-corrected models performed reasonably well in their simulations (although, unlike the NCARC model, these do not have a dynamic ocean).

The hemispheric spatial temperature distribution in the CSIRO9 and NCARC model simulations (examples of a good flux-corrected and a comparatively poor non-flux-corrected model experiments respectively) along with the observed temperature distributions are illus-

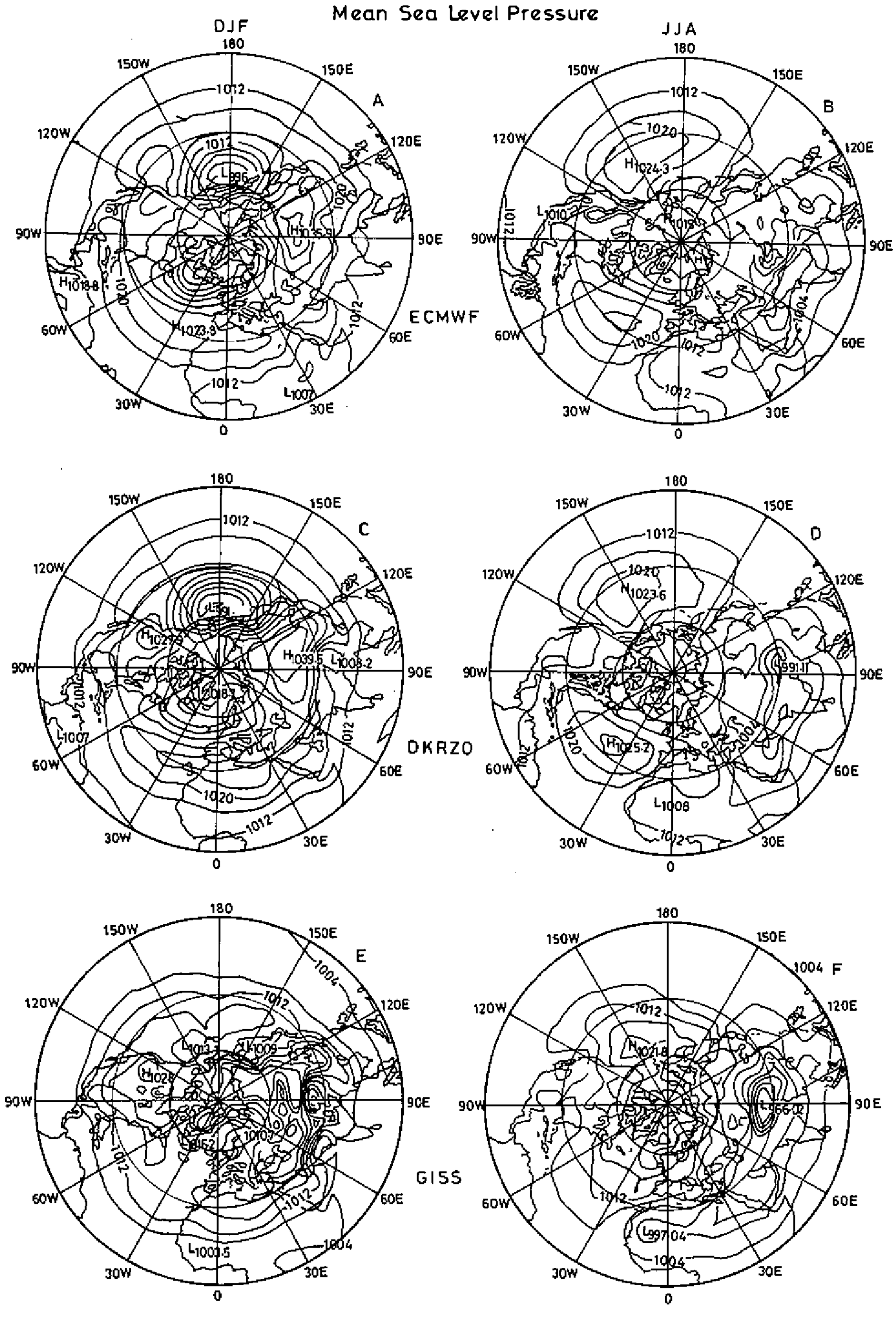


Fig. 2. The spatial distribution of observed mean sea level pressure patterns as well as that simulated in DKRZO and GISS experiments over the Northern Hemisphere.

trated in Figure 3. The surface temperature is simulated quite realistically by the CSIRO9 model except around mountainous regions.The horizontal resolutions of these GCMs do not appear to be sufficient to produce the realistic surface air temperatures in the vicinity of high mountains. The ocean surface temperatures are also well simulated by the CSIRO9 model (although the flux correction is designed to produce realistic sea surface temperature) whereas these are poorer in the non-flux-corrected NCARC model experiment. Surface air temperature is an important element of the climatic state of a region and plays a significant role for systems ranging from ecosystems to energy use. We will concentrate more on this important climate parameter while discussing the model performance over the Indian subcontinent.

The performances of all the model experiments in representing the observed hemispheric surface temperature can be considered as acceptable, but the coarse horizontal resolution of the GCMs restricts their ability to represent the observations very well over mountainous areas. The analyses also reveal that models without flux correction can have significant errors in temperatures over the oceans.

3.3 Precipitation

Comparison statistics of the simulated northern hemispheric precipitation with observations is presented in Figure 4. The pattern correlations are lower than they were for MSL

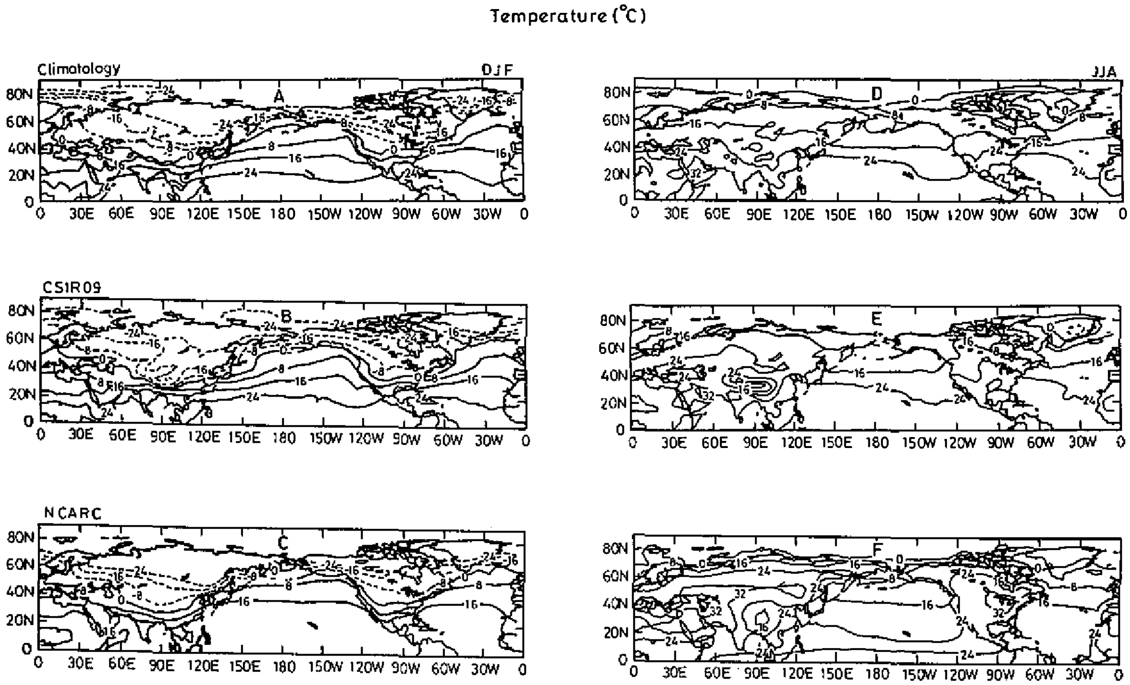


Fig. 3. The spatial distribution of observed surface and/or near surface temperature patterns as well as that simulated in CSIRO9 and NCARC experiments over the Northern Hemisphere.

pressure and temperature. The precipitation is dependent on many complex atmospheric processes and varies significantly over smaller spatial scales. The precipitation data for UKMOC and GFDLC model experiments were not available to us when these calculations were performed. Our analysis showed that ,during both the seasons, DKRZO simulation best represents the observed precipitation patterns over the northern hemisphere (r = 0.76 in DJF and r = 0.73 in JJA). The DKRZL and UKMOH simulations are also good (r > 0.65 in both the seasons). With the exception of the CSIRO4, GISS and NCARC experiments, all other models show moderate skill in simulating the observed precipitation patterns (r > 0.55 in both the seasons). The correlation coefficient in the CSIRO4 model simulation is rather low in JJA months (r = 0.49) while the GISS model performs poorly during the DJF months (r = 0.45). The NCARC correlation coefficients are low in both seasons (r = 0.51 in DJF and 0.49 in JJA). The models have a tendency to produce lower correlation coefficients during summer compared to winter.

It is interesting to note from Figure 4 that the spatial distributions of hemispheric precipitation are best simulated by the medium resolution flux-corrected models (r > 0.55 in both the seasons) except in the case of the CSIRO4 model. Although, the UKMOH simulation is good (r = 0.75 in DJF and 0.67 in JJA), in general the higher resolution model simulations are not better than those for the medium resolution models.

Figure 5 depicts the spatial distribution of observed precipitation and that simulated in the UKMOH and CSIRO4 model experiments over the northern hemisphere. On a broader scale, the UKMOH simulation of precipitation matches fairly well with the observed climatological precipitation. During JJA, the UKMOH model is markedly better than that of the

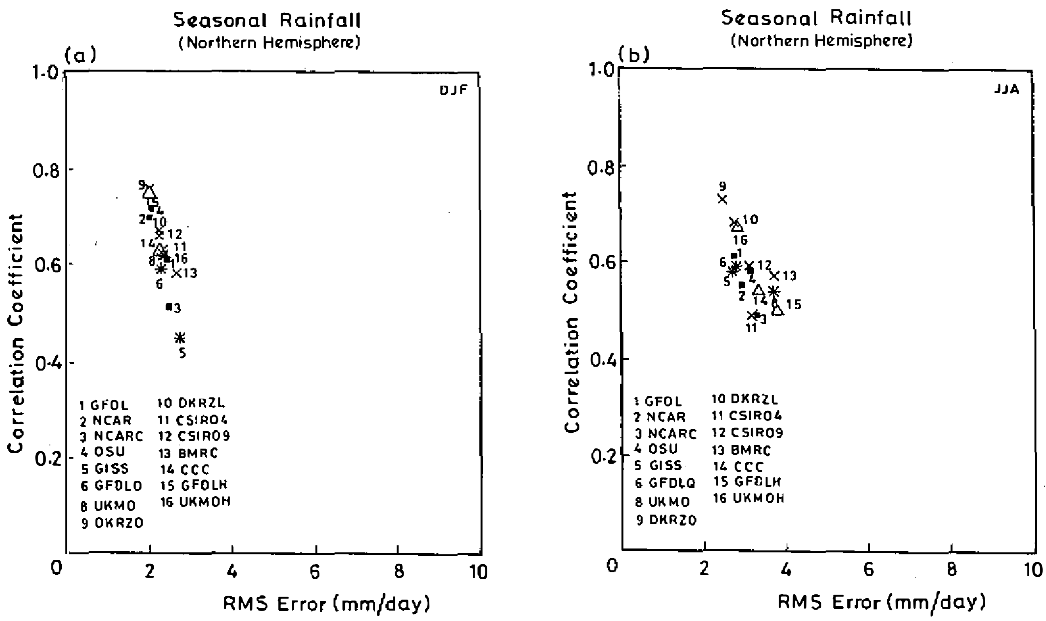


Fig. 4. The pattern correlation coefficients and RMS errors between observed and model-simulated precipitation fields over the Northern Hemisphere.

CSIRO4 model in simulating the spatial distribution of summer monsoon rainfall.The high precipitation over the equatorial Pacific ocean along the west coast of America is also simulated well in the UKMOH model experiment during both seasons.

From the above, we conclude that apart from the poor simulations of precipitation by the CSIRO4, GISS and NCARC experiments, all other models exhibit some skill in their control experiments.

4. COMPARISON OF MODEL SIMULATIONS WITH OBSERVED CLIMATE OF THE INDIAN SUBCONTINENT

In this section, we compare the performance of the models in simulating the observed MSL pressure, surface air temperature and precipitation over the Indian subcontinent. Some key climatic features of the observed climate over the study area will be taken into account and the performance of individual models will be assessed according to their ability in capturing these features.

4.1 MSL Pressure

In the summer, the monsoon trough lies along the Indo-Gangetic plains of northern India. The western end of the trough merges with the heat low over Pakistan whereas the eastern end extends to the Bay of Bengal where a series of monsoon depressions develop. On the

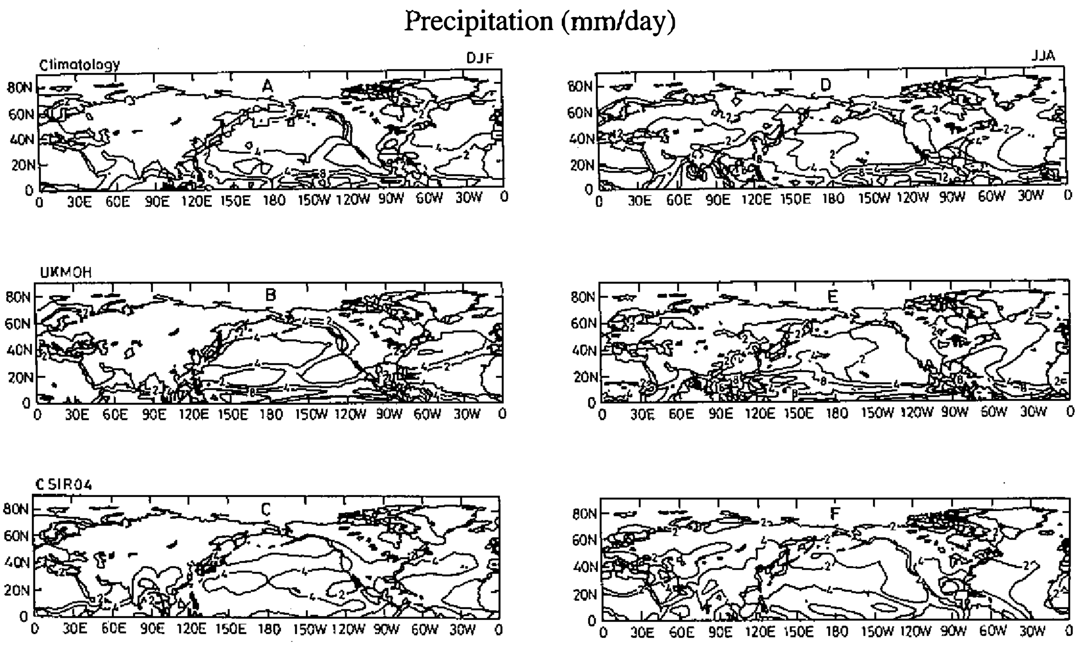


Fig. 5. The spatial distribution of observed precipitation patterns as well as that simulated in UKMOH and CSIRO4 experiments over the northern hemisphere.

other hand, during winter, pressure decreases from land to sea due to the lower heat capacity of the land with respect to the oceans which causes the air over the land to become relatively cooler. An attempt to assess the skill of GCMs in simulating these unique pressure patterns in the winter and summer seasons over the Indian subcontinent is made by correlating the MSL pressure data sets generated in their reference control experiments with the observed climatological data. The results are presented in Figure 6.

During DJF, the UKMOC, BMRC, CSIRO4, UKMO, UKMOH, CCC, NCAR, NCARC and OSU model experiments perform well (r > 0.85 and e < 5 hPa). The GFDL model experiments (GFDL, GFDLC, GFDLQ and GFDLH) show somewhat larger RMS errors (e > 7.5 hPa, r > 0.70) due to the inherent pressure bias. The other model experiments (DKRZO, DKRZL, CSIRO9 and GISS) have low skill (0.5 < r < 0.70).

In summer, the pattern correlations are generally lower and RMS errors higher than they are in winter. Although this indicates a generally poorer performance, this may stem from the fact that the summer regional pressure pattern is more complex (i.e.,a low pressure centre over the region, whereas in winter there is simply a gradient in pressure across the region). Of the eight experiments that had pattern correlations greater than 0.85 in winter, only one (UKMOH) shows similar skill in summer and only three more (OSU, UKMOC and BMRC) have pattern correlations greater than 0.7. Of the remaining models, DKRZL and NCARC stand out as noticeably poorer than the rest (r < 0.4). The results for NCARC in particular (r = 0.32, e = 8.5 hPa) suggest serious deficiencies in this model in its simulation of surface pressure over India in summer.

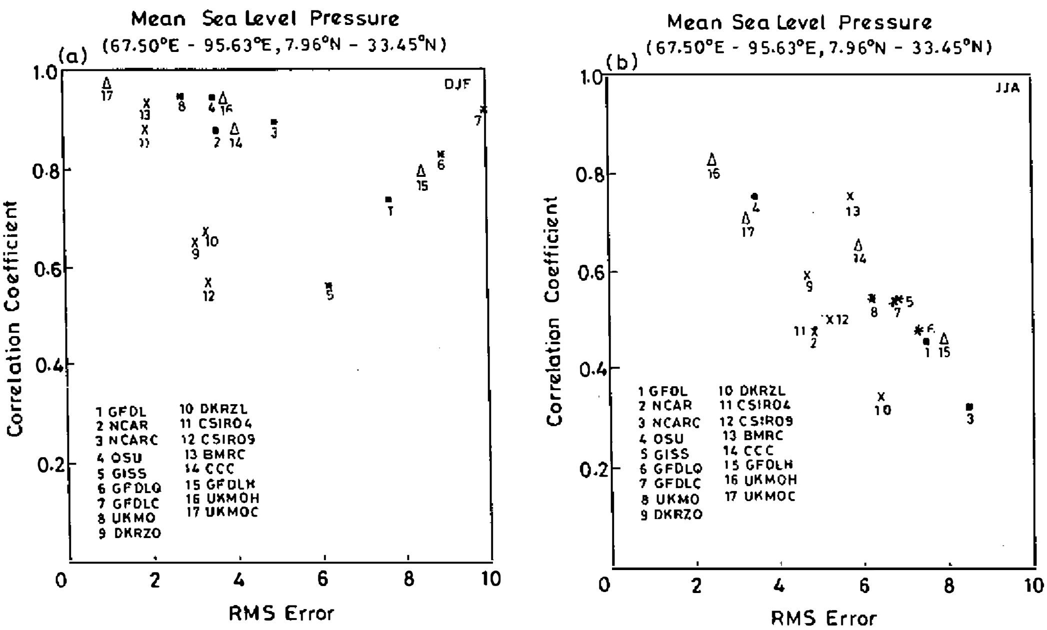


Fig. 6. The pattern correlation coefficients and RMS errors between observed and model-simulated mean sea level pressure over the Indian subcontinent.

In Figure 7we present the spatial distributions of MSL pressure in both seasons as simulated in the UKMOC experiment (which performed very well in the statistical tests) and the DKRZL (which did not perform well),and as observed. During the northern hemisphere summer, a heat low persists over the northwest semi-arid regions of the Indian subcontinent. Although the UKMOC model simulates the dominating low pressure system over northwest India marginally displaced to the southwest, the monsoon trough lies over the Indo-Gangetic plain as is observed. On the other hand, the DKRZL model simulation produces a low pressure over the Himalayas well to the northeast of the observed location. In winter, the UKMOC model simulation is very good while DKRZL simulates an unrealistic low pressure over the north-eastern region of Indian subcontinent.

A further indication of how all the models perform in simulating the heat lowover the subcontinent during summer is illustrated in Figure 8. The dark regions in the figure represent the zone where the pressure is low (< 996 hPa). The UKMOHand UKMOC model simulations have significant skill in reproducing the low pressure as wellas the position of the mon-

Mean sea level pressure

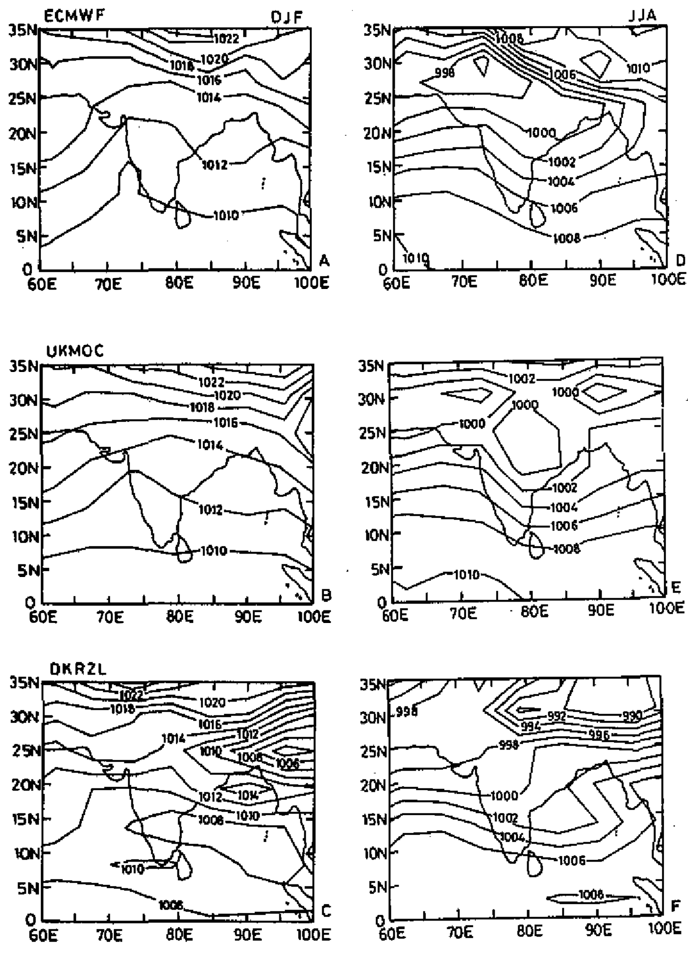


Fig. 7. The spatial distribution of observed mean sea level pressure patterns as well as that simulated in UKMOCand DKRZL experiments over the Indian subcontinent.

soon trough. Most of the other models considered in this study have coarser resolution and the poor placement of the heat low or monsoon trough could be attributed, at least partially, to this factor. This suggests that perhaps, with higher resolution, the models could more realistically simulate the position of monsoon trough over the Indian subcontinent.

However, as is evident from Figure 6, GCMs with higher horizontal or vertical resolution or a flux-corrected ocean do not necessarily exhibit better skill in simulating the observed climatology on a regional scale. The OSU model, with no flux correction and only two vertical levels in the atmosphere, performed well in simulating the MSL pressure patterns over the Indian subcontinent (although we saw earlier that it performed poorly over the hemispheric scale). On the other hand, the DKRZL and CSIRO9 model simulations, which have moderately high horizontal and vertical resolution (and are flux-corrected), performed considerably more poorly than the OSU model simulation. The complex atmospheric processes on regional scales are yet to be fully understood and more elaborate sensitivity studies with improved parameterization of physical processes are needed to be performed with GCMs to ensure that they are able to accurately simulate the observed regional climatology.

The simulations of MSL pressure distribution over the Indian subcontinent are unacceptably poor in the case of NCARC and DKRZL model experiments. The UKMOC and UKMOH simulations exhibit the highest skill whereas all other models perform only reasonably well.

During the monsoon season, the surface winds across the equator over the Indian Ocean are southeasterlies and become southwesterlies over the Arabian Sea, Peninsular India and the Bay of Bengal. The Somali jet off the East African coast is a major circulation feature of the summer monsoon in this region. In the present study, winds from CSIRO9, GFDLH and UKMOH GCMs have been analysed to ascertain if the observed features of the major circulation features associated with summer monsoon are replicated by these GCMs in their control experiments. The 850 hPa winds obtained in control simulations of these three GCMs and the observed (Ramage & Raman, 1972) mean wind patterns during JJA are shown in Figure 9. Pattern correlations for the zonal winds range between 0.88 for the CSIRO9 model and 0.93 for the UKMOH model during JJA, and between 0.81 for the GFDLH model and 0.84 for the CSIRO9 model during DJF. The RMS errors in both the seasons range between 2.2 to 3.3 $m\ s^{-1}$. In general, the major features of the monsoonal flow such as the Somali Jet have been captured by these GCMs. However, the magnitude of wind speed and locations of maxima vary among the models, as is evident from RMS error values. The wind data from other model experiments were not available.

4.2 Surface Air Temperature

The pattern correlation and RMS error analyses for surface air temperature over the Indian subcontinent are illustrated in Figure 10. As in the case of hemispheric data analysis, we find that all the model simulations have quite high correlation coefficients during both the seasons. The observed temperature pattern during the winter season (which has a strong north-south temperature gradient determined by both latitude and the land-ocean temperature contrast) is well simulated by the models ($r > 0.9$). The UKMOH, DKRZL, BMRC, CCC and GFDLQ model simulations have, however, large RMS errors ($e > 7.5°C$). The DKRZO, GFDL,

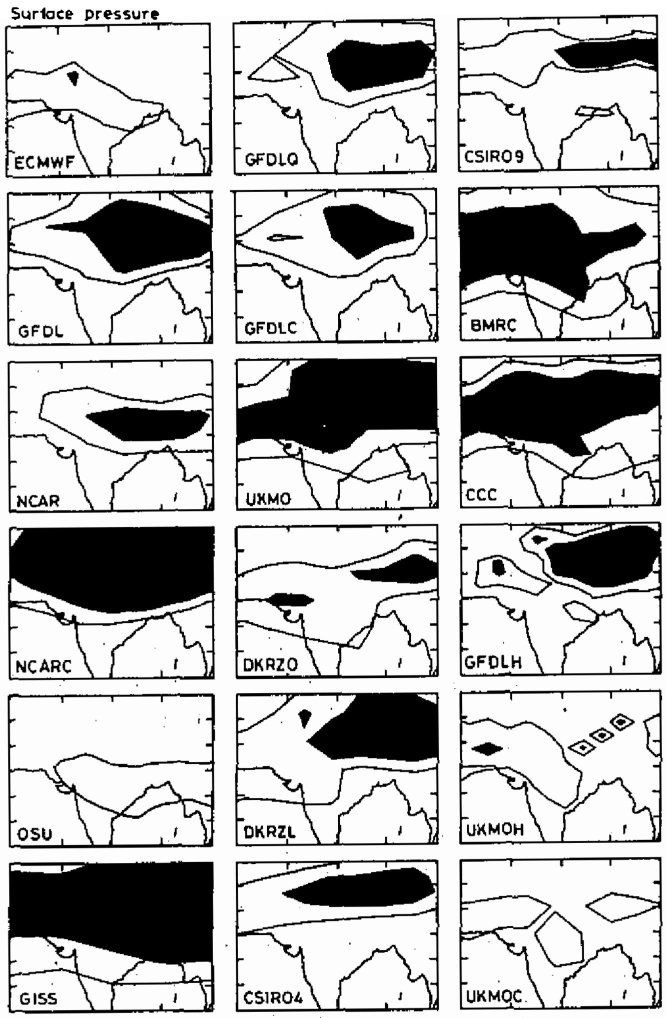


Fig. 8. The position of JJA seasonal heat low over the northwest India as observed and simulated in different GCM experiments. The dark region represents the zone where the pressure is lower than 996hPa.

GISS and OSU model simulations perform well with moderate RMS errors (e < 5.0°C). During summer, pattern correlations are poorer than winter, but RMS errors are lower. This could perhaps be expected given the weaker observed temperature gradients during this season. The performances of most models are reasonable (r > 0.8, 3.0°C<e<6.0°C). The GFDLQ, GFDLC and CSIRO4 model experiments have only moderate skill (r > 0.7), but the NCARC stands out as noticeably poorer (r < 0.6) in representing the observed temperature patterns.

Figure 11depicts the spatial distribution of surface temperature as simulated in the BMRC and GFDLC model experiments and as observed.Over the Indian subcontinent, the BMRC

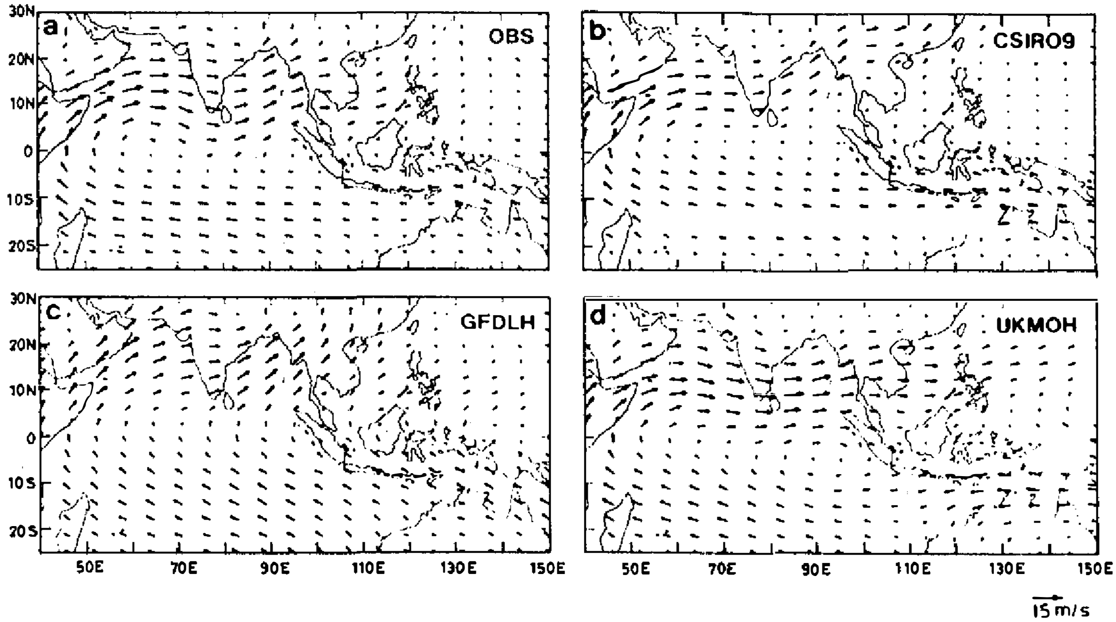


Fig. 9. Observed wind vectors for JJA at 850 hPa (a) and winds simulated for present day conditions by CSIRO9 (b), GFDLH (c) and UKMOH (d) models. The winds for CSIRO9 and UKMOH are at 850 hPa and winds for GFDLH at 0.99 sigma level.

model is able to simulate the observed temperature patterns with a better skill than the GFDLC model experiment. During summer, the surface temperatures simulated by GFDLC model are too high over the northwest and central Indian region when compared with the observed climatology. Notably, both these model experiments produce excessively low temperatures during winter over the northern extremes of India. Many models have large departures over the Himalayas thus affecting the inferred RMS error values. Due to poor representation of these mountains at current model resolution and the associated large errors over this area, we decided that it would be useful to undertake further analysis of the temperature data focusing just on the north-central Indian region which excludes the Himalayas.

The inter-seasonal temperature ranges over north-central Indian region (73.12°E - 84.38°E and 17.52°N - 27.08°N) between JJA and DJF are depicted in Figure 12. For this purpose, the temperature data from all the models were interpolated to a common grid (5.6° long X 3.3° lat) and the temperature values were averaged over a total number of 12 grid points. The observed temperature range is represented by the parallel lines. Almost all the models show an excessively wide temperature range. The BMRC, GISS and CSIRO9 model experiments demonstrate the best skill in reproducing the seasonality and absolute value of temperature. Both the DKRZL and CSIRO4 model simulations underestimate the JJA temperatures whereas significant over-estimations are produced by the GFDL, NCAR, OSU, GFDLQ, GFDLC, DKRZO, GFDLH, UKMOH and UKMOC model simulations. This tendency is most extreme in the GFDL model simulation and marked in the NCAR, GFDLQ and GFDLH simulations. It is

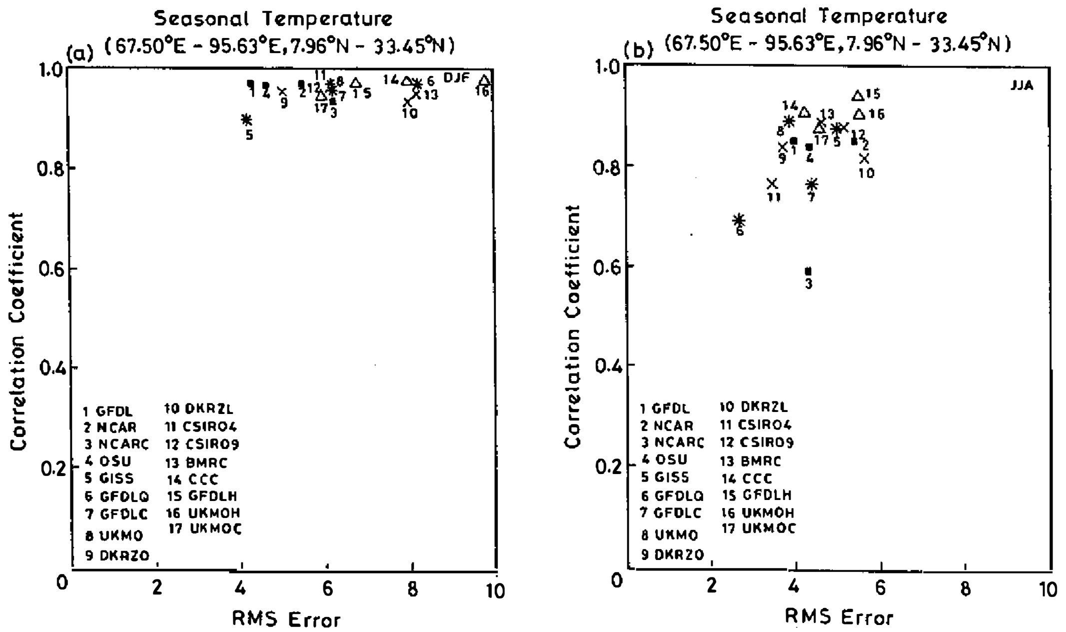


Fig. 10. The pattern correlation coefficients and RMS errors between the observed and model-simulated surface and/or near-surface temperature fields over the Indian subcontinent.

interesting to note that all the models simulate lower than observed temperatures during winter except the GFDL simulation. Summer temperatures are well simulated in the NCARC and CCC model experiments but winter temperatures are too low. This could be attributed to lower than observed temperatures simulated by almost all the models over the higher latitudes of Indian subcontinent. As may be expected, the four non-flux-corrected simulations have significant errors in temperature, but only in the case of the GFDLand NCAR simulations are these errors larger than what is typical for the flux corrected experiments. The errors in the GFDL experiment are very large, and suggest a serious deficiency in this simulation.

The land to sea temperature gradient during the monsoon season is regarded as the main driving force behind the monsoon circulation over the Indian subcontinent. With a view to examine this aspect in the model simulations, we averaged the model-simulated surface air temperatures over northwestern India (67.5°E - 78.8°E and 23.9°N - 30.3°N), where the observed heat low dominates, and over the oceanic area near the east coast of Somalia (50.6°E - 61.9°E and 4.8°N - 11.2°N) from where the monsoon winds turn during the northern hemispheric summer. The surface air temperature data generated by all the models were interpolated to a common grid (5.6° long. X 3.3° lat.) to give nine grid points in each region for computing the averages. Table 2 lists the findings of this analysis. The CCC, CSIRO9 and UKMO model experiments best simulate the observed temperatures and, hence, the thermal gradients. In the case of the DKRZL and OSU model simulations, the temperature differences

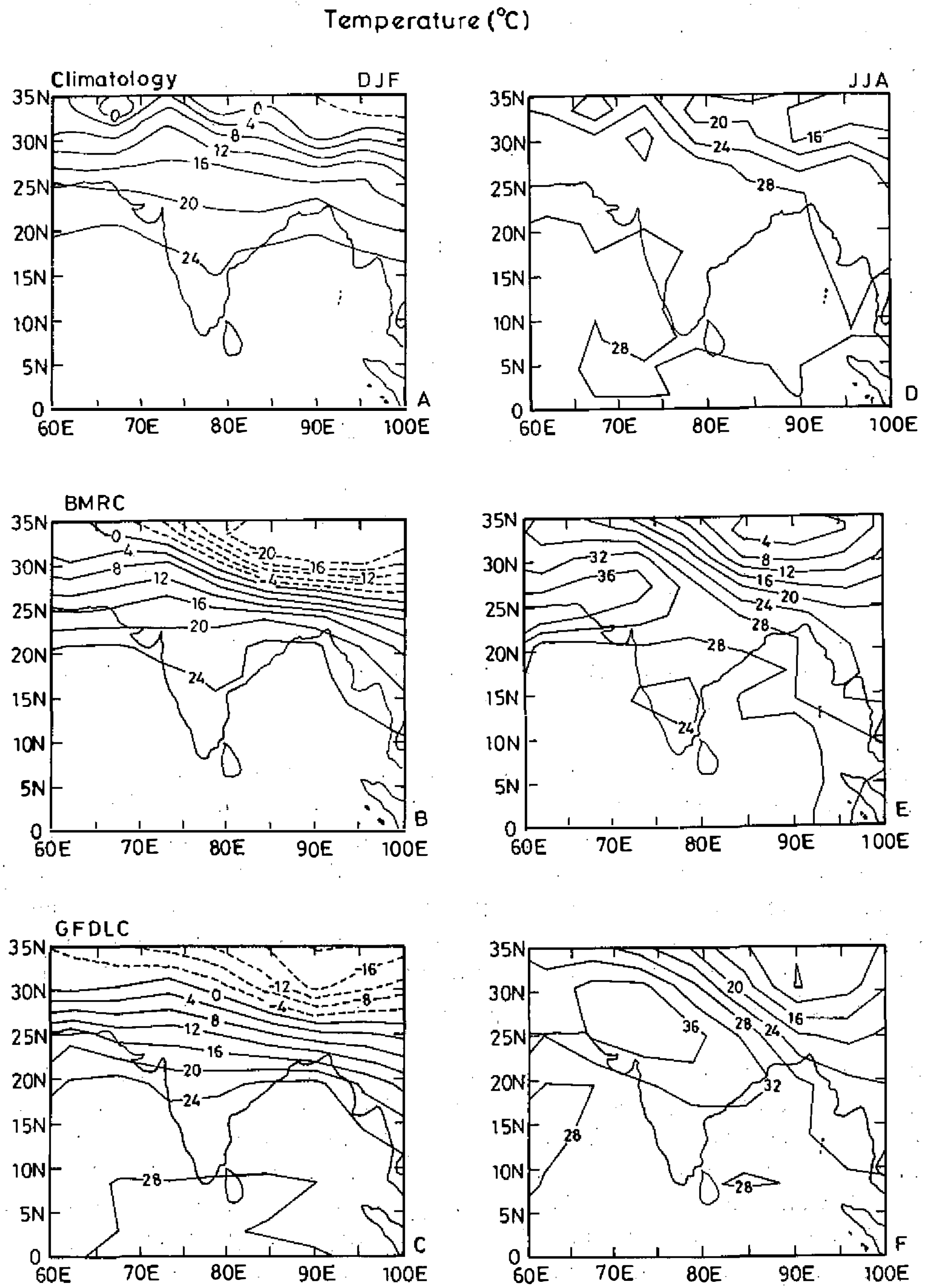


Fig. 11. The spatial distribution of observed surface and/or near-surface temperature patterns as well as that simulated in BMRC and GFDLC experiments over the Indian subcontinent.

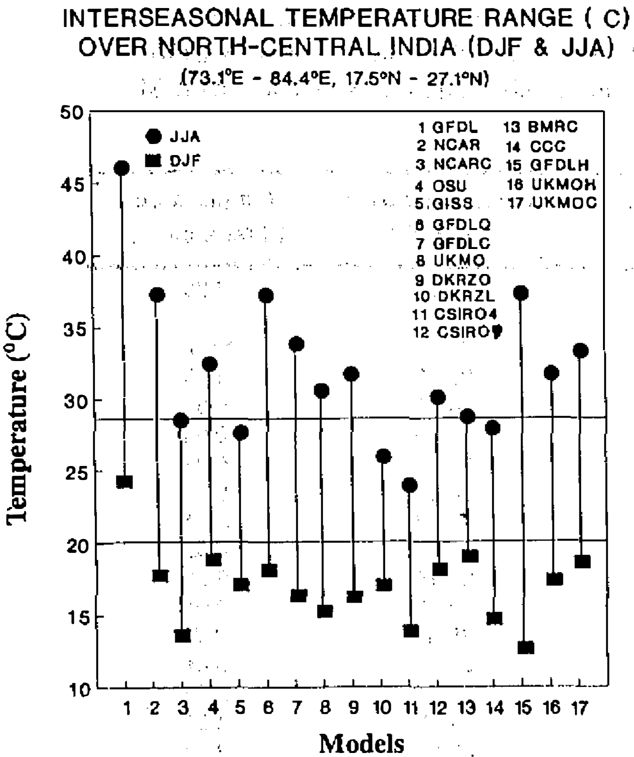


Fig. 12. The inter-seasonal (between JJA and DJF seasons) temperature range over north central India as simulated in different model experiments. The parallel lines intersecting the model-simulated ranges represent the observed inter-seasonal temperature range over the region.

are near zero, while the CSIRO4 model shows an unrealistic negative temperature gradient. The other models simulate steeper temperature gradients than that observed in this region.

The regional temperature simulations of all models deviate significantly from the observed temperatures. However, some allowance needs to be made for the inevitable discrepancies due to highly smoothed model topography and the use of surface temperature rather than air temperature in some comparisons. All things considered, the CSIRO4 and GFDL experiments perform unacceptably poorly in representing the observed land to sea temperature gradient in the summer season and inter-seasonal temperature range respectively. The NCARC experiment exhibits a poor skill in projecting the observed summer temperature distribution over the study region.

4.3 Precipitation

A realistic simulation of total precipitation and its spatial distribution over the Indian subcontinent associated with the summer monsoon is of considerable practical importance. The pattern correlation and RMS error analyses of the simulated precipitation data with the observed climatology are illustrated in Figure 13. Note that the precipitation data for the UKMOC and GFDLC model simulations were not available.

In DJF, the observed rainfall is very low over India and the pattern correlations with the

Table 2. The temperature difference between the northwest Indian subcontinent (67.5°E-78.8°E & 23.9°N-30.3°N) and the eastern Arabian Sea (50.6°E-61.9°E & 4.8°N-11.2°N) during JJA months as simulated in GCM experiments.

Models	Temperature over Land, °C	Temperature over ocean, °C	Temperature Difference, °C
Observed	29.53	27.24	2.29
GFDL	43.54	31.14	12.40
NCAR	35.81	30.52	5.29
NCARC	31.48	24.57	6.91
OSU	29.15	28.86	0.29
GISS	27.39	27.12	0.27
GFDLQ	36.30	26.32	9.98
GFDLC	35.99	27.48	8.51
UKMO	30.56	26.54	4.02
DKRZO	32.86	27.15	5.71
DKRL	26.36	26.35	0.01
CSIRO4	24.86	26.63	-1.77
CSIRO9	31.15	27.31	3.84
BMRC	32.97	27.24	5.73
CCC	29.62	26.42	3.20
GFDLH	36.68	26.89	9.79
UKMOH	32.64	26.44	6.20
UKMOC	33.62	27.53	6.09

observed climatology are, thus, of less importance. A range of experiments (DKRZO, OSU, GISS, NCAR, GFDLH, CCC, UKMOH, CSIRO4, DKRZL) have pattern correlation coefficients greater than 0.6, BMRC and CSIRO9 simulations have correlations greater than 0.5, and the UKMO, NCARC and GFDLQ simulations have correlations nearer 0.4. The GFDL simulation represents the winter rainfall pattern very poorly ($r < 0.2$).

During JJA, which is considered as the main rainy season over India, pattern correlation varies greatly amongst models but there is little variation in RMS error. This may be due to the fact that the complex observed precipitation pattern is largely orographically induced and the coarse resolution of the GCMs does not allow them to capture the local orography realistically. The DKRZL, UKMOH, CCC and DKRZO model simulations demonstrate best skill in representing the rainfall in JJA over the region of study ($r > 0.55$). The GFDLQ, GFDLH, BMRC, CSIRO9 and UKMO model simulations are poorer but exhibit some skill ($r > 0.40$). The GFDL, GISS and NCARC model experiments have rather lowcorrelation coefficients ($r < 0.40$) while the CSIRO4, NCAR and OSU model simulations are very poor ($r < 0.20$).

Figure 14 depicts the spatial precipitation distributions as observed and as simulated in both seasons for the DKRZL and CSIRO4 model experiments (examples of high and low pattern correlations in JJA respectively). During JJA, the DKRZL model simulation captures the precipitation distribution over the Arabian sea and along the west coast of India in terms of its intensity. The model is, however, not able to reproduce the observed sharp gradient from the west to east coast over the south India due to its coarse resolution. The precipitation simulated by the CSIRO4 model over the land is substantially lower than the observations.

The area-averaged total summer precipitation over the Indian subcontinent (67.5°E - 95.6°E, 7.8°N - 33.5°N) as produced in each of the model experiments is depicted in Figure 15a. The DKRZL simulation represents observed seasonal rainfall well, while the BMRC simulation is slightly too wet and the CSIRO9, NCARC and DKRZO model simulations are too dry. Other models show a marked under-estimation of rainfall which is severe in the case of the OSU and NCAR simulations.

However, perhaps even more important than a correct simulation of total monsoonal rainfall, is a correct simulation of the marked seasonality of Indian rainfall (a correct representation of seasonality indicates that the regional climate of the model responds appropriately to the seasonal cycle in radiation). Figure 15b & 15c illustrate the performance of models in representing the rainfall seasonality over the Indian subcontinent. The regional rainfall seasonality for a season is defined as the percentage of total annual rainfall occurring in that season. In summer (Figure 15b), the observed rainfall raction is 55% and this is reasonably well simulated in the NCARC, DKRZO, DKRZL, CSIRO9, BMRC, GFDLH and UKMOH model experiments. On the other hand, the NCAR, OSU and GISS model simulations produce less than 25% of total annual rainfall during JJA which represents a complete failure to simulate the monsoon rainfall maximum over India. The GFDL, GFDLQ, UKMO, CSIRO4 and CCC model simulations also under-estimate the seasonality in monsoon rainfall over the

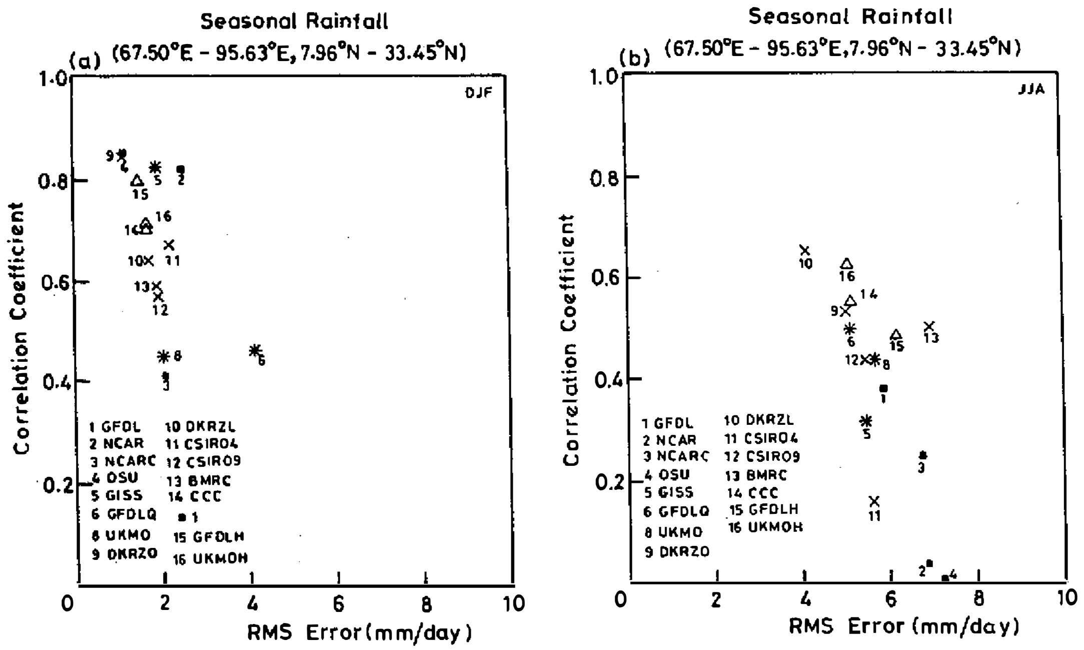


Fig. 13. The pattern correlation coefficients and RMS errors betwee the observed and model-simulated precipitation fields over the Indian subcontinent.

Indian subcontinent to some extent.

In contrast to JJA, less than 10% of the total annual rain falls during winter. This is reasonably well simulated in the DKRZO, DKRZL, CSIRO9, BMRC, GFDLH and UKMOH model experiments. The GFDL, NCAR, GISS and CSIRO4 model experiments show substantial over-estimation of the observed winter rainfall contribution. In particular, the NCAR and GISS simulated values exceed by 25%, indicating that these simulations fail to produce the winter rainfall minimum.

In summary, the NCAR, OSU, GISS, CSIRO4 and GFDL model simulations of precipitation are unacceptably poor over the Indian ubcontinent. Of the acceptable simulations, the DKRZO, CCC, GFDLH, UKMOH, DKRZL, CSIRO9 and BMRC experiments exhibit the best skill.

5. DISCUSSION

Of the seventeen GCM experiments considered in the present study, five are judged as acceptable on all the hemispheric and regional testsand as performing with skill on some of those tests. These are the DKRZO, UKMOH, CCC, BMRC and CSIRO9 experiments. The salient features regarding the simulation skill of the selected models over our study region are briefly discussed below.

The DKRZO simulation emerges as the best in simulating the observed present-day climatology on the hemispheric scale. The inter-seasonal temperature range over north-central India and the summer rainfall amount and seasonality are realistically simulated by this model, although the land to sea temperature gradient is rather high compared to observations. Regional pressure simulation in this experiment is poorer in that an unrealistic secondary low is simulated over the northeastern part of India in JJA. The hemispheric performance of the UKMOH experiment is reasonably skilled. Over the Indian subcontinent, it may be judged as superior to the DKRZO simulation when the pattern correlation coefficients are taken into account. It shows a very realistic representation of the observed heat low over northwest India, although its simulation of the amount and seasonality of summer rainfall is not as good as some other models. In the CCC experiment, the inter-seasonal temperature range over north central India and the land to sea temperature gradient in summer are simulated with fairly high skill, although the simulation of the total rainfall amount and its seasonality is poor in this model experiment too. In the BMRC experiment, the total rainfall amount and its seasonality are very well simulated. The inter-seasonal temperature range over north central India is also simulated well but the summer land to sea temperature gradient is too high. The CSIRO9 model experiment simulates total rainfall amount and its seasonality over India with reasonable skill. The inter-seasonal temperature range over north-central India and the summer seasonal land to sea temperature gradient are also well simulated by this model. This experiment has, however, low skill in its simulation of hemispheric and regional pressure patterns.

The UKMO, GFDLQ and GFDLH experiments were also considered acceptable on all tests, but in general these did not perform as well as the five simulations discussed above. The DKRZL experiment exhibited a mixed performance. Its simulation of the summer pressure

Precipitation (mm/day)

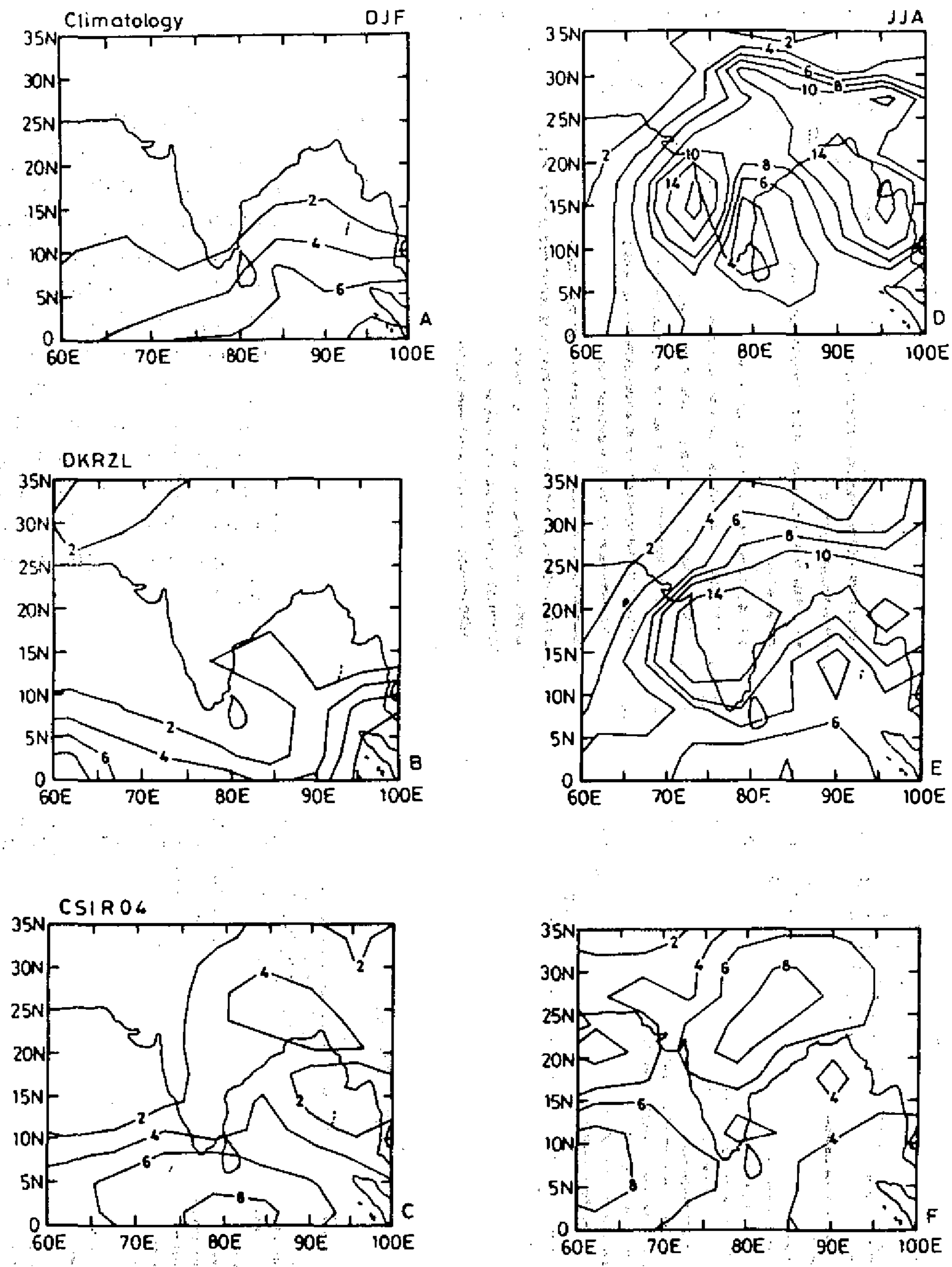


Fig. 14. The spatial distribution of observed precipitation patterns as well as that simulated in DKRZL and CSIRO4 experiments over the Indian sub-continent.

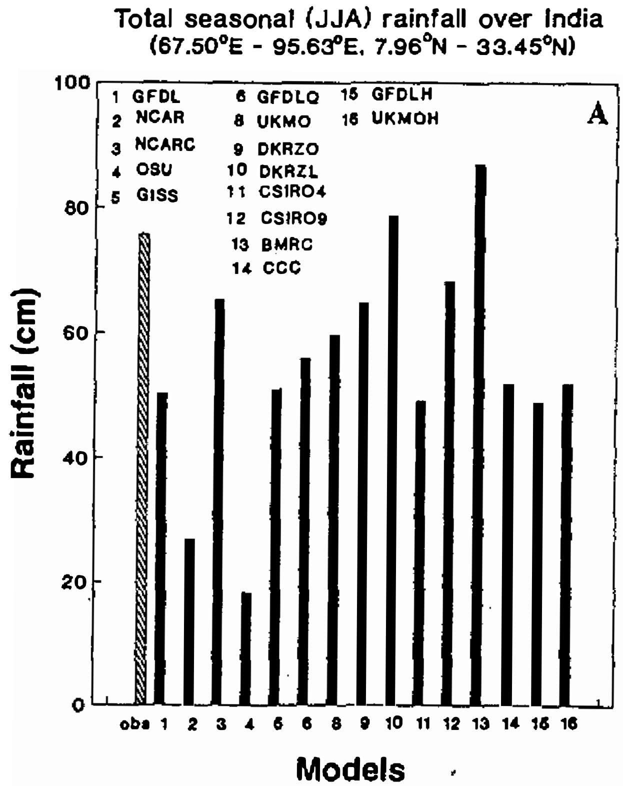
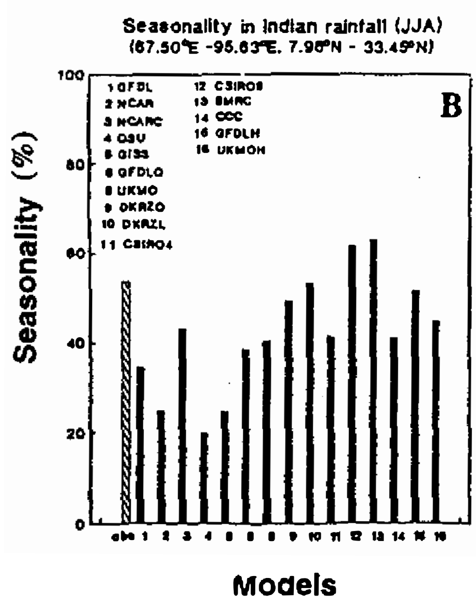
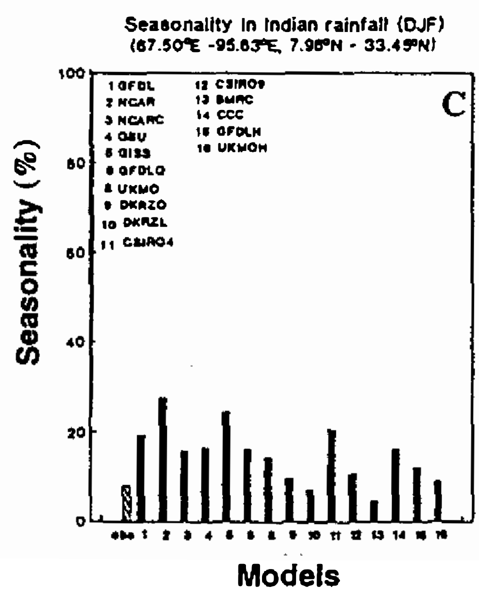


Fig. 15. (a) The observed and model-simulated cumulative JJA rainfall over the Indian subcontinent in different GCM experiments, (b) The seasonality in JJA rainfall as observed and simulated in different GCM experiments over the Indian subcontinent and (c) The seasonality in DJF rainfall as observed and simulated by different GCM experiments over the Indian subcontinent.





pattern over India is poor but on most of the other tests this experiment performed with reasonable skill and its simulation of summer rainfall over India was particularly good. Overall we class the UKMO, GFDLQ, GFDLH and DKRZL experiments as acceptable with only moderate degree of confidence. Note also that the GFDLC and UKMOC simulations were also acceptable, but their skill in simulation of precipitation was not tested due to unavailability of data.

Six of the model experiments considered had unacceptably poor simulations of the observed climatic features over our study region. These are the GFDL, NCAR, NCARC, OSU, GISS and CSIRO4 simulations. We summarize below the important deficiencies of these models in simulating the observed climatology.

Over the Indian subcontinent, the temperature and rainfall are poorly simulated in the GFDL model experiment. The summer land to sea temperature gradient is much too high and the inter-seasonal temperature range over north central India is the poorest of all the models considered. The NCAR simulation fails to show a summer rainfall maximum over the Indian subcontinent and very poorly simulates the rainfall pattern in summer. The simulated temperature range over north central India is also very high compared to the observations. The OSU experiment fails completely in representing the observed seasonality in rainfall over India.The northern hemispheric pressure is also simulated poorly by the OSU model. The GISS experiment poorly simulates the MSL pressure distribution over the region. The observed seasonality in rainfall over India is also not simulated by the model. The performance of the CSIRO4 experiment is unacceptable because of its poor simulation of temperature and rainfall over India. The average temperatures over north central India both in summer and winter are too low and the summer temperature gradient between land and sea is of wrong sign. The simulated pattern of summer rainfall is also very poor. The NCARC model experiment performed poorly in many of the tests over the region.

Horizontal and vertical resolution appears to be related to model performance in that the best performing model experiments have higher resolution and the unacceptable experiments are of medium to low resolution. In particular, the OSU and CSIRO4 model experiments have only two and four vertical levels respectively. The GISS model experiment has the coarsest horizontal resolution. The best performing experiments are those with recent model versions which include improved parameterisation schemes as well as high resolution. It is quite notable that all of the experiments which did not employ a flux correction have poor skill. Use of a dynamic ocean did not seem to be a distinguishing factor in model performance.

6. CONCLUSIONS

The results of control simulations from seventeen general circulation model experiments have been analysed to assess their relative performance in representing the observed climatology over the northern hemisphere and Indian subcontinent. Considering the overall performance of all the GCMs in representing theclimatological features over the northern hemisphere and, more specifically, over the Indian subcontinent, we find that the DKRZO, UKMOH, BMRC, CCC and CSIRO9 model experiments have demonstrated considerable skill in their control simulations. The anomaly experiments (under enhanced greenhouse gas conditions) performed with these model experiments should be able to provide meaningful information on the future climate change over the region of interest for impact assessment studies. The performances of the UKMO, GFDLQ, GFDLH and DKRZL model experiments may be acceptable but only to a moderate degree of confidence. The simulation of monsoon climatology in the GFDL, NCAR, NCARC, OSU, GISS and CSIRO4 model experiments is rather poor and unacceptable. The non availability of model-simulated data in the case of the GFDLC and UKMOC experiments restricts us to judge their performance over the region of interest.

Several caveats should be noted. We have considered only three climatic elements (MSL pressure, surface air temperature and precipitation) in our study. The statistical approach which we have used in our analyses has limitations and may not be regarded as a perfect tool to evaluate the performance of a model. Assessment of model performance was at the regional to sub-regional scale, so we did not focus on the quite large errors of even the best simulations in reproducing climate at the scale of model grid points (200 to 600 km apart). Finally it should be noted that the assessment of GCMs over the Indian region was intended to identify those experiments most likely to provide reliable estimates of future climate change over the region. It should not be extended to rating the models concerned for any other purpose.

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