Implications of increasing greenhouse gases and aerosols on the diurnal temperature cycle of the Indian subcontinent

M. Lal *, G. Srinivasan and U. Cubasch†**

*Centre for Atmospheric Sciences, Indian Institute of Technology, New Delhi 110 016, India
**India Meteorological Department, New Delhi 110 003, India
†Deutsches Klimarechenzentrum GmbH, D-20146 Hamburg, Germany

The response to transient increase of greenhouse gases and sulphate aerosols in the Earth's atmosphere on the diurnal temperature cycle over the Indian subcontinent is examined using the data generated in coupled atmosphere–ocean model experiments. The spatial distribution of changes in seasonal mean maximum and minimum temperatures over the Indian subcontinent as simulated in combined greenhouse gas and sulphate aerosol forcing experiment for the decade 1980–89 with respect to the control climate of decade 1880–89 is found to be in fair agreement with observations. An increase in annual mean maximum and minimum surface air temperatures of 0.7 and 1.0°C respectively is projected over the land regions of the Indian subcontinent in the decade 2040s with respect to 1980s. The projected rise in maximum temperature is found to be most pronounced during the monsoon season while the rise in minimum temperature has its peak during the post-monsoon months over the region. A significant decrease in the diurnal temperature range over the Indian subcontinent during winter and no appreciable change during the monsoon season is suggested for the future.

ONE important aspect of the observed temperature change relates to its asymmetry during the day and night. Observed warming in surface air temperatures over several regions of the globe have been reported to be associated with increase in minimum temperatures (accompanied by increasing cloudiness) and decrease in diurnal temperature range[1–3]. General circulation model simulations with increasing concentrations of CO_2 in the atmosphere have also shown pronounced increase in minimum temperatures and decrease in diurnal temperature range[4,5]. The Indian region provides an interesting case in that while the observed mean surface air temperatures over India have been reported to exhibit a warming trend close to the global and hemispheric trends[6], an increase in diurnal temperature range accompanied with increasing maximum temperatures and relatively steady minimum temperatures have been reported over many parts of India[7]. In a study, Hansen *et al.*[8] reported that the observed changes of the diurnal cycle result from a combination of local negative forcing due to sulphate aerosols over continental regions and globally-distributed positive forcing due to greenhouse gases. Model simulations of diurnal temperature range are also sensitive to parameterization of physical processes as changes in diurnal temperature range could result from changes in atmospheric water vapour, cloud optical properties, cloud cover and land surface properties. We examine here the influence of sulphate aerosols on the simulation of maximum and minimum temperatures over the Indian subcontinent using the data from a series of recent coupled climate model experiments (performed at Deutsches Klimarechenzentrum, Germany with greenhouse gas forcings as well as combined greenhouse gas and sulphate aerosol forcings). Lal *et al.*[9] have demonstrated that the model experiment with combined greenhouse gas and sulphate aerosol forcings replicates the observed changes in surface air temperatures over the Indian subcontinent during the past century.

We discuss here the salient findings of our analysis on a comparison of area-averaged (land regions only) observed and model-simulated trends in maximum and minimum surface air temperatures and diurnal temperature range over the Indian subcontinent for the period from 1880s till 1980s. A comparison of regional trends in maximum and minimum temperatures as simulated by the model and those observed over the past century provides a potentially stringent test of the model's credibility. A comparison of the spatial distribution of observed and model-simulated changes in maximum and minimum temperatures over the region is made. A plausible future scenario of changes in maximum and minimum temperatures and diurnal temperature range for the Indian subcontinent is also presented here.

The model experiments and region of interest

The present study is based on analysis of data generated in numerical experiments performed with the *E*uropean *C*ommunity *HAM*burg. (ECHAM version 3) atmospheric model coupled to a *L*arge *S*cale *G*eostrophic ocean model (hereafter referred to as ECHAM3+LSG model) at T-21 resolution. ECHAM3 is the third generation atmospheric general circulation model used for global climate modelling investigations in Germany. The LSG ocean model is based on a numerical formulation of the primitive equations appropriate for large-scale geostrophic motion. The ECHAM3 and LSG are coupled by the air–sea fluxes of momentum, sensible and latent heat, short and long wave radiation and fresh water[10]. For further details on the model, the reader is referred to Lal *et al.*[9], Maier-Reimer *et al.*[11] and DKRZ[12].

In the first experiment (hereafter referred to as C), the control reference atmosphere has been simulated with the coupled climate model over a 170 year period (1880–2049) with constant levels of atmospheric CO_2 concentration and no anthropogenic sulphur emissions. The second experiment (hereafter referred to as G) included the observed changes in atmospheric equivalent CO_2 (CO_2 and other greenhouse gases) concentrations for the period 1880–1989 and the projected increase (based on *Business-as-usual* scenario of IPCC[13] and representing a ~1.3% per year compound increase of CO_2) in equivalent CO_2 concentrations for the period 1990–2049. In the third experiment (hereafter referred to as S), the effects of both the greenhouse gases (equivalent CO_2) as well as the sulphate aerosols were considered. The anthropogenic sulphate burden information was obtained from Langner and Rodhe's calculations[14] and the direct radiative forcing was mimicked by a change of the surface albedo following the algorithm developed by Charlson *et al.*[15] The global mean sulphate forcing increased continuously since 1880s, and more rapidly from 1950 onwards. The spatial distribution of sulphate loading for the present-day atmosphere and that expected by the middle of next century over the Indian subcontinent are given in Lal *et al.*[9]

The geographic region of interest for our data analysis reported herein was mainly confined to the region bounded by ~5°N to 30°N latitude and ~65°E to 95°E longitude (Indian subcontinent and adjoining seas). It may be noted that, in spite of the fact that the horizontal resolution in the ECHAM3+LSG model experiments stated above is rather coarse (5.625° latitude × 5.625° longitude), the model has demonstrated[9] reasonable skill in simulating the monsoon circulation and the seasonal cycle of observed climatology for the region.

Comparison of past observed and simulated regional diurnal temperature cycle

Observed and model-simulated trends in maximum and minimum temperatures

Analysis of the recent simulated global and Northern Hemispheric mean near-surface temperatures has proved that an anthropogenic climate change signal in observed records of near-surface air temperature change can be detected at 95% confidence level[16]. The study also suggests that model-simulated past trends in global mean surface warming can be reconciled with the observed warming trends only when the cooling effect of aerosols on climate is accounted for. In order to place a high degree of confidence in future climate change, climate models must replicate the past trends in key climate elements within the limits of natural variability. In this respect, the year-to-year variability in model-simulated surface air temperature and monsoon rainfall over the Indian subcontinent has been found to be in fair agreement with the observed climatology[9].

Figure 1 depicts the 5-year running mean anomalies in area-averaged maximum and minimum surface air temperatures as observed[7] for the period from 1901 to 1994 and as simulated by the model for the period 1880–2049 in experiments G and S for the Indian subcontinent (land points only). The observed series[7] is based on spatial means of 121 stations over India while the model simulated data series is based on the spatial average of 19 land points only. On regional scales, the higher level of year to year variability obscures any systematic differences in maximum and minimum surface air temperatures simulated in experiments G and S in the first half of this century. All India mean annual maximum temperature, has a significant trend of 0.6°C/100yr in observational records while the minimum temperature is found practically trendless[7]. Both the annual mean maximum and minimum temperature anomalies in experiment G show a much higher increasing trend (0.85°C/100yr in maximum temperature and 0.84°C/100yr in minimum temperature respectively) than observed in the past century. In experiment S, the annual mean maximum temperature anomalies exhibit an increasing trend of 0.61°C during the past century which is in excellent agreement with observed trends. The annual mean minimum temperature anomalies have an increasing trend of 0.18°C during the past century in experiment S. Moreover, both the maximum and minimum temperature anomalies simulated by the model in experiment S are found to be closer to the observed anomalies in the recent years, thus signifying the importance of aerosol forcing (Figure 1). The interannual variability generated by the model is found to be rather large in a statistical sense as compared to that

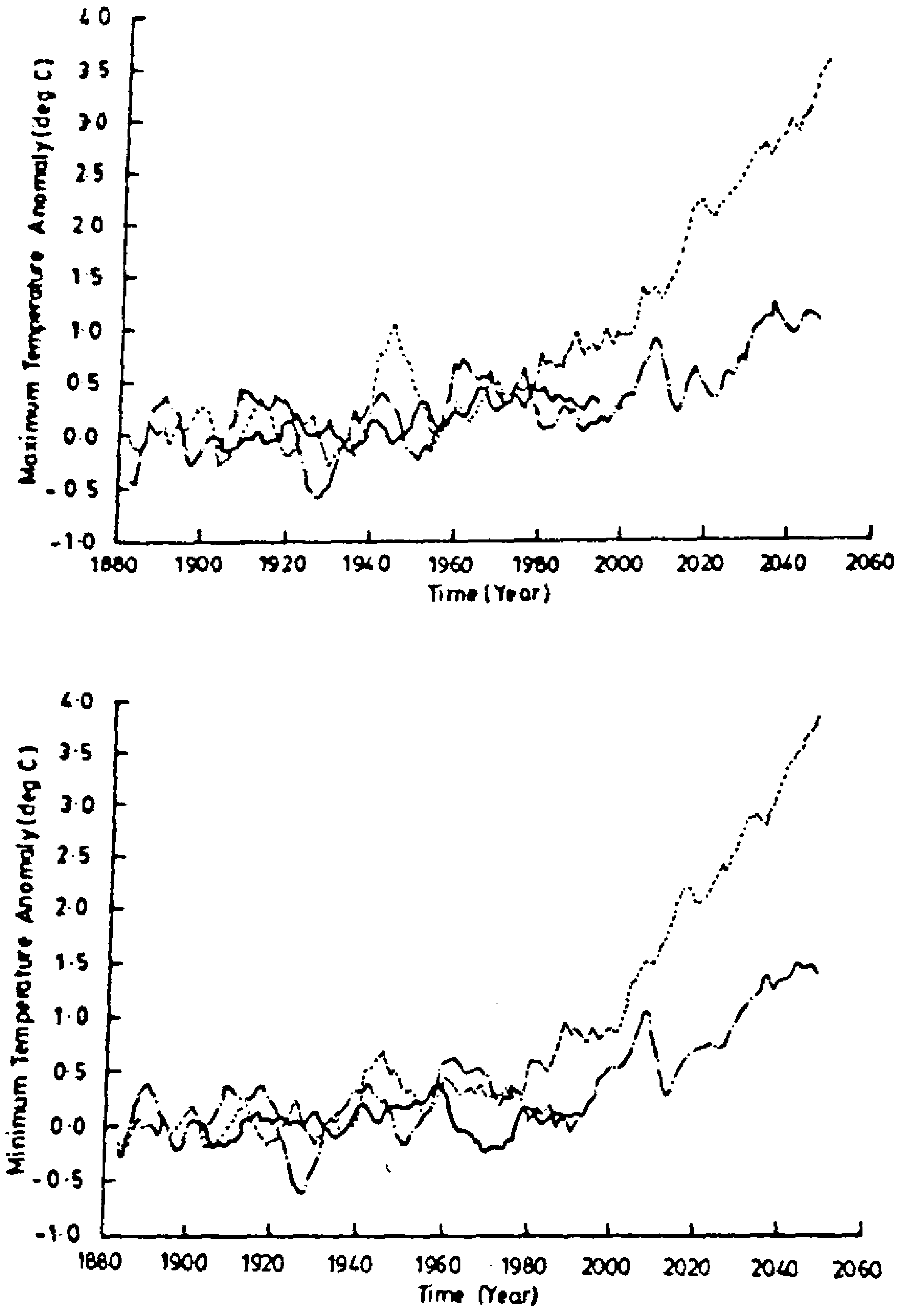

Figure 1. Observed (1901–1994) and model-simulated (1880-2049) trends in area-averaged anomalies in annual mean maximum (upper) and minimum (lower) surface temperatures (5 year running means, land regions only; °C) over the Indian subcontinent. (Solid thick line is for observed anomalies; solid thin line is for anomalies simulated in CO_2 + aerosol experiment and dotted line is for CO_2 only experiment.)

observed over the region even though we recognize that these climate model simulations do not attempt to precisely simulate individual years.

Table 1 gives the mean annual and seasonal (winter and monsoon) changes in area-averaged maximum and minimum surface air temperatures in the decade 1980–89 with respect to the decade 1880–89 over the Indian subcontinent as simulated in the experiments G and S and the observed[7] linear trends per 100 year period. While the diurnal temperature range over the region simulated by the model in experiment G is found to decrease (during winter) or remain unchanged (during monsoon) in the past century, it has increased on seasonal as well as on annual mean basis in experiment S which is in agreement with observations (but unlike the observed and/or simulated trends over many parts of the globe).

Two important points emerge from Table 1. The first is that the minimum temperature changes simulated by the model in a season or on annual mean basis in the greenhouse gas forcing only experiment are significantly higher when compared to the observed changes over the past century over the Indian subcontinent. The increasing trends in maximum and minimum temperatures simulated in experiment S are lesser as compared to G due to negative forcing exerted by the introduction of sulphate aerosols. The combined greenhouse gas and sulphate aerosol forcing experiment is able to replicate the observed changes in maximum and minimum temperatures over the region in a broad sense on seasonal as well as on annual mean basis. The second point is that, while the differences in maximum temperatures simulated in experiments S and G are less pronounced, a relatively smaller increase in minimum temperature is simulated in experiment S as compared to G on seasonal as well as annual mean basis. This could have been induced by a reduction in high cloud amount as, in high clouds, an increase in albedo could be offset by a change in cloud infrared emissivity, leading to decrease in warming effect during the day and increase in cooling effect during the night[17]. This further suggests the possibility that the direct influence of sulphate aerosols (trapping of solar radiation) may not be as dominating as the indirect effect (through its influence on clouds). The general notion that an increase in cloud cover takes place due to industrial sulphur emissions[3] may not be valid over the monsoon region. The significant decline in the nighttime temperatures in experiment S is supported by a reduction of about 0.8% in area-averaged fractional cloud cover in the decade 1980s with respect to the control climate of 1880s over the monsoon region. Decreased cloud cover and consequent suppressed water vapour feedback in a relatively drier atmosphere should produce lower minimum temperatures. The precise modulating role of clouds in numerical models is, however, not yet fully understood. The results from experiment S are in conformity with the observations in that both exhibit an increase in diurnal temperature range accompanied with increasing maximum temperatures over the region.

Spatial distribution of observed and model-simulated changes in diurnal temperature cycle

A comparison of spatial patterns of observed and model-simulated (Experiment S) maximum and minimum temperatures and diurnal temperature range over the region of interest for the present-day atmosphere (1980s) suggests reasonable similarity between them during both winter and monsoon seasons (Figures 2 and 3). During winter, the simulated maximum temperatures are lower and simulated minimum tem-

Table 1. A comparison of model-simulated and observed linear trends (°C) per 100 years in area-averaged (land only) maximum and minimum surface temperatures over the Indian subcontinent (based on data from 1901 to 1990

Period	Experiment G		Experiment S		Observed	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
Annual	0.85	0.84	0.61	0.18	0.6	0.1
Winter (DJF)	0.86	0.97	0.78	0.29	0.9	0.2
Monsoon (JJAS)	0.83	0.83	0.37	0.08	0.4	− 0.3

peratures are higher than the observed climatology (Figure 2). Consequently, the simulated diurnal range is lower than the observed. A better agreement is found between the spatial patterns of observed and simulated magnitude of maximum and minimum temperatures during the monsoon season (Figure 3). The model due to its rather coarse resolution has not been able to realistically portray the observed locations of extremes in maximum or minimum temperatures. The scanty observations limit verification of the model simulations of the diurnal temperature cycle in the Himalayan region.

In order to quantify the similarity between the observed and model-simulated spatial distribution of maximum and minimum temperatures, we performed calculations of the pattern correlation coefficient and root mean square error between the observed and model-simulated climatology of maximum and minimum temperatures for winter and monsoon season over the region of interest. For this purpose, both the observed and model-simulated data were first interpolated on to a common 2.5° square grid configuration with a cubic spline fit. The pattern correlation coefficient gives a measure of similarity of the pattern structure of the observed and simulated fields throughout the region whereas the root mean square error gives an overall measure of the absolute error in simulating the field over the region. During winter, the pattern correlation coefficient between the observed and simulated climatology is 0.61 for maximum temperature and 0.69 for minimum temperature. The root mean square error is 3.6°C for maximum temperature and 2.9°C for minimum temperature. During monsoon season, the correlation coefficients are 0.63 and 0.59 while the root mean square errors are 3.7°C and 4.1°C for maximum and minimum temperatures respectively. Keeping in view the fact that the spatial distribution of model-simulated temperatures considered here are based on only 19 land points as against the spatial distribution of observed climatol-

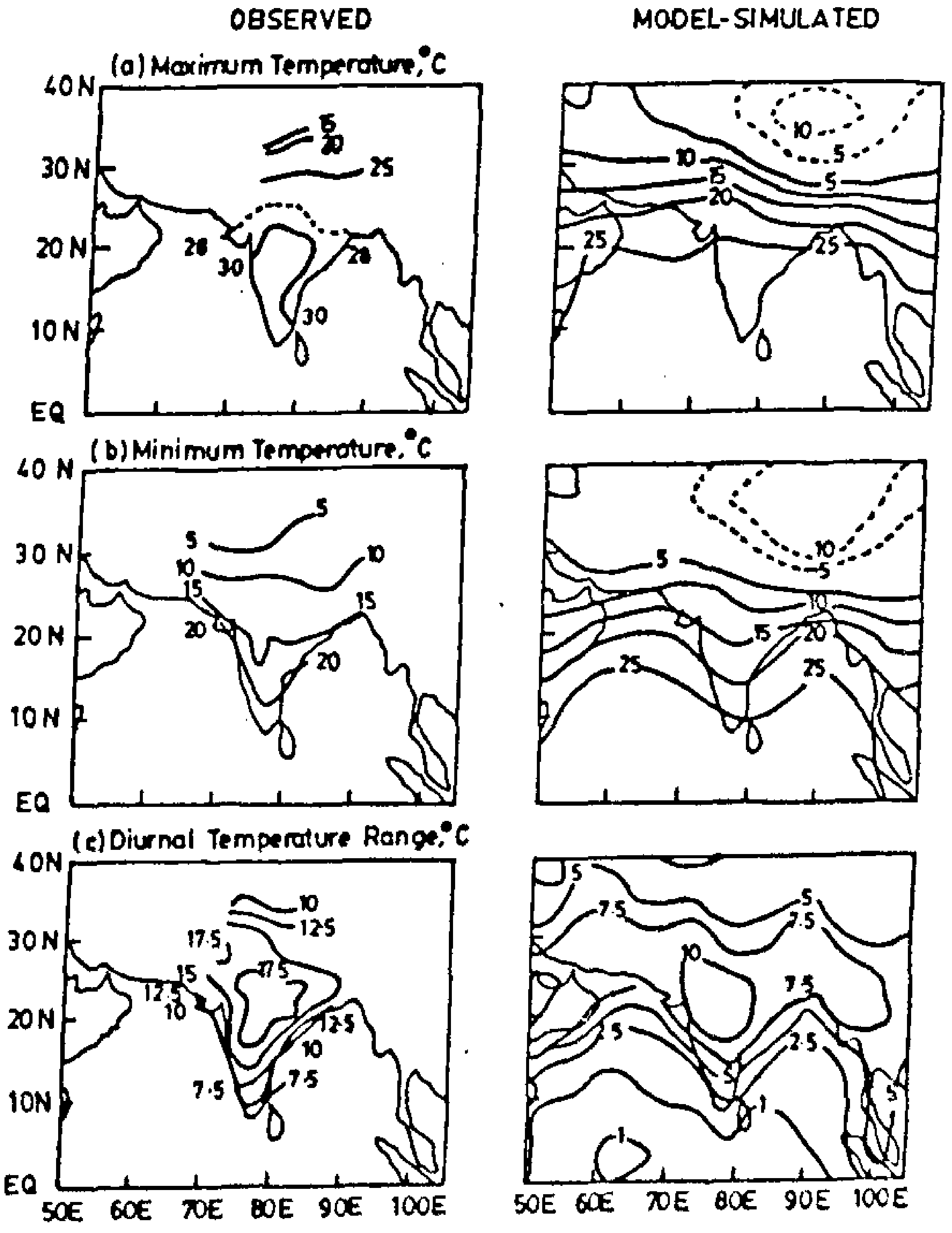

Figure 2. Spatial distribution of present-day (1980s) observed and model-simulated (under combined equivalent CO_2 and aerosol forcings) maximum and minimum temperatures and diurnal temperature range (°C) over the Indian subcontinent during winter season.

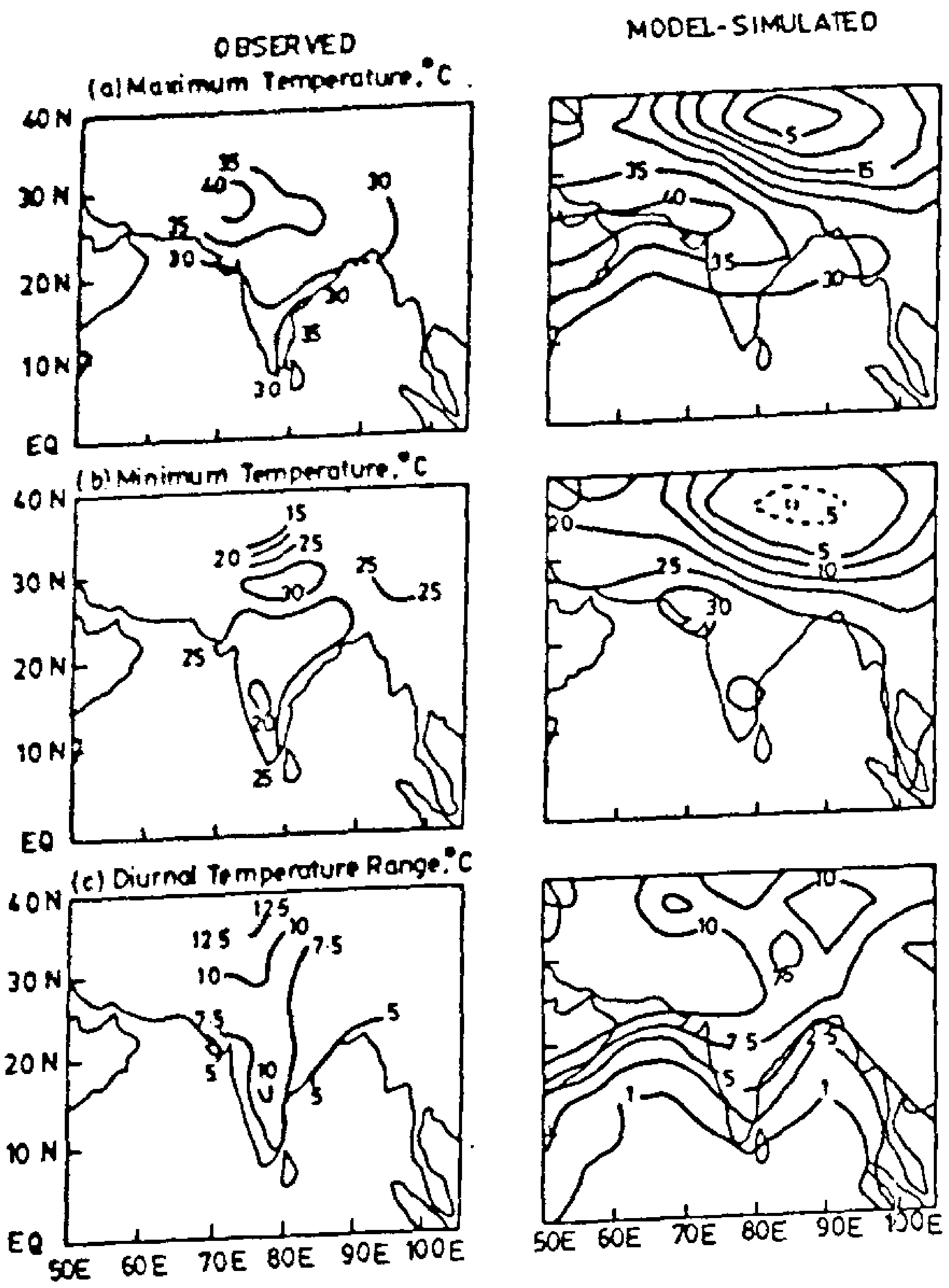

Figure 3. Spatial distribution of present-day (1980s) observed and model-simulated (under combined equivalent CO_2 and aerosol forcings) maximum and minimum temperatures and diurnal temperature range (°C) over the Indian subcontinent during monsoon season.

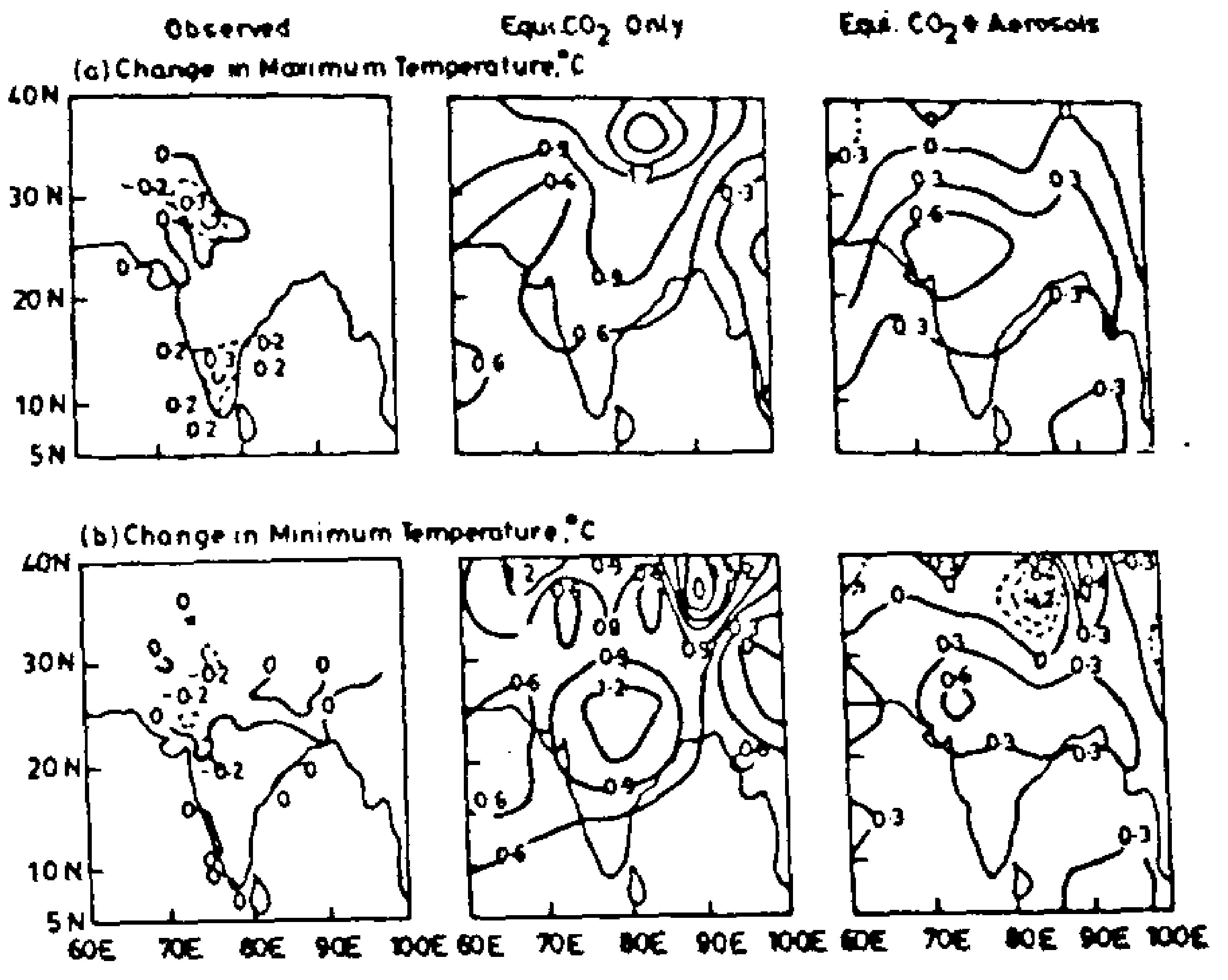

Figure 4. Spatial distribution of observed and model-simulated (equivalent CO_2 forcing and combined equivalent CO_2 and aerosol forcings) changes in annual mean maximum (*a*) and minimum (*b*) surface temperatures (C°) in the decade 1980s with respect to 1880s over the Indian subcontinent.

ogy based on data from 121 stations, the pattern correlations higher than 0.6 suggest that model simulations perform reasonably well in simulating the maximum and minimum temperature patterns over the region.

The spatial distribution of observed[6] changes in the annual mean temperatures in the decade 1980s with respect to 1880s over the Indian subcontinent suggested a rising trend in the maximum temperature at almost all stations south of 23°N and a decreasing trend north of 23°N. The minimum temperatures showed increasing trend in almost all parts of central and Peninsular India barring some pockets along west and east coasts with nominal falling trend. Decreasing trends in the simulated maximum and minimum temperatures over the north India and increasing trends over the Peninsular India in the experiment S are in fair agreement with observations (Figure 4) except in the Himalayan highlands. The differences in the highlands could be due to sparse observations and also due to coarse resolution of the model over the region. The experiment with only CO_2 forcing produced consistently higher than realized changes in maximum and minimum temperatures over the region on annual mean basis. The combined CO_2 and aerosol forcing is able to reproduce the observed changes in diurnal temperature cycle during the past century better than the CO_2 forcing only (Figure 4). Our findings on the future projections of regional changes in maximum and minimum temperatures and diurnal temperature range based on the combined CO_2 and aerosol forcing experiment should, therefore, have a better degree of confidence.

Future changes in diurnal temperature cycle

Table 2 gives the area-averaged annual and seasonal changes during the decade of 2040s over the Indian subcontinent in the maximum and minimum temperatures as simulated by CO_2 forcing only as well as by combined CO_2 and aerosol forcing. The projected annual mean changes in maximum and minimum temperatures in CO_2 forcing only experiment are more than a factor of two higher relative to those in combined CO_2 and aerosol forcing experiment.

In the combined CO_2 and aerosol forcing experiment, while the projected rise in maximum temperature is found to be most pronounced during the pre-monsoon and monsoon seasons, in minimum temperature it is for the post-monsoon and winter months. A decline in the diurnal temperature range is simulated by the model for the decade 2040s on annual mean basis. The projected decline in diurnal temperature range during winter is most pronounced (0.6°C) and

Table 2. Changes (°C) in model-simulated area-averaged maximum and minimum temperatures (land only) during 2040s as compared to 1980s over the Indian subcontinent

	Equivalent CO_2		Equivalent CO_2 + aerosol	
Period	Maximum	Minimum	Maximum	Minimum
Annual	2.38	2.73	0.74	1.01
Winter (DJF)	2.60	2.62	0.47	1.10
Pre-monsoon (MAM)	3.23	3.15	0.87	0.99
Monsoon (JJAS)	1.61	2.50	0.88	0.88
Post-monsoon (ON)	2.32	2.96	0.64	1.17

is found to be statistically significant at 90% confidence level. During the monsoon season, no change is simulated in the diurnal temperature range for the future.

In its spatial distribution, while no significant rise in maximum temperature is expected over northeast India by the middle of next century, a rise of about 1.5°C is simulated along the western margins of India (Figure 5). A marginal decline in the minimum temperature of about 0.5°C is likely over the northeast India whereas a rise of above 1.5°C is possible along the western Indian subcontinent. The model-simulated changes in both maximum and minimum temperatures are found to be characteristically smaller over northeast India compared to rest of the region. The model results suggest a decline in diurnal temperature range (~0.5°C) over most parts of India due to relatively larger increase in the minimum temperature. The diurnal temperature range over northeast India may, however, increase by about 0.5°C.

Discussions and conclusion

A comparison of observed and model-simulated trends in annual mean area-averaged maximum and minimum surface temperatures suggests that the combined greenhouse gas and sulphate aerosol forcing experiment has been able to reproduce the observed changes in diurnal temperature cycle over the region during the past decades in a broad sense. The spatial distribution of changes in annual and seasonal mean, maximum and minimum temperatures over the Indian subcontinent as simulated in combined greenhouse gas and sulphate aerosol forcing experiment for the decade 1980s with respect to the control climate of decade 1880s is found to be in fair agreement with observations. Thus, the inclusion of aerosol forcings in coupled climate model experiments has

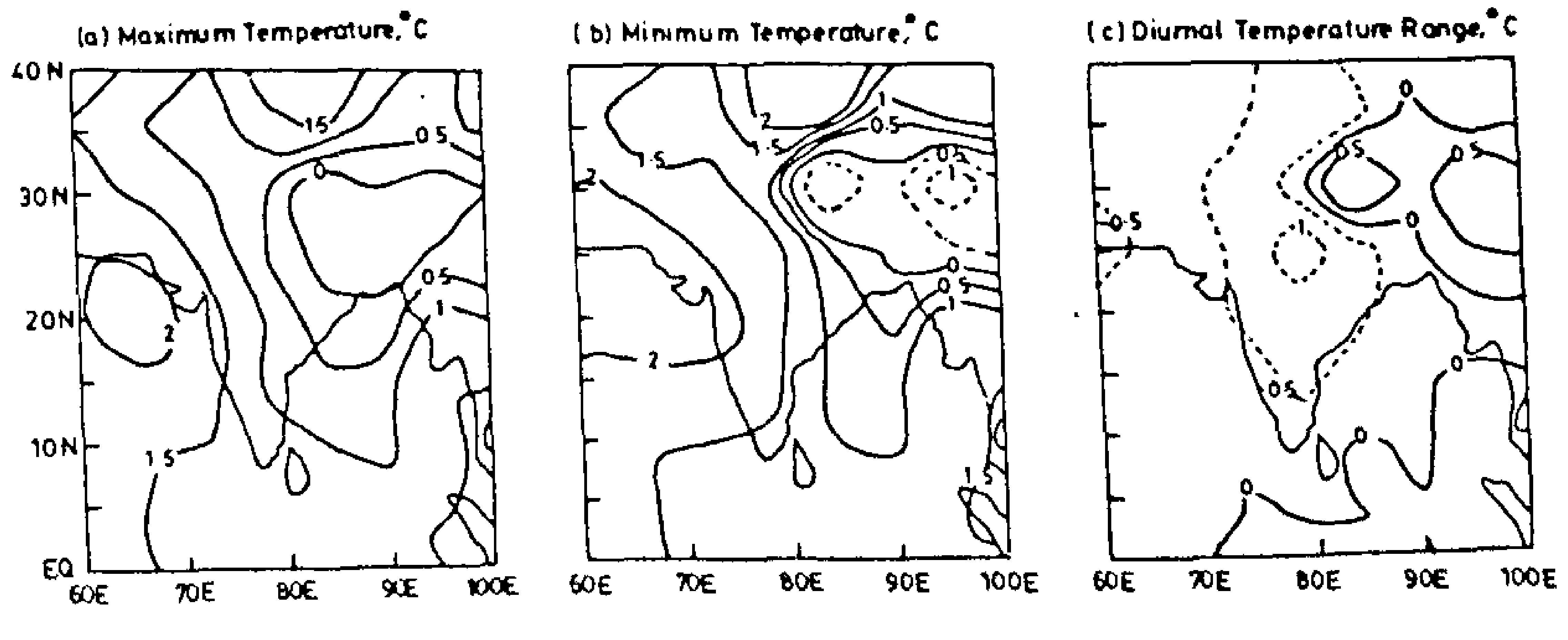

Figure 5. Spatial distribution of changes in annual mean maximum and minimum temperatures and diurnal temperature range (°C) during the decade 2040s with respect to the decade 1980s over the Indian subcontinent as simulated by the model due to combined equivalent CO_2 and aerosol forcings.

provided us some insights on how to explain, in general, the observed asymmetry in the diurnal temperature cycle over the region.

An increase in annual mean maximum and minimum surface air temperatures of 0.7 and 1.0°C respectively over the land regions of the Indian subcontinent by the middle of next century is simulated by the model taking into account the projected emission of greenhouse gases and sulphate aerosols. The projected rise in maximum temperature is found to be most pronounced during the monsoon season while the rise in minimum temperature has its peak during the post-monsoon months over the region. A significant decrease in the diurnal temperature range over the Indian subcontinent during the winter season and no appreciable change during the monsoon season is simulated. The projected changes in the maximum and minimum temperatures and the diurnal temperature range could have significant impact on the patterns of agricultural productivity over the Indian subcontinent.

The key factors that affect the regional scale performance of global climate models are the horizontal resolution and physical parameterization schemes. The coarse resolution may introduce systematic errors in the depiction of coastlines as well as high mountains with consequent effects on the simulation of regional circulation and temperatures. In this respect, the projections given here have only a limited degree of confidence. Since, at present, only the direct effects of sulphate aerosols are considered in model experiments (in terms of surface albedo), we cannot judge precisely the influence of aerosols in modulating the cloud microphysics. When the resolution of available climate models increases with the availability of enhanced super-computing power and improved parameterization schemes of subgrid-scale physical processes such as clouds are incorporated, a general increase in accuracy in regional projections may be expected.

---

1. Karl, T. R., Kukla, G., Razuvayev, V. N., Changery, M. J., Quayle, K. G., Heim, R. R., Easterling, D. R. and Fu, C. B., *Geophys. Res. Lett.*, 1991, **18**, 2253–2256.
2. Karl, T. R., Jones, P. D., Kukla, G., Plummer, N., Razuvayev, V. N., Gallo, K. P., Lindseay, J., Charlson, R. J. and Peterson, T. C., *Bull. Am. Meteorol. Soc.*, 1993, 74, 1007–1023.
3. Kukla, G., Quayle, R. G. and Karl, T., Proceedings of the International Speciality Conference on Global Climate Change: Science, Policy and Mitigation Strategies, Phoenix, Arizona, 1994, pp. 158–163.
4. Rind, D., Peteet, D. and Kukla, G., *J. Geophys. Res.*, 1989, **94**, 12851–12871.
5. Cao, H. X., Mitchell, J. F. B. and Lavery, J. R., *J. Climatol.*, 1992, **5**, 920–943.
6. Srivastava, H. N., Dewan, B. N., Dikshit, S. K., Prakash Rao, G. S., Singh, S. S. and Rao, K. R., *Mausam*, 1992, **43**, 7–20.
7. Rupakumar, K., Krishnakumar, K. and Pant, G. B., *Geophys. Res. Lett.*, 1994, **21**, 677–680, (updated data series obtained from India Meteorological Department, Delhi).
8. Hansen, J., Sato, M. and Ruedy, R., Proceedings of the International MINIMAX Workshop held at Maryland during Sept 27–30, 1993 under the auspices of NOAA/DOE (eds Kukla, G., Karl T. R. and Riches, M. R.), 1994, pp. 301–325.
9. Lal, M., Cubasch, U., Voss, R. and Waszkewitz, J., *Curr. Sci.*, 1995, **69**, 752–763.
10. Cubasch, U., Hasselmann, K., Hock, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B. D. and Sausen, R., *Clim. Dyn.*, 1992, **8**, 55–69.
11. Maier-Reimer, E., Mikolajewicz, U. and Hasselmann, K., *J. Phys. Oceanogr.*, 1993, **23**, 731–757.
12. DKRZ, Technical Report No. 6, Hamburg, 1994, p. 184.
13. Houghton, J. T., Jenkins, G. J. and Ephraums, J. J. (eds), *Climate Change: 1990*, Intergovernmental Panel on Climate Change, Cambridge University Press, 1990, p. 365.
14. Langner, J. and Rodhe, H., *J. Atmos. Chem.*, 1991, **13**, 225–263.
15. Charlson, R. J., Langner, J., Rodhe, H. and Warren, S. G., *Tellus*, 1991, **43**, 152–163.
16. Hasselmann, K., Bengtsson, L., Cubasch, U., Hergerl, G. C., Rodhe, H., Roeckner, E., Storch, H. V., Voss, R. and Waszkewitz, J., *Geophys. Res. Lett*, 1995, (communicated).
17. Somerville, R. C. J and Iacobellis, S., *J. Met. Soc. Jpn.*, spl. issue, (ed. Matsuno, T.), 1987, 177–185.

ACKNOWLEDGEMENTS. M. L. thanks Deutsches Klimarechenzentrum GmbH (DKRZ) and Max Planck Institute for Meteorology, Hamburg for generous hospitality and for extending facilities to take up this study during his one-year stay at Hamburg. The visit of M. L. to DKRZ was funded by the German Ministry for Education, Research and Technology (BMBF). We thank Prof. K. Hasselmann and Prof. L. Bengtsson for their keen interest in this study and J. Waszkewitz and R. Voss for their assistance in processing of data.

Received 27 December 1995; revised accepted 11 October 1996