Variability of climate change in India

S. K. Dash* and J. C. R. Hunt

In this article meteorological measurements in India are analysed showing marked trends of increasing temperature over the past quarter century, but significant variations in these trends during different seasons and over different regions of India. Marked differences between the variations in minimum temperatures in North and South India have been brought out. Tentative explanations are proposed in terms of the effects of variations in cloudiness. The effects of airborne dust on clouds and on precipitation, as well as the interactions between air flow over the mountains and the monsoon may also have a significant effect on climatic variations. The practical implications of these changes in climate for agriculture and the effects on human health through increasing temperature are likely to be serious, and vary significantly across the regions of India. For India, the importance of dealing with climate change as an integral part of its economic and social development is strongly emphasized.

Keywords: Climate change, climate models, global warming, temperature variation.

WITH a warmer atmosphere, more water evaporates from the oceans and the land. However, if the vapour condenses, thus forming more clouds, the solar radiation reaching the surface will decrease leading to a lower temperature. On the other hand, if the water vapour stays mainly as uncondensed vapour, it helps absorb the long-wave radiation from the ground and adds to the 'greenhouse' heating of the atmosphere. Numerical computer models based on fundamental laws of physics simulate both these processes and have concluded that the latter is the primary effect of enhanced water vapour concentration in the atmosphere. Thus the rise in temperature is predicted to increase by about 50% more as a result of water vapour. Overall these models predict an increase of about 4°C over land by 2100.

Basic effects of radiation of greenhouse gases (GHGs) and water vapour play a vital role in determining the variation in climate over large areas of the globe. In particular, they are critical for determining the variations of the climate change during the seasons and across the regions of India. In addition, the special features of the geography of the subcontinent affect India's local climate and also its variation as the global climate changes. The atmosphere and ocean dynamics have to be calculated in greater detail to model the effects of orography, coastal interactions and cloud processes. Global climate models, such as that of the Hadley Centre, have improved sufficiently to calculate the mean trends and variations in average global

temperature over the past 150 years. They have been accepted by panels of objective and critical experts[1] on the International Panel for Climate Change. The models have accounted for the effects of human-induced emissions of GHGs, and natural variability, including aerosols from volcanoes, etc. They are now being extended so as to simulate variations in the regional climate. In India, the first aim is to ensure the models describe the current characteristics of the climate during the seasons and across all the regions of the subcontinent. Secondly, the models should predict how the regional climate will change as a result of local effects and the progressively serious changes in the global climate. These connections are complex, since studies of the global variability of temperature trends show that in some regions[2] the trends may be significantly greater than other global trends. However, local trends may also be less than global trends, or may even be in the opposite sense (e.g. in terms of precipitation).

India has the high Himalaya mountains to the north of the central plain and desert areas. These mountains are relatively young geologically. Before 20 million years ago, when the mountains reached a height of about 5000 m, monsoon winds did not extend[3] over the subcontinent as they do now. Also the monsoon winds did not influence the wind over the Arabian Sea. From a fluid dynamics perspective[4], the heating of the slopes of the Himalayas drives the airflow towards the north. Strong thermal convection[5] over a flat slope can reinforce an airflow circulation once it has been set up. This may contribute to the monsoon flow. The Indian monsoon[6] extends over a distance of nearly 3000 km, directed to the southwest from the Himalayas. The effects of the earth's rotation deflect the up-slope flow towards the eastern end of the Himalayas, where it also intensifies[7,8], this causes the extremes of precipitation

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in this region. These dynamical effects also mean that any anomalous cooling of the Himalayas by excess snow[9] can affect the upslope winds and therefore the whole climate over India.

Another important aspect of the Indian climate may come from the effects of dust[10] arising naturally from the desert, and from wood/charcoal burning and fossil-fuel combustion. The latter component is increasing as a result of the rapidly growing population. More research is needed to understand the effects of aerosols on Asian monsoons. Studies on dust particles and the process of precipitation indicate that they may suppress the formation[11] of clouds and continuous rain, but may promote occasional but extreme precipitation events.

Measurements of climate trends in India

A recent study[12] based on the measurements of the India Meteorological Department (IMD) has shown that the all-India mean annual temperature has increased by 0.5°C in the period 1901–2003. The warming trend has been associated with a rise in maximum temperature by 0.7°C during the same period. However, during the last three decades the warming trend has been contributed by both maximum and minimum temperatures. The study has also shown that the rise in minimum temperature varies significantly between the winter and post-monsoon seasons, where it is 0.4°C and 0.7°C respectively. The present study extends the recent results of warming in India, with a view to highlight certain trends and suggest how they might be explained in terms of aerosols, cloud sources and the local effects of the Himalayas.

We have divided the entire year into two halves, namely post-monsoon and winter (October to February), and pre-monsoon and monsoon (March to September). Anomalies of average land surface maximum and minimum air temperatures relative to their respective mean value for the period 1901–2003 are shown in Figure 1 a–d. The smoothed curve shown is obtained by applying the 21-point binomial filter. A well-marked warming trend is observed in the maximum temperature in the post-monsoon and winter months (Figure 1 a). The smoothed lines indicate that in the last hundred years or so, the maximum temperature over India during October to February has increased by more than 1.25°C (Figure 1 a), whereas the increase in the rest of
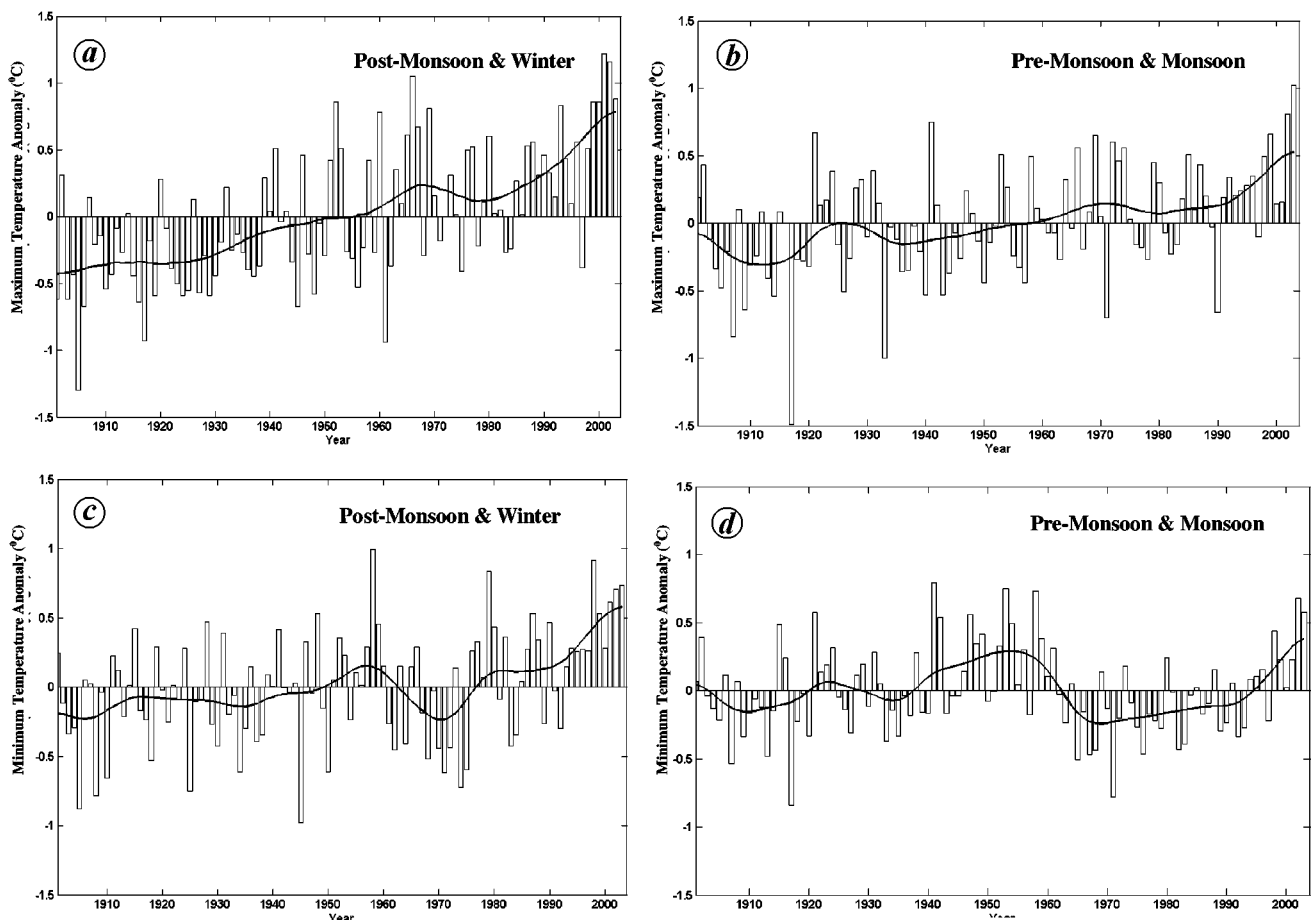

Figure 1. Anomalies of average land surface maximum and minimum air temperatures (°C) relative to their respective mean (1901–2003) values in the two halves of the year over the whole of India. The smoothed curve is obtained using 21-point binomial filter.

the months of the year was less, may be 0.75°C (Figure 1 b). The minimum temperature also increased in the last 100 years, but not as much as the maximum temperature. The increase in minimum surface temperature was about 0.75°C (Figure 1 c) during October to February and 0.3°C (Figure 1 d) in the other half of the year. Figure 1 a and b shows that the maximum temperature anomaly became positive after about 1955 and that since 1980, the positive enhancement became sharp throughout the year, although the increase in the winter phase (Figure 1 a) was more both in magnitude and consistency than in the summer phase (Figure 1 b).

The scenario with the minimum temperature anomaly was somewhat different from that in the maximum temperature. After 1950, the minimum temperature during post-monsoon and winter months increased (Figure 1 c) for about 5 years and then decreased till 1970; thereafter it has been increasing sharply by about 0.25°C per decade. In the two decades prior to 1960, the minimum temperature during May to September (Figure 1 d) was consistently higher and after a sharp decrease it remained low for about three decades. In the last decade the minimum temperature has again started rising. The sharp decrease in the minimum temperature during 1955–70 was similar during all the months of the year. Since then, the rise during post-monsoon and winter has been much sharper than that during the rest of the year, as shown by an earlier study[12]. The annual average increase in both maximum and minimum temperatures which is observed for all the seasons of the year, was consistent with the global warming. However in India, during the last 2–3 decades, the increase in the maximum and minimum temperatures during October to February has been about 0.3°C more than that during the rest of the months. This seasonal gradient in the temperature rise needs further detailed examination, focusing more on the regional aspects.

To study the variability of climate change in India, the country has been divided into north and south zones by the latitudinal circle 21°N. The north zone consists of northwest, north-central and northeast regions and western Himalayas, while the southern part consists of the interior of the peninsula, east coast and west coast. Changes in the maximum and minimum temperatures were examined over these two regions. Figure 2 a and b shows that during last century, the maximum temperature has increased by about same 0.75°C over both these regions. In the last two decades
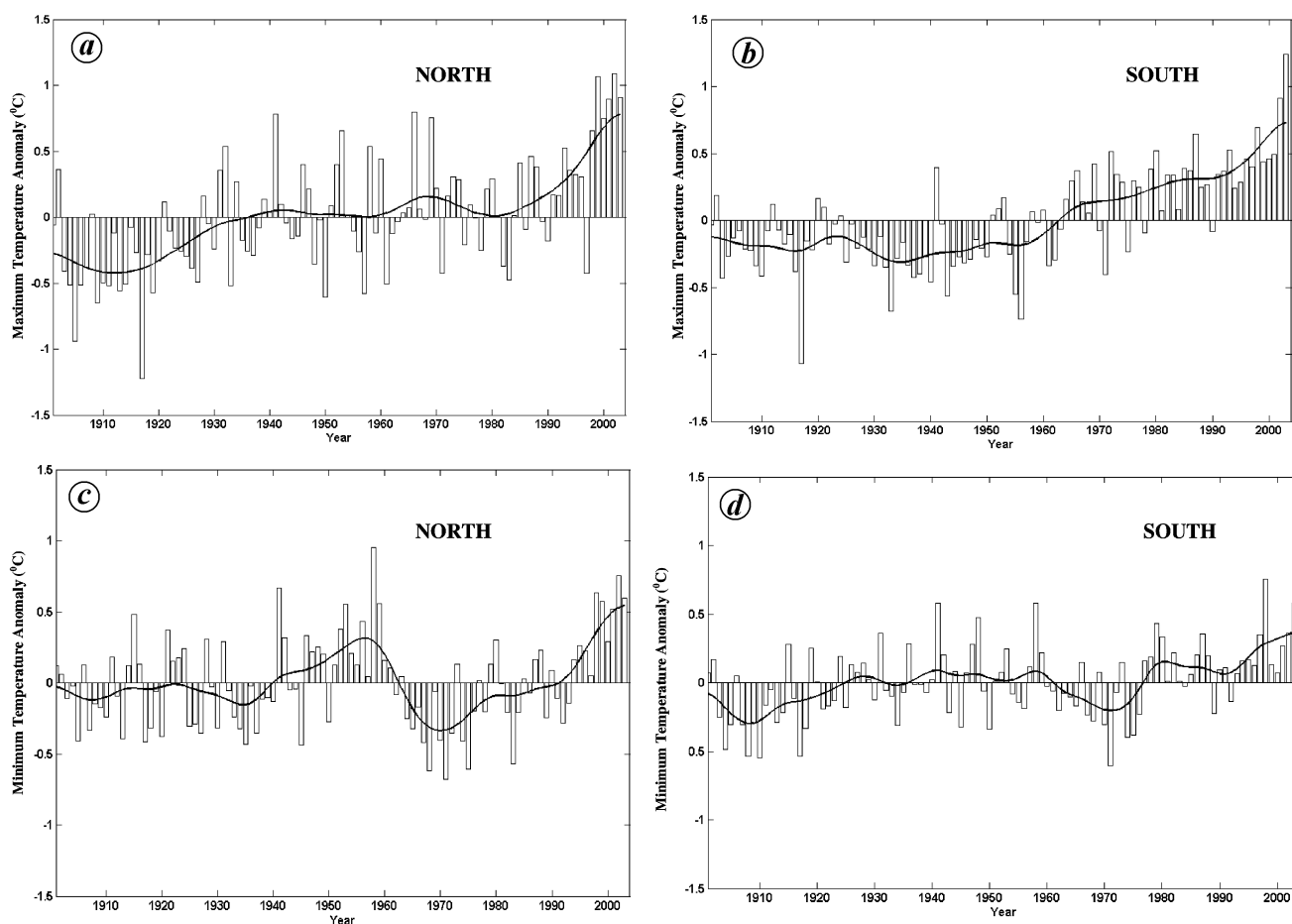

Figure 2. Anomalies of average land surface maximum and minimum air temperatures (°C) relative to their respective mean (1901–2003) values over northern and southern parts of India. The smoothed curve is obtained using 21-point binomial filter.
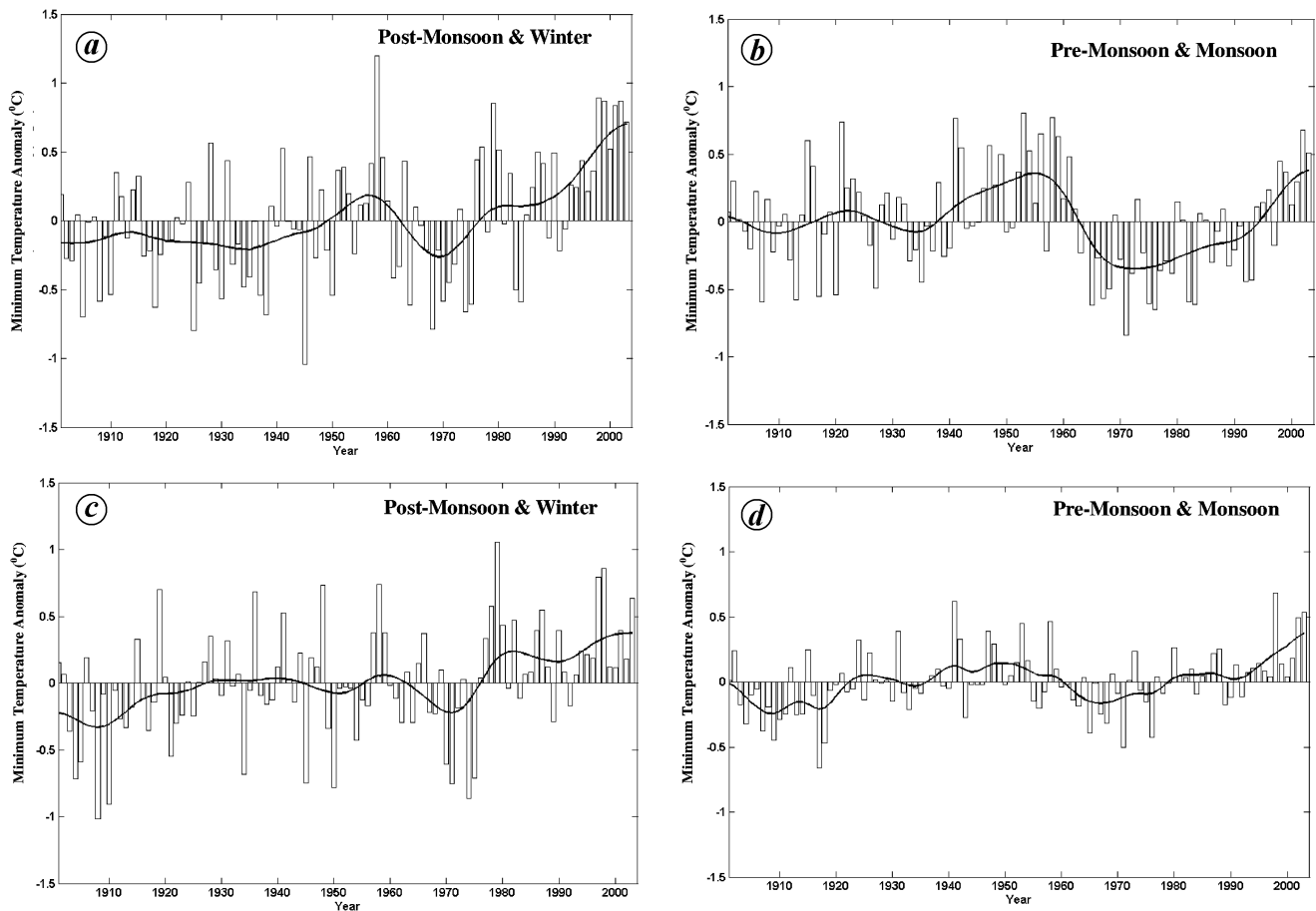
Figure 3. Anomalies of average minimum temperature (°C) relative to the mean (1901–2003) value in the two halves of the year over northern (*a*, *b*) and southern parts (*c*, *d*) of India. The smoothed curve is obtained using 21-point binomial filter.
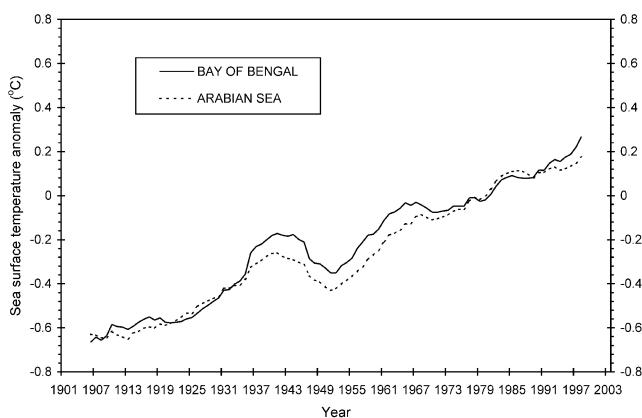

Figure 4. Time series of sea surface temperature anomaly (°C) of the Arabian Sea (7–24°N and 63.8–75°E) and the Bay of Bengal (7–21°N and 78.8–91.9°E).

the maximum temperature over North India has been rising sharply, whereas in the South (Figure 2 *b*) the rise has been less sharp spreading over the last three decades. Figure 2 *c* indicates that during the last seven decades, the minimum temperatures over North India had a periodicity in about 20–25 years timescale. In the South, such a periodicity

did not exist. In the last decade there has been indication of sharp rise in the minimum temperatures in the North compared to South India. Comparison of Figure 1 *c* and *d* with Figure 2 *c* and *d* clearly indicates that the sharp decrease in the minimum temperature during 1955–70 and then the equally sharp rise over the past 3–4 decades has been mainly contributed from the northern part of India compared to its southern part. We have also examined the seasonal changes in minimum temperatures in North (Figure 3 *a* and *b*) and South India (Figure 3 *c* and *d*) separately. This leads to the inference that the highest rise of about 1°C in the minimum temperature over the country has occurred during post-monsoon and winter months in the last three decades in North India. The second point to note is that the fluctuation in minimum temperature during the period 1950–75 mainly occurred in North India. The third point of significance is the highest magnitude in the pre-monsoon and monsoon months (Figure 3 *b*) in North India.

We have looked at the Reynolds sea surface temperature (SST) data, available at National Climatic Data Center, over the Arabian Sea (7–24°N and 63.8–75°E) and the Bay of Bengal (7–21°N and 78.8–91.9°E). The time
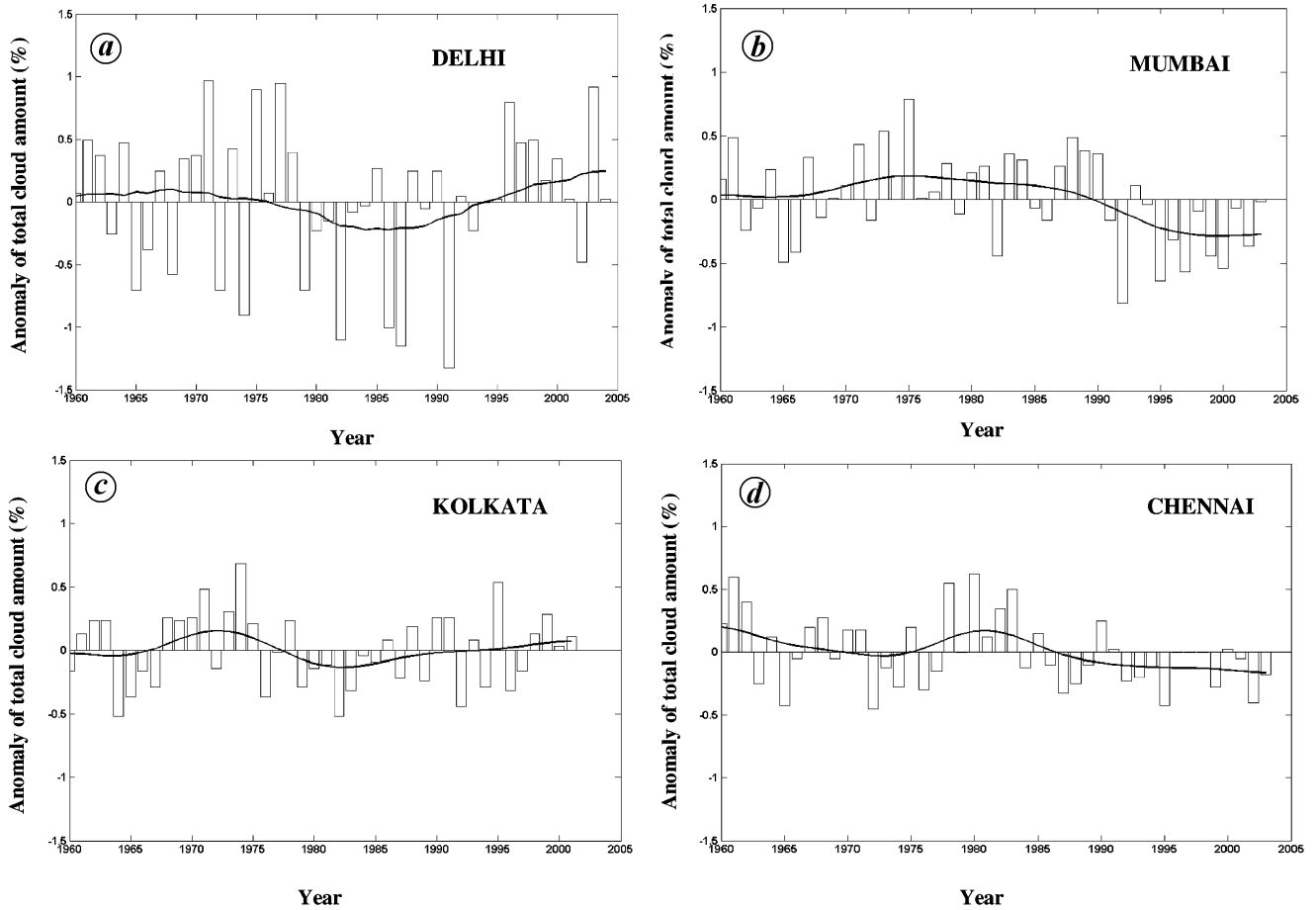
Figure 5. Anomalies of average total cloud amount (%) at 12 UTC for June–September relative to their respective mean (1960–2004) values over four metropolitan cities in India. The smoothed curve is obtained using 21-point binomial filter.
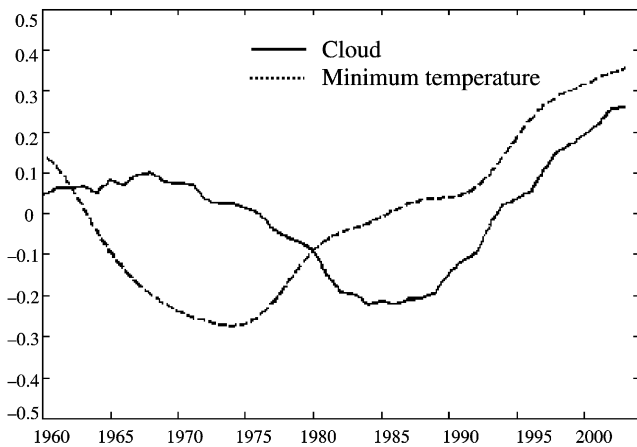

Figure 6. Anomalies of average minimum temperature (°C) and total cloud amount (%) for June–September relative to their respective mean (1960–2004) values over North India and Delhi respectively. The smoothed curve is obtained using 21-point binomial filter.

series of SST has been depicted in Figure 4, which indicates that during the last 100 years, the Bay of Bengal and Arabian Sea SSTs have increased by about 0.8°C.

This rise in SST is about 50% greater than that in the ocean temperature over the rest of the globe[13], though the explanation is not yet clear.

Clouds have a crucial role to play in the weather and climate of India, especially during the monsoon months. The measured cloud amount available from the IMD archive for the period 1960–2005 has been examined over four major Indian cities, i.e. Delhi, Mumbai, Kolkata and Chennai, representing the north, west, east and south of India. Figure 5 a indicates the increase in cloud amount over North India in the last decades. Figure 5 b and d indicates decrease of cloud amount in South India in the last two decades, whereas there is not much change in the cloud amount in East India (Figure 5 c). The increase/decrease in cloud amount in the North/South India in the recent past needs more careful examination in future. Nevertheless, the trend of increasing cloudiness in the morning hours is consistent with the increasing minimum temperatures in North India. The simultaneous rise in the cloud amount in Delhi and the minimum temperature in North India in the last three decades is shown in Figure 6.

In order to further examine the relationship between minimum temperature and cloud amount in North India, the time series of cloud amounts at Delhi available for the

period 1960–2003 and the minimum temperatures for the same period were subjected to wavelet analysis. This allows visualization of the time evolution of various scales present in the multi-scale time series. Wavelet transforms have better information regarding various scales/frequencies present in the time series in a particular domain. The most commonly used continuous wavelets are the Morlet wavelet and the Mexican hat wavelet. The Morelet wavelet is widely used for the geophysical time series as it decays quickly in both time and frequency domains and is therefore able to localize both the time and frequency to the maximum extent. Figures 7 and 8 show the results of wavelet analysis of the time series of minimum temperatures and cloud amounts respectively. The similarities between the two time series wavelet power spectra of minimum temperature and cloud amount are clearly brought out in
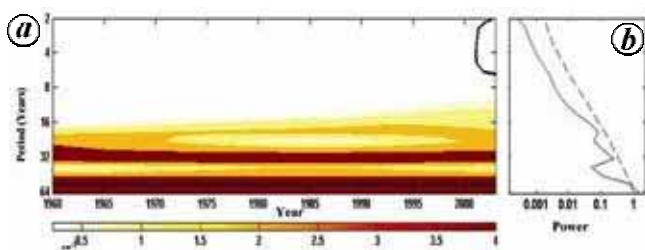
these two figures. The powers of both minimum temperature and cloud amount are maximum in the period of 16–64 years, which is a slow timescale.

Conjectures about climate variability and change

In the warming atmosphere more summer rainfall is expected. Recent data have shown reduced snowfall over the Himalayas and also over the high mountain ranges of the Alps in a warming climate[14]. Some modelling studies[15] also suggest inverse relationship between the Tibetan Plateau snowfall in spring and the subsequent summer monsoonal rainfall. Time series of measurements of the summer monsoon rainfall over the past few years shown in Figure 9, indicates some reduction and also high variability. We suggest that reduction of summer monsoon rainfall in the warming atmosphere can partly be explained by considering the combined effects of climate change and meso-scale influences of the mountains on the monsoon flow. This is shown schematically in Figure 10. As the troposphere becomes less stable and the mean height of the tropopause rises[16] in a warming climate, the warmer boundary layer air may flow from lower levels to the top of the mountains. This can produce deeper clouds and more rain on the slopes of the mountains, less formation of snow and more melting. These effects may be related to the increased atmospheric moisture observed at lower levels during winter when the air flows from the mountains towards the southwest. Effectively the 'dividing stream-line height' is reduced[17], which is also likely to lower the depth and weaken the strength of the up-slope monsoon flow near the base of the mountains.

The monsoon cloudiness mostly seen in South India is also reduced by increased concentrations of small dust particles in the lower troposphere and thus the summer monsoon rainfall also reduces[10,11,18]. Although this suppresses lower-level precipitation, parcels of air can rise higher before precipitation occurs leading to the formation of deeper clouds. This is also made possible by the reduced stability of the atmosphere associated with climate change. These cloud processes are consistent with the observation that over the plains of India and the slopes of the Himalayas, and the Western Ghats, more of the precipitation now occurs in the form of infrequent heavy deluges, associated with local flooding. The global nature of these changes is evident since they are also observed in the increase in rainfall and reduced snow patterns over high mountain ranges in Europe, Asia and Africa.

Figure 7. Wavelet analysis of minimum temperature anomaly (°C) over North India for the period 1960–2003. *a*, Wavelet power spectrum; *b*, Global wavelet spectrum.
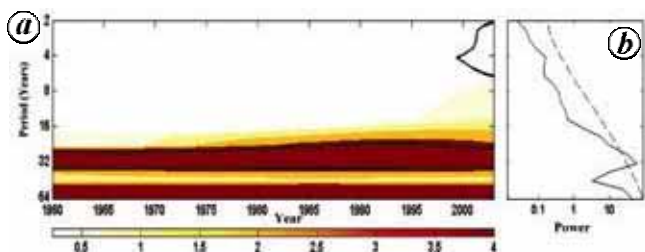

Figure 8. Wavelet analysis of anomaly of cloud amount over Delhi for the period 1960–2003. *a*, Wavelet power spectrum; *b*, Global wavelet spectrum.
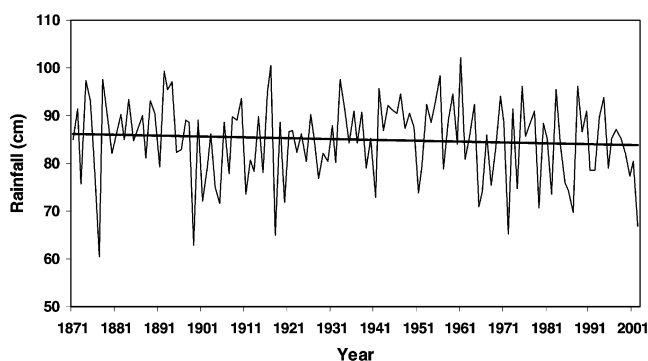

Figure 9. Time series of rainfall in India during monsoon months of June–September. The solid straight line indicates trend significant at 99% level.

Conclusions

Although palaeoclimatic studies have shown that India has experienced a strong monsoon ever since the uplift of the Himalayas more than 10 million years ago[4], there is now a distinct possibility that the current climate changes
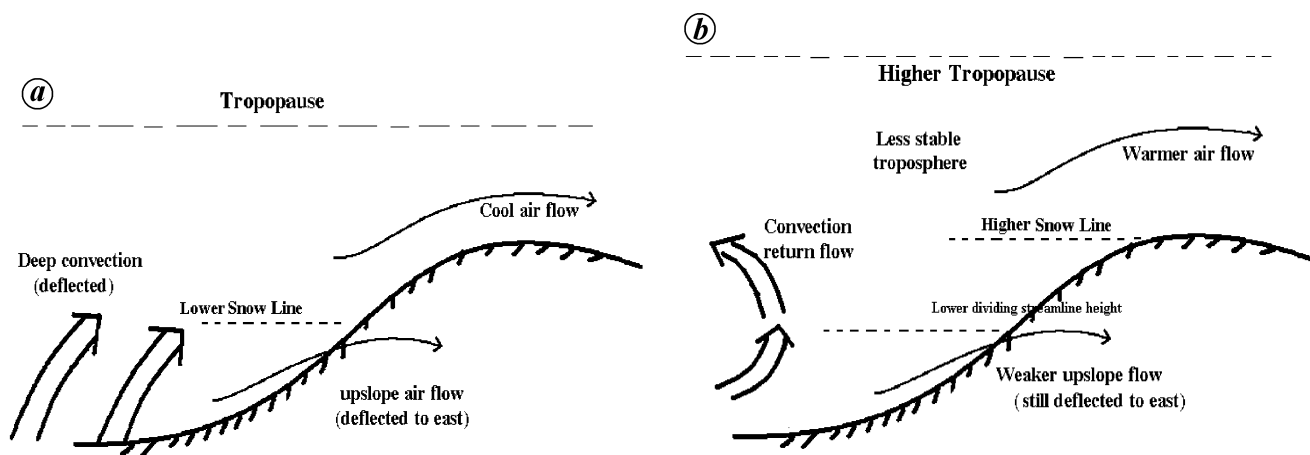
Figure 10. Shematic diagram showing the snow line and height of tropopause in (*a*) normal atmosphere and (*b*) warmer atmosphere.

in the atmosphere, which are unprecedented over this period, may during this century lead to some significant changes in the monsoon flow and pattern of precipitation. Analysis of meteorological measurements in India already indicates large differences in trends in the minimum temperature and cloud amounts between North and South India. There is also asymmetry in the increasing temperature trends between different seasons in a year. These observations along with the occurrence of extreme weather events lead to the importance of regional climate changes. The interplay between the aerosols, clouds and mesoscale flows around the Indian mountains in the global warming atmosphere may play a crucial role in the regional climate in the future. These interacting effects show why every effort should be put in understanding the gaps in the science of climate changes, especially at the regional scale. Improvements in the observational network, regional climate modelling and more information on socio-economic aspects are also vital.

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