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SIMULATION OF THE INDIAN MONSOON CLIMATOLOGY IN ECHAM3 CLIMATE MODEL: SENSITIVITY TO HORIZONTAL RESOLUTION

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ABSTRACT

The ability of the current generation of climate models, in their long-term simulations, to replicate the observed atmospheric behaviour on a wide range of spatial and time scales provides support in applying these models to the greenhouse gas-induced climate change projections on regional scales. A series of long time-slice control experiments have been performed recently with the ECHAM3 atmospheric general circulation model at T21, T42 and T106 horizontal resolutions (30 years each with T21 and T42 and 5 years with T106). All these model experiments use a common sea-surface temperature climatology in their control experiment inferred from a coupled ocean–atmosphere climate model (ECHAM1 + LSG) experiment. In this paper, we examine the ability of the ECHAM3 model to simulate the Indian monsoon climatology at these three different horizontal resolutions. Because the Indian summer monsoon circulation evolves through a characteristic sequence of events, it is important that the climate models should be able to realistically portray these important features of the circulation over adequate spatial and time scales.

We focus on the model's simulation of selected variables representative of the thermal, dynamic and hydrological components in zonal mean cross-sections and area-averaged monthly as well as seasonal regional distributions. Generally, with respect to large-scale features of the circulation, the largest differences among the simulations occur at T42 relative to T21. At both T21 and T42 horizontal resolution, however, the model does not have a high degree of correspondence with observations as regards the spatial distribution of mean sea-level pressure, surface air temperature, 850 hPa winds and precipitation. On regional scales, T106 resolution best captures both the spatial and temporal characteristics of the Indian climatology. Both the diurnal and seasonal cycles of area-averaged surface air temperature over the region simulated by the model at T106 resolution are within 1 to 2°C as compared with observed climatology. The development and migration of the monsoon trough over Central India and the adjoining Bay of Bengal during the monsoon season is best simulated at T106 resolution. There is a distinct improvement in the spatial distribution as well as the total area-averaged summer monsoon rainfall in the model simulations with finer resolution. Although the modelled and observed mean summer precipitation is similar in overall structure at T106 resolution, underestimation of the total seasonal rainfall in the model even at high resolution is a reflection of the sensitivity of simulated precipitation to local climate forcings, e.g. tropical convergence zone, and deficiencies of parameterization schemes for convection and land surface processes. © 1997 by the Royal Meteorological Society. *Int. J. Climatol*., 17: 847–858 (1977)

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KEY WORDS: global climate models; ECHAM3 model; regional climates; Indian climatology; horizontal resolution; Indian monsoon.

1. INTRODUCTION

The Asian summer monsoon constitutes the most spectacular manifestation of regional anomalies in the general circulation of the atmosphere resulting from land–sea thermal contrasts and orographic features. Regional peculiarities assume a dominant role with respect to the monsoonal features over India and its neighbourhood. The thermal structure of the adjoining sea areas — the Arabian Sea, the Bay of Bengal and the south Indian Ocean — and its temporal variations appear to have a modulating influence on the monsoon circulation. Because

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a major improvement in the high-resolution models is the more detailed topography, we may expect significant differences between model simulations at varying horizontal resolution over the Indian subcontinent, where atmospheric flow is predominantly influenced by the topographic features of the Western Ghats and Himalayas. The summer monsoon circulation over the Indian subcontinent becomes established towards the end of May and continues till the end of September. It accounts for over 70 per cent of the annual rainfall over most of India. Simulation of the Indian summer monsoon is of particular interest in climate models because the Tibetan Plateau strongly influences the patterns of monsoon rainfall. Much of the monsoon rainfall over the central plains of India is associated with the low pressure vortices that develop over the head of the Bay of Bengal and move on to the subcontinent along a north-westerly track. It still remains a challenging task to realistically simulate these low pressure vortices and associated interannual and intraseasonal variability in monsoon rainfall in many climate models. This also limits our confidence in scenarios for climate change over the region likely to be expected due to enhanced greenhouse effect.

Considerable improvement in the ability of climate models to simulate the present-day climate on regional scales seems to have taken place in recent years with the introduction of finer horizontal resolution and improved parameterization of physical processes. The general conclusion has been that T42 resolution is adequate for the simulation of large-scale climatological features (Williamson *et al*., 1994). Because orographic features of the Indian subcontinent are more precisely resolved at T106 than at either T42 or T21 horizontal resolution, we may expect significant differences in the simulated climatological fields on temporal and spatial scales here. Only two studies on the sensitivity of model resolution to simulation of monsoon circulation are reported in the literature to date. Tibaldi *et al*. (1990) suggested that although large-scale features of monsoon rainfall were not improved significantly at resolutions higher than T42, T106 simulations produced thc small-scale features of rainfall distribution better. Sperber *et al*. (1994) demonstrated that the European Centre for Medium Range Weather Forecasts (ECMWF) model exhibited distinct improvement in simulating the spatial and temporal distribution of rainfall during the East Asian summer monsoon at higher resolutions. Both these studies were based on only one annual cycle model integrations (except that T42 simulation in Sperber *et al*., 1994 was extended to two annual cycles) and therefore may not truly represent the mean regional climate. Recently, a series of long time-slice control experiments (Perlwitz *et al*., 1993) have been carried out at the Max-Planck Institute for Meteorology (MPIM), Germany using the ECHAM (version 3) climate model at T21, T42 and T106 horizontal resolutions (30 years each at T21 and T42 and 5 years at T106 resolution). All these model experiments use a common sea-surface temperature (SST) climatology in their control experiment. In this paper, we examine the sensitivity of the ECHAM climate model in its ability to simulate the Indian monsoon climatology in its control experiment at the three horizontal resolutions selected.

2. THE MODEL

The present study is based on the analysis of data generated in numerical experiments performed with the so-called ECHAM3 model. This model is the third generation general circulation model (GCM) used for global climate modelling investigations in Germany. The prognostic variables include vorticity, divergence, temperature, log surface pressure, water vapour and cloud water. The model has 19 layers in the vertical hybrid coordinate system. The integration is performed following a semi-implicit scheme with leap frog time filter at a 40 m time interval for T21, at a 24 m interval for T42 and at a 12 m interval for T106 resolution. The global scale performance of the ECHAM3 model has been discussed in Arpe *et al*. (1994).

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

In the next section, we shall briefly describe the numerical experiments performed with the ECHAM3 model and specify the region for which detailed data analysis has been conducted. Our findings on the model's performance in simulating the Indian monsoon climatology at varying resolution will be presented in section 4.

3. THE EXPERIMENT, REGION OF INTEREST AND DATA ANALYSIS

The findings reported in this paper are based on the data generated by the ECHAM3 global climate model described above in numerical simulations in time-slice mode for 30 years each of control experiment at T21 (5·625° latitude/longitude) and T42 (2·812° latitude/longitude) resolutions and for 5 years of control experiment at T106 (1·125° latitude/longitude) resolution. The time-slice method has the advantage that the atmospheric model alone can be integrated for several decades around the time of interest at higher resolution with a credible distribution of sea-surface temperatures to give a large statistical sample of simulated climate. The climatological sea-surface temperatures (averaged for the period 1979–1988) were prescribed as the boundary condition for simulation of the present-day climate.

The geographical region of interest for our data analysis reported herein was confined mainly to the region bounded by 5°N to 30°N latitude and 65°E to 95°E longitude. The total numbers of model grid-points for this region were 30 (19 land points), 110 (46 land points) and 672 (318 land points) at T21, T42 and T106 resolutions. Figure 1 depicts the representation of orography at three model resolutions over the region of interest. It can be seen that orientation of Western Ghats as well as the spatial structure of the Himalayas is best resolved at T106 resolution. Various diagnostics have been performed on the data in order to examine the skill of the model in simulating the monsoon climatology at the three horizontal resolutions. These include calculation of pattern correlation coefficients and root-mean-square errors between the observed climatology and those simulated by the model at different resolutions for two time periods (winter and monsoon seasons) over the region of interest. The calculations involve interpolation of the observed and model-simulated data to a common T106 grid specification with a cubic spline fit (a weighting function is used to compensate for the equator to pole shrinking effect). The annual cycle of monthly mean climatology (land point area-averaged) simulated by the model is also compared with the observed climatology. The key climatic elements considered in this study include mean sea-level pressure, surface air temperature, diurnal temperature range, surface and upper air winds and precipitation. The observed mean sea-level pressure climatology used is based on the data sets for the period 1985–1990 analysed and compiled by the European Centre for Medium Range Weather Forecasts, UK (ECMWF, 1993). The observed surface air temperature and precipitation climatology is based on the data sets compiled by Legates and Willmott (1990a,b). In the next section, we shall discuss on the salient features of the performance of the ECHAM3 climate model in simulating the Indian monsoon circulation at different horizontal resolutions based on the findings from our data analysis.

4. RESULTS AND DISCUSSION

4.1. Mean sea-level pressure

During winter (December–February), the sea-level pressure increases from south to north across the Indian subcontinent; the reverse conditions prevail during the monsoon season (June–September). The observed south–north increase of pressure over the region during winter is about 6 hPa (Rao, 1976). The model simulates the south–north increase of sea-level pressure over the region during winter close to 12, 10 and 7 hPa at T21, T42 and T106 resolutions, respectively. A comparison of the spatial distribution of mean sea-level pressure during the monsoon season simulated by the model at various resolutions is depicted in Figure 2. It is seen from Figure 2 that the south–north decreases across the Indian subcontinent in mean sea-level pressure during monsoon season simulated by the model at T21, T42 and T106 resolutions are 6, 9 and 12 hPa respectively. The corresponding south–north decrease of mean sea-level pressure in observed climatology is reported to be about 12 hPa (Rao, 1976). During monsoon season the orientation of the monsoon trough (a quasi-stationary low pressure zone) over

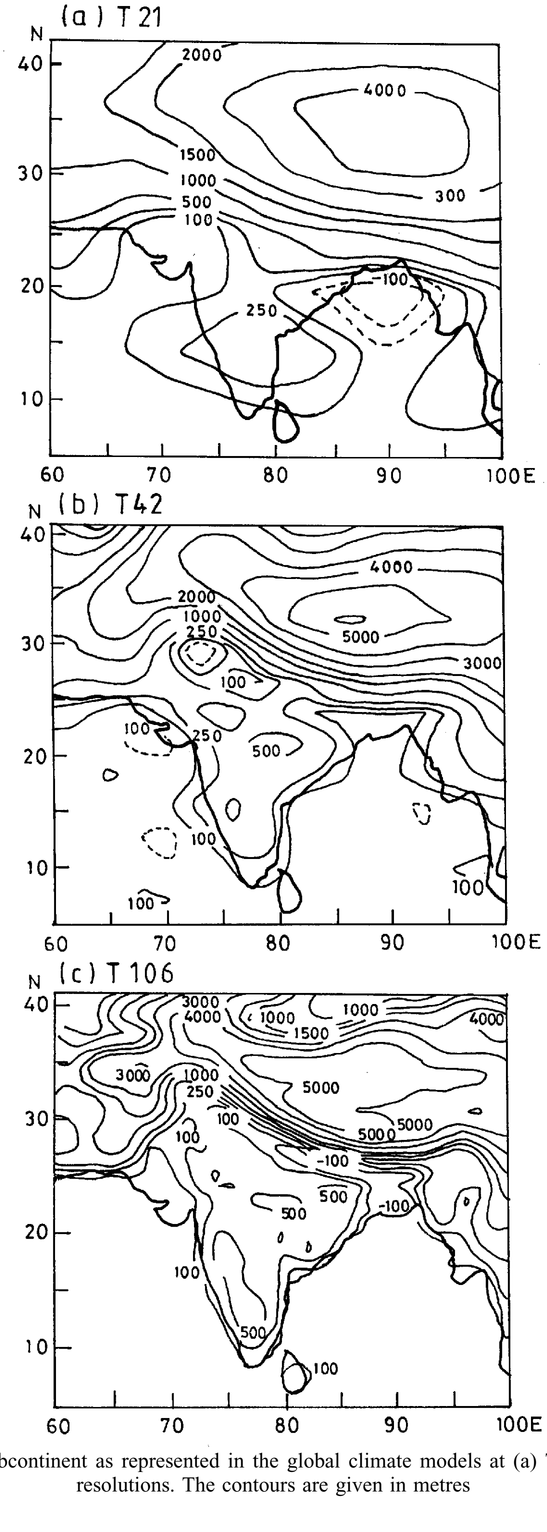

Figure 1. Orography of the Indian subcontinent as represented in the global climate models at (a) T21, (b) T42 and (c) T106 horizontal resolutions. The contours are given in metres

the plains of north India is simulated close to that observed at T42 as well as T106 resolution. However, its development as well as migration is resolved more realistically only at T106 resolution. The eastern edge of the simulated monsoon trough is shifted southward of the observed position at T21 resolution. In terms of spatial distribution of mean sea-level pressure, the pattern correlation coefficient between the observed and model-simulated sea level pressures increases with higher resolution, suggesting improvement in the simulation at T106

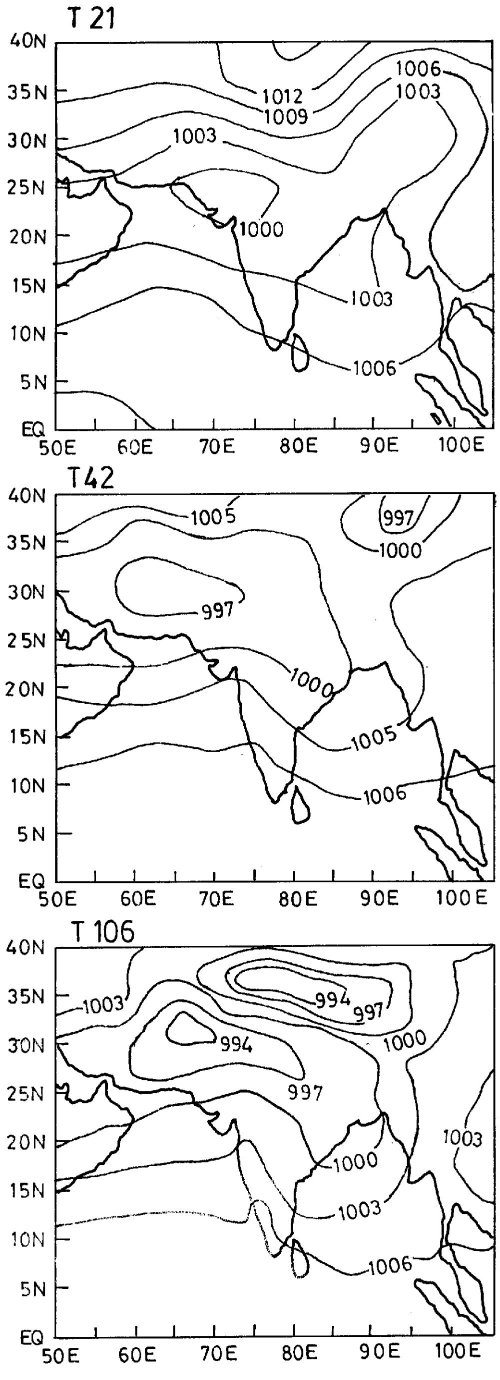

Figure 2. Mean sea-level pressure (in hPa) pattern over the Indian subcontinent during the monsoon season as simulated by the model at (a) T21, (b) T42 and (c) T106 horizontal resolutions

Table I. The pattern correlation and root-mean-square (RMS) statistics between observed[a] and model-simulated mean sea-level pressure (*P*), surface air temperature (*T*) and rainfall (*R*) over the Indian subcontinent (*ca.* 5°N–35°N, 65°E–95°E) during winter and monsoon seasons

Models	Pattern correlation coefficient						RMS error					
	Winter			Monsoon			Winter			Monsoon		
	P	*T*	*R*	*P*	*T*	*R*	*P*	*T*	*R*	*P*	*T*	*R*
[b]ECHAM3 (T21)	0·41	0·63	0·51	0·32	0·40	0·37	5·23	7·98	3·62	7·54	6·88	6·13
[b]ECHAM3 (T42)	0·59	0·85	0·72	0·41	0·67	0·59	3·96	6·83	2·87	4·68	3·93	5·82
[b]ECHAM3 (T106)	0·61	0·84	0·75	0·63	0·79	0·61	2·87	6·14	2·76	4·81	3·81	5·87

[a]ECMWF climatology for mean sea-level pressure (hPa), and Legates and Willmott's climatology for surface air temperature (°C) and rainfall (mm day^{-1}).
[b]Interpolated to T106 common grid prior to applying statistics.

resolution during both the winter and the monsoon seasons (see Table I). It is thus clear that although the climate model is capable of reproducing the seasonal reversal in mean sea-level pressure at all resolutions, the precise magnitude of the pressure gradient across the Indian subcontinent as well as the spatial distribution of mean sea-level pressure during both the winter and the monsoon seasons is best simulated at T106 resolution.

4.2. Surface air temperature

Over thc Indian subcontinent, the amplitude of the annual cycle in surface air temperature is much greater over the land than over the adjoining oceans. This results in seasonal reversal of the land–ocean temperature gradient. In winter, the Indian subcontinent is colder than the Indian Ocean and adjoining seas to the south; during the monsoon, however, the reverse is true. The reversal of the meridonal surface air temperature gradient across India from winter to summer progresses from south to north (Rao, 1976). This feature has been simulated realistically by the climate model at all the three horizontal resolutions considered in the study. Figure 3 depicts the annual cycle of area-averaged monthly mean surface air temperatures for the region as observed (based on Legates and Willmott's climatology) and those simulated by the model at T21, T42 and T106 resolutions. It is seen that the largest differences (ca. 4°C) occur in the model-simulated surface air temperatures during December and January at different resolution. As the resolution increases, the model-simulated surface air temperatures approach closer to observed climatology. In general, the area-averaged monthly mean surface air temperatures over the Indian subcontinent simulated by the model are best simulated at T106 resolution. The diurnal range of area-averaged monthly mean surface air temperatures over the region simulated by the model at T106 resolution are within 1 to 2°C as compared with observed (Rupakumar *et al.*, 1994) climatology (Figure 4). The model simulation at T106 resolution is also able to reproduce the observed spatial distribution of surface air temperatures both on annual mean basis as well as for seasonal means. At both T21 and T42 horizontal resolution, however, the model simulation does not have a high degree of correspondence with the spatial distribution of observed surface air temperatures over the region. Significant differences occur between the observed annual mean surface air temperature pattern and those simulated by the model at T21 and T42 resolutions (Figure 5). It may be noted here that there exists a reasonable doubt in observed climatology over the north and north-east India as observations are extremely scanty from higher elevations in Himalayas. The correlation coefficients between the observed and model-simulated surface air temperature spatial patterns show considerable improvement with the increase in horizontal resolution both during winter and monsoon seasons (Table I). The largest differences among the simulations occur at T42 relative to T21 in the spatial distribution of surface air temperature. At all the three model resolutions, correlation coefficients (but also the RMS errors) between the observed and model-simulated surface air temperature spatial patterns are higher during the winter than during the monsoon season.

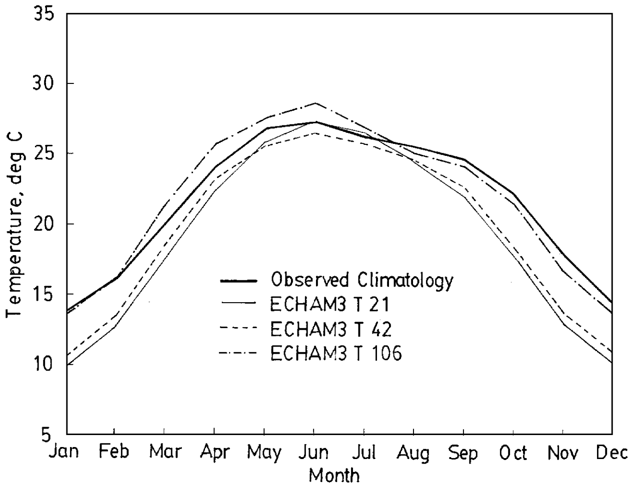

Figure 3. Area-averaged monthly mean observed (Legates and Willmott, 1990a) and model-simulated (at T21,T42 and T106 resolutions; land points only) surface air temperatures over the Indian subcontinent

4.3. Winds

During winter, the general flow of surface air over the Indian subcontinent is from north to south; north to north-west over the central plains and north-east over the Peninsular India and neighbouring seas. The air over much of the subcontinent during this season is of continental origin. At higher levels, westerly winds prevail over the subcontinent, which attain a core speed of over 30 m s^{-1} at about 150 hPa level over north India. During the monsoon season, the general flow of air over the region is reversed. The direction of winds over the Arabian Sea, Bay of Bengal and south Peninsular India is south-westerly during this season. Easterly winds prevail over much of the northern parts of India. A trough of low pressure is established over north India between westerlies to the south and easterlies to the north by the end of June and persists throughout the monsoon season. Westerly winds over Peninsular India increase with height from the surface and attain a maximum speed of about 10 m s^{-1} between 900 and 800 hPa (Rao, 1976). The reversal of surface winds with the season is simulated realistically in the ECHAM3 model at all the three resolutions. The low-level cross-equatorial flow and the Somali jet that characterize the monsoon circulation are also present in the model simulations. However, the location of Somali jet is displaced northward by about 2° latitude in the model simulation and the core speeds are weaker (12–15 m

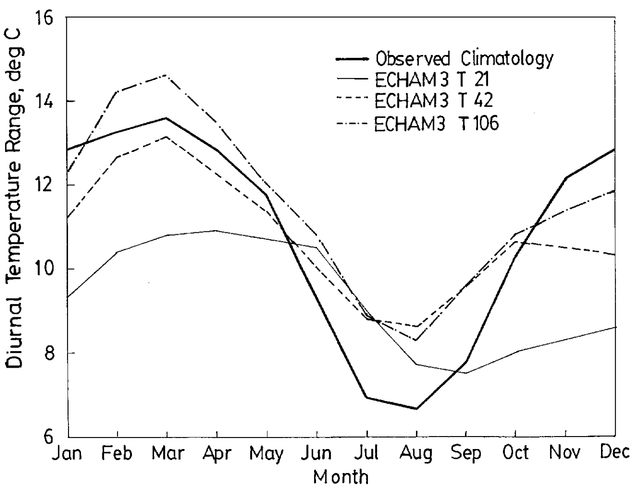

Figure 4. Area-averaged monthly mean observed (Rupakumar *et al.*, 1994) and model-simulated (at T21, T42 and T106 resolutions; land points only) diurnal ranges of surface air temperature over the Indian subcontinent

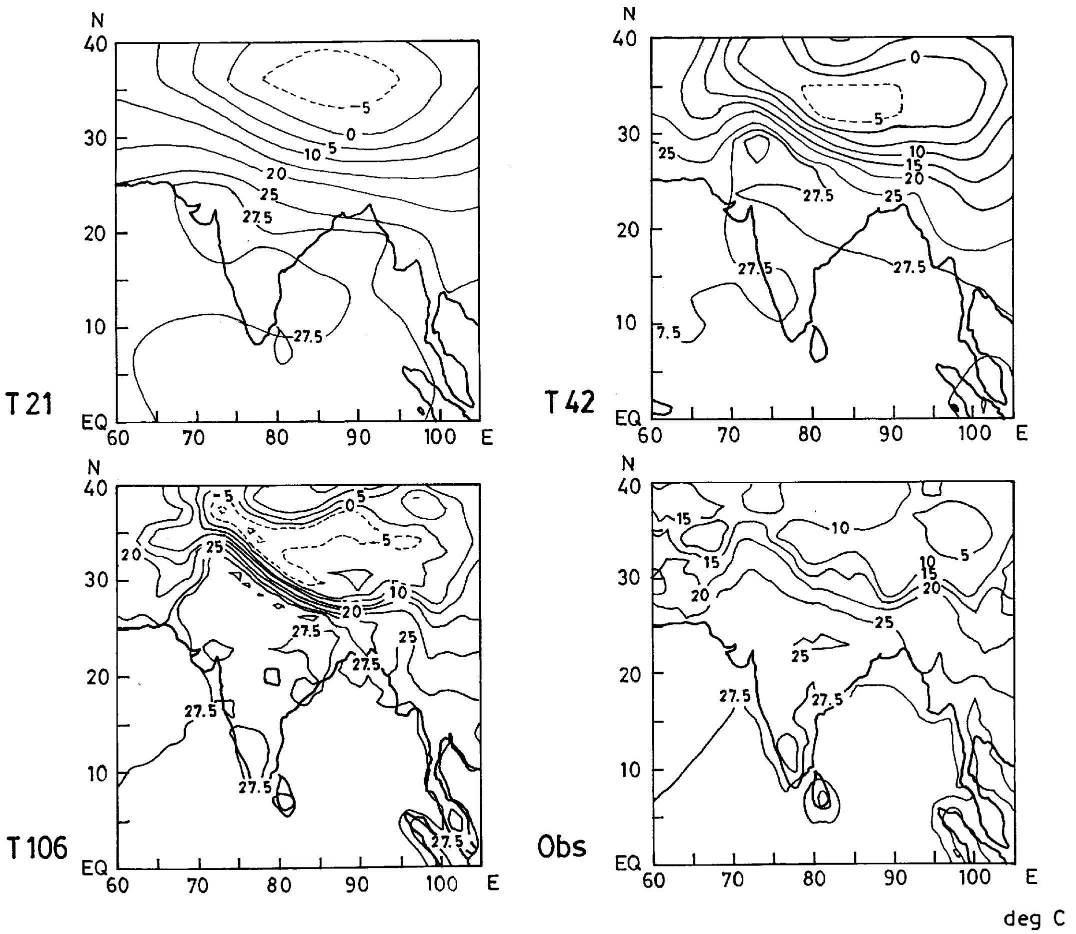

Figure 5. Spatial distribution of annual mean surface air temperatures over the Indian subcontinent as simulated by the model at T21, T42 and T106 resolutions and as represented in the observed (Legates and Willmott, 1990a) climatology

s^{-1} as against 15–18 m s^{-1} at T106 resolution) at T21 and T42 resolutions. The onshore low-level flow along the north-west coastline of India is also strong, whereas over the south-west coast the flow is rather weak. In addition, the simulated surface winds over central Indian Ocean are stronger than observed climatology at T42 and T106 resolutions. Whereas the simulated low-level westerly winds over Peninsular India during the monsoon are close to the observed climatology at T106 resolution, they are stronger at T21 and weaker at T42 (Figure 6). As is observed, these low-level westerlies decrease with height between 800 and 500 hPa levels. Above 300 hPa, easterly winds strengthen with height, reaching a maximum at about 100 hPa level over Peninsular India. This reversal of moderately strong westerlies of the lower troposphere to strong easterlies in the upper troposphere is due to southward decrease of temperature in the troposphere. Although the observed features of the disappearance of upper tropospheric westerlies over Peninsular India during the monsoon and shift of the westerly jet to the north of the Himalayas are simulated realistically by the model at all resolutions, the simulated peak easterly winds at 100 hPa to the south of 20°N are lower in magnitude relative to climatology even at T106 resolution.

4.4. Precipitation

During winter, rainfall over the region as a whole is only about 15 per cent of the annual, and is confined primarily to north of the Indian subcontinent and in the extreme south-east. About 70 per cent of the annual rainfall over the Indian subcontinent occurs during the monsoon season (June–September). The ECHAM3

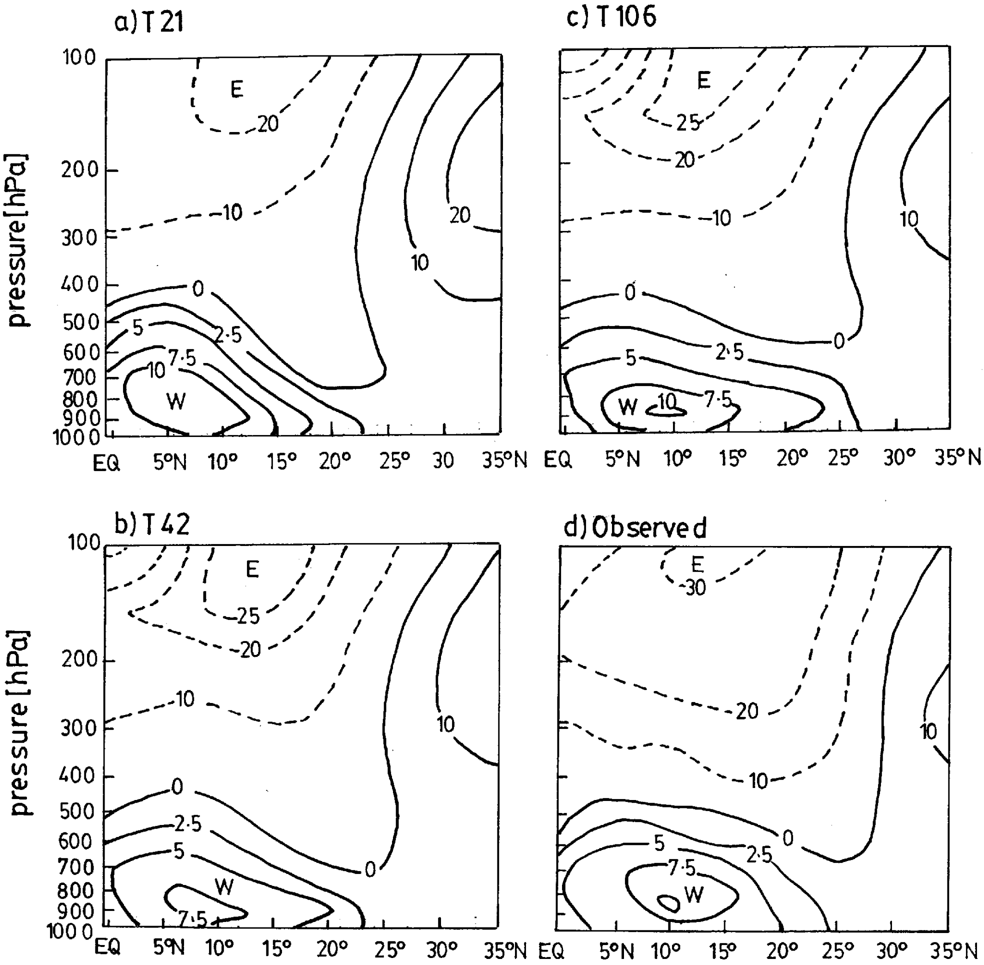

Figure 6. Vertical cross-sections of mean zonal winds (in m s^{-1}; E: easterly winds, W: westerly winds) for July averaged between 50° and 100°E as simulated by the model at (a) T21, (b) T42 and (c) T106 horizontal resolutions and (d) as observed (after Keshavamurty and Shankar Rao, 1992)

climate model faithfully reproduces the observed seasonality in rainfall over the region at all three resolutions. An examination of area-averaged daily rainfall over the Indian subcontinent between 1 May and 31 October reveals that the commencement (onset) and termination (withdrawal) of monsoon rainfall simulated by the model at T42 and T106 resolutions are in better agreement with observations. The simulated onset of summer monsoon rains over India is delayed by 3 weeks at T21 resolution. This is also reflected in the shifting of the peak in monthly mean rainfall averaged over the land regions of the subcontinent (Figure 7). Unlike in the T21 simulation, heavy rains, particularly along the west coast and over north-east India, are simulated during the pre-onset period of early May in the model at T42 and T106 resolutions. The cessation of modelled monsoon rain is rather abrupt at T42 resolution but gradual at both T21 and T106 resolutions. During the active monsoon period, a series of low-pressure vortices form over north Bay of Bengal and move north-westward along the monsoon trough. These low-pressure vortices are responsible for much of the rain over the central plains of India. The model is not able to resolve these vortices at the coarser T21 resolution. At T42 resolution, even though these vortices are identified in 850 hPa wind and vorticity fields, their development, intensity and movement is not clearly discernable. The model simulates the structure, intensity, frequency, movement and lifetime of these vortices quite realistically at T106 resolution (discussed in more detail in Lal *et al.*, 1995). There is distinct improvement in the spatial distribution as well as the total area-averaged summer monsoon rainfall in the model

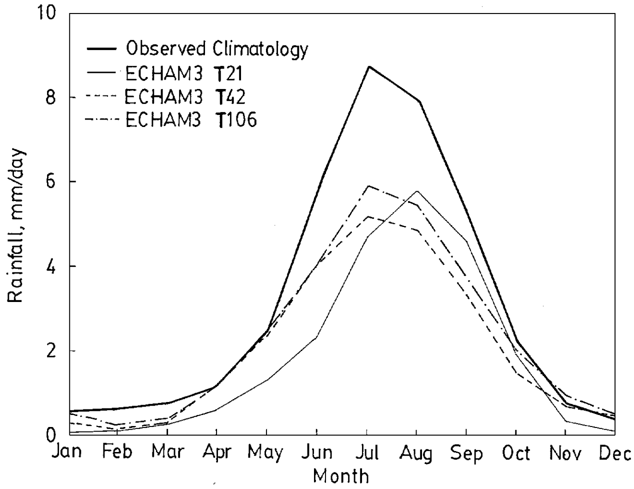

Figure 7. Area-averaged monthly mean observed (Legates and Willmott, 1990b) and model-simulated (at T21, T42 and T106 resolutions; land points only) rainfall over the Indian subcontinent

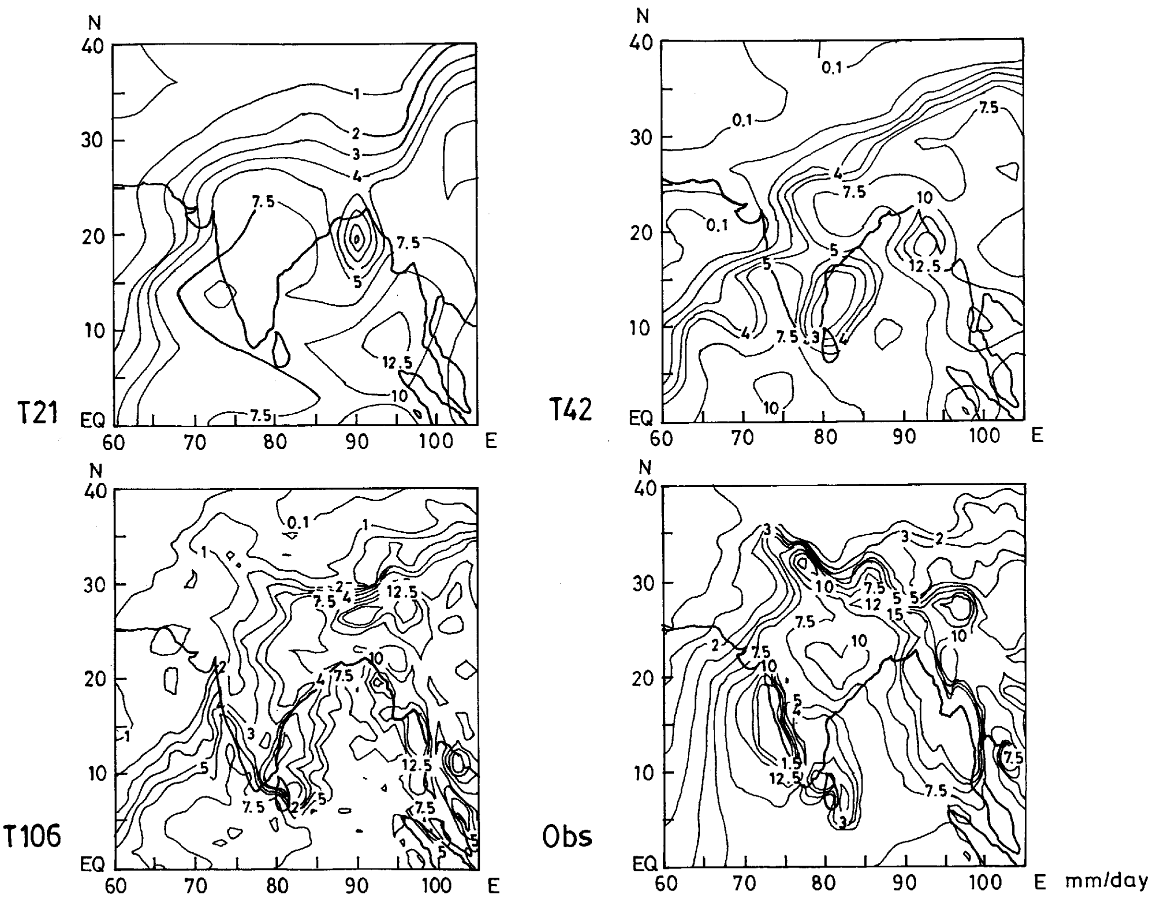

Figure 8. Spatial distribution of monsoon rainfall over the Indian subcontinent as simulated by the model at T21, T42 and T106 resolutions and as represented in thc observed (Legates and Willmott, 1990b) climatology

simulations with finer resolution (Table I). As is observed, a steep gradient in monsoon rainfall from the west coast towards the east (a rain-shadow effect on the lee side of the Western Ghats) is simulated best at T106 resolution (Figure 8). However, the model-simulated average monsoon rainfall over the land area is only 69, 63 and 72 cm at T21, T42 and T106 resolutions respectively, against the observed climatological rainfall of 85 cms. Although the modelled mean summer precipitation is quite realistic in its spatial distribution at T106 resolution, the model underestimates the total seasonal rainfall in the model even at high resolution.

5. CONCLUSION

The study suggests that climate model simulation at T106 resolution is superior in realistically portraying both the spatial and temporal characteristics of the Indian climatology. Both the diurnal and seasonal cycles of area-averaged surface air temperature over the region simulated by the model at T106 resolution are within 1 to 2°C as compared with observed climatology. The development and migration of the monsoon trough over Central India and the adjoining Bay of Bengal during the monsoon season is simulated realistically only at T106 resolution. Moreover, there is distinct improvement in the spatial distribution as well as the total area-averaged summer monsoon rainfall in the model simulations with finer resolution. Although the modelled and observed mean summer precipitation is similar in overall structure at T106 resolution, underestimation of the total seasonal rainfall in the model even at high resolution is a reflection of the sensitivity of simulated precipitation to local climate forcings, as also the deficiencies of parameterization schemes for convection and land surface processes.

Current climate models are highly sensitive to treatment of clouds, hydrological cycle and land surface processes, and there are not yet satisfactory means for evaluating the correctness of such treatments. The parameterization of subgrid-scale physical processes such as convection, boundary layer mixing and surface fluxes needs to be reformulated to more adequately represent their interaction with increasing horizontal resolution for accurate portrayal of regional climates. Further improvements in the parameterization of penetrative cumulus convection and the regional moisture convergence on which the tropical precipitation is critically dependent should increase the model's ability to produce more realistically the observed monsoon rainfall on desired spatial and temporal scales. The acquisition of new long-term observational data sets under GEWEX from *in situ* and satellite sources for distribution of radiation, cloudiness, water vapour, precipitation and land surface properties should be useful in better overall evaluation of both model parameterizations and performance.

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