Changing long-term trends in tropospheric temperature over two megacities in the Indo-Gangetic Plain

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The radiosonde data over two megacities in the Indo-Gangetic Plain, viz. Delhi and Kolkata are examined to study the long-term trends in air temperature at various pressure levels between 850 and 150 hPa during 1973–2008. The maximum increase in temperature occurs at 700 hPa over both the stations during this period. The warming trends are seen until 400 hPa, whereas cooling trends are found to occur above this altitude. Overall, the annual long-term trends vary between +0.3 and –0.2°C/decade for the altitude range studied. Long-term trends in different seasons reveal highest warming during winter until 300 hPa over Delhi. Over Kolkata, the highest warming occurs during monsoon at heights above 700 hPa. These trends are found to be the lowest during post-monsoon. The important point that has emerged from this study is that there has been an accelerated rise in temperature during 1973–2008 when compared with a previous study which reported negative trends during an earlier period, i.e. 1958–1985.

Keywords: Megacities, temperature trends, troposphere, warming.

THE vertical temperature profile in the troposphere is the result of a balance of radiative processes involving solar radiation, greenhouse gases (GHGs), and aerosols along with the role of moist convection, clouds and dynamical motions. Solar radiation, the source of energy for the Earth's climate system, is absorbed mostly at the surface and partly by the atmosphere. The absorbed radiation and the outgoing longwave emission from the Earth balance each other to yield a steady-state climate. These radiation components result in an excess of net radiative heating of the climate system in the tropics, with a deficit in the high latitudes. The thermal gradients set up dynamical motions which coupled with convection and Coriolis effect give rise to the climatological horizontal and vertical thermal structure.

The potential utility of changes in the vertical structure of the atmosphere in the diagnosis of climate change is well known[1]. The global air temperature is increasing due to increase in GHGs mainly CO_2 (ref. 2). The Indo-Gangetic Plain (IGP) in North India is one of the most populated regions in the country, with major agricultural and industrial activities. Increasing emissions of pollutants from this region substantially affect the environment and hence the climate. Anthropogenic emissions of both trace gases and aerosols from biomass burning, industries, power plants and vehicles cause relatively higher levels of pollutants in this region[3,4]. The two megacities, viz. Delhi (28.58°N, 77.20°E) and Kolkata (22.65°N, 88.45°E) in the IGP are being confronted with a multitude of environmental challenges, including soaring air-pollution levels and drastic extremes in meteorological conditions. Delhi's population is gradually nearing 20 million with SO_2, NO_2 and SPM levels of the order of 9, 50 and 330 μg m^{-3} respectively[5]. Black carbon (BC) and dust have been recognized as potential warming agents in the lower troposphere[6–9] in addition to the GHGs, which are already known as major radiation absorbers[2].

There have been many studies related to long-term trends in surface air temperature in India. During 1901–2003 average long-term trend of 0.05°C/decade was found in the all-India annual mean surface air temperature[10]. The recent period of 1971–2003 has seen a relatively accelerated warming of 0.22°C/decade. Recently, surface air temperatures in different parts of India were analysed for the period of 1901–2003 (ref. 11) and an increasing trend (0.03–0.09°C/decade) was found over India, except in the northwestern part (with decreasing trend of –0.01°C/decade). However, there have been limited studies related to changes in air temperature at different heights. Radiosonde data for different places in India have been analysed[12], and decreasing trends of 1–2°C/decade over Delhi and 0.8–2.6°C/decade over Kolkata have been reported at various pressure levels between 850 and 200 hPa during 1958–1985. However, satellite data showed warming in the 4–7 km altitude range over the IGP[9] during 1979–2007. This was attributed to heating due to BC. However, there has been no recent study on the long-term changes in the vertical temperature profiles over the Indian region.

In this article, we present long-term changes in the vertical profiles of temperature over these two megacities as well as a reference location in southern India using balloon-borne radiosonde data. These temperature data

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provide the longest record of upper air measurements and offer a distinct advantage over satellite data in accessing changes in the vertical structure because they provide better height resolution.

Data

Daily radiosonde flights are being made by the India Meteorological Department (IMD) at several locations over the country. These balloon flights are made twice a day at 00 and 12 GMT. An international inter-comparison held in 1985 (ref. 13) showed that the quality of Indian sonde data was comparable with that of others. The IMD data have been used by several researchers[11,12,14]. For example, these radiosonde data were used to examine long-term trends in tropopause height (TPH) and tropopause temperature (TPT), and a positive trend of 0.57%/decade in TPH and a negative trend of 0.53%/decade in TPT over New Delhi during 1965–1996 was reported[14].

These radiosonde data, starting from 1973 to 2008 for Delhi and Kolkata, available at the University of Wyoming website (www.weather.uwyo.edu), have been used in the present study. The daily data, filtered for 00 GMT values, are averaged into monthly values for standard pressure levels of 850, 700, 600, 500, 400, 300, 250, 200 and 150 hPa. Over India, 00 GMT corresponds to a local time of 5.30 a.m., which is pre-sunrise time and the effect of warming of sensors due to solar radiation is minimum[15]. As a quality control, values lying outside three sigma have been removed. Average temperatures calculated for each standard pressure level correspond to +5 to –5 hPa of those pressure levels. Annual and seasonal average data have been used to estimate trends at different heights. Time series of anomalies based on the annual averages have also been studied.

Results and discussion

The average temperature profiles for the entire period of 1973–2008 have been studied over both the stations. The average temperatures at 850 hPa differ by ~1°C between the two stations. However, the temperature over Delhi falls off more rapidly than that over Kolkata between 850 and 600 hPa. The lapse rate is 6.4°C/km over Delhi and 5.6°C/km over Kolkata in this region. These values represent moist adiabatic processes, which vary with atmospheric temperature; a typical rate of ~5.5°C/km was reported for the tropical lower troposphere[16]. The average temperatures at 850 hPa are 17.6 ± 0.6°C and 18.6 ± 0.7°C for Delhi and Kolkata respectively, while temperatures at 700 hPa are 6.9 ± 0.7°C and 9.5 ± 0.7°C in the same order. For Thiruvananthapuram, the temperature values are 17.5 ± 0.6°C and 9.3 ± 0.7°C for 850 and 700 hPa respectively. At 600 hPa or above, temperatures go below the freezing level over both Delhi and Kolkata. Average temperatures at 500 hPa, over all the three stations, exhibit negative values (–9.9 ± 0.8°C for Delhi, –5.9 ± 0.9°C for Kolkata and –5.8 ± 0.9°C for Thiruvananthapuram). The 200 hPa temperatures are almost equal over Delhi and Kolkata (–52.7 ± 1.2°C and –52.7 ± 1.4°C respectively).

Long-term annual trends

The long-term (1973–2008) annual averages of temperature data after correcting for outliers have been subjected to linear trend analysis. Linear trends are used here as a metric of climate change in the comparison of observed temperatures[1]. The significance of the trends at various pressure levels has been computed with a *t*-test under a null hypothesis of no trend.

A comparison of temperature trends found in the present study to those obtained by an earlier study[12] is given in Table 1. The earlier analysis[12] was done for two time slabs, viz. 1958–1985 and 1970–1985. The trends reported for the second time slab, which also nearly juxtaposes the present study period till 1985, are almost similar with the values obtained in this study for the period 1973–1985. For example, at 500 hPa over Kolkata, both studies report –1.3°C/decade, whereas at 200 hPa over Delhi, both studies report –1.5°C/decade. Even at lower levels, the difference in values is always less than 0.5°C/decade. The slightly different period used in the present study (1973 instead of 1970) could also be one possible reason for this difference. It can also be seen from Table 1 that the warming trend at 850 and 700 hPa over Thiruvananthapuram is comparable with those of Delhi and Kolkata, though the former is not a megacity. One of the reasons could be that warming seen over stations in southern India is more than those in the northern part of the subcontinent due to different circulation patterns[12]. However, the increase in trend from 850 to 700 hPa is far less over Thiruvananthapuram than over either Kolkata or Delhi. The other datasets presented in Table 1 are: (i) Integrated Global Radiosonde Archive (IGRA) and (ii) Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC). All these data have been taken from an earlier work[17]. The trend for Kolkata at 850 hPa is close to the RATPAC and IGRA values, while Delhi shows a larger warming trend at this level. Delhi trends exhibit a close match with the IGRA dataset at 200 hPa.

Considering the entire period of the present study (1973–2008), temperatures over Delhi at 850 hPa exhibit a positive trend (0.25°C/decade; significant at 95% confidence level (CI)), whereas Kolkata shows a trend of 0.05°C/decade (Figure 1). The trend values are close to each other at 700 hPa (Delhi, 0.29°C/decade; Kolkata, 0.27°C/decade; both significant at 95% CI); these values are also the maximum for the entire profiles. The trend value at 700 hPa over Thiruvananthapuram (0.21°C/decade) is low compared to Delhi and Kolkata (Table 1). In a recent

Table 1. Temperature trends for different periods over Delhi, Kolkata and Thiruvananthapuram. The trends during 1958–1985 and 1970–1985 have been taken from Kumar *et al.*[12]. The trends during 1979–2004 involve data from (i) Integrated Global Radiosonde Archive (IGRA) and (ii) Radiosonde Atmospheric Temperature Products for Assessing Climate (RATPAC), which have been taken from Douglass *et al.*[17]

		Temperature trend (°C/decade)			
Station	Period	850 hPa	700 hPa	500 hPa	200 hPa
Delhi	1958–1985	–1.0	–1.0	–1.0	–2.0
	1970–1985	–0.2	–0.6	–0.9	–1.5
	1973–1985	0.0	–0.9	–0.8	–1.5
	1973–2008	0.25	0.29	0.25	–0.06
Kolkata	1958–1985	–0.8	–1.0	–1.1	–2.6
	1970–1985	–0.3	–0.8	–1.3	–2.1
	1973–1985	–0.6	–0.4	–1.3	–2.2
	1973–2008	0.05	0.27	0.23	–0.14
Thiruvananthapuram	1958–1985	–0.1	–0.3	–0.2	–0.1
	1970–1985	1.3	0.7	0.8	1.3
	1973–1985	1.1	0.34	0.9	1.3
	1973–2008	0.20	0.21	–0.05	–1.16
RATPAC	1979–2004	0.08	0.08	0.07	–0.02
IGRA	1979–2004	0.10	0.06	0.03	–0.07

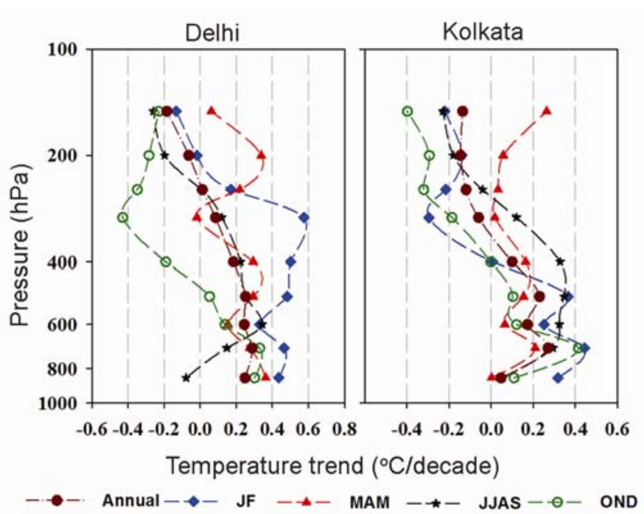

Figure 1. Trends in temperature for the period 1973–2008 for winter (JF), summer (MAM), monsoon (JJAS) and post-monsoon (OND) and annual over Delhi and Kolkata for different pressure levels.

study by Ramanathan *et al.*[8] related to warming over Asia, the authors have emphasized that the tropical atmosphere warms in response to the imposed atmospheric brown cloud heating, with peak annual mean warming between 2 and 4 km amsl, i.e. around 700 hPa. All the three stations show a dip in warming rates at 600 hPa, e.g. the value for Delhi is 0.24°C/decade (significant at 95% CI). However, the decrease in trend from 700 to 600 hPa over Thiruvananthapuram is much more rapid than the other two stations. The 600 hPa trend for Thiruvananthapuram is ~0.01°C/decade and the 500 hPa trend is ~–0.05°C/decade. Temperature trends observed over Thiruvananthapuram become negative (show cooling) at and above 500 hPa. Trend value at 400 hPa for Delhi is ~0.18°C/decade and for Kolkata it is 0.10°C/decade. The trends become negative for Kolkata above 400 hPa, whereas this situation occurs for Delhi further up. In the tropics, the transition to cooling aloft occurs at a considerably greater altitude, and an increase in warming at lower altitudes is explained by moist adiabatic theory[18].

It is to be noted that even in the earlier study[12], considerably less cooling was observed during the period 1970–1985 compared to the extended period 1958–1985 (Table 1). Thus, there is already a signature of warming with time in the study[12]. The present study, which accounts for the recent period 1973–2008, clearly shows the warming trend in the lower troposphere. This implies that there has been a change from cooling to warming during the recent period over these urban locations. The last three decades have also witnessed ~340% increase in carbon dioxide emissions from consumption and flaring of fossil fuels (from 293 million tonnes in 1980 to 1293 million tonnes in 2006), a 260% increase in carbon dioxide emissions from petroleum burning (from 91 million tonnes in 1980 to 332 million tonnes in 2006), and 338% increase in coal consumption (from 115 million tonnes in 1980 to 489 million tonnes in 2006) over India (http://www.eia.doe.gov). Local processes such as urbanization and industrialization could play a role in causing differential vertical temperature trends[19]. Kumari *et al.*[20] have observed a reduction of solar radiation at the surface by –1.44 (± 0.27) and –1.28 (± 0.18) W/m^2/yr for Delhi and Kolkata respectively, during the period 1981–2004. The higher reduction of solar radiation at the surface over Delhi implies more heat being trapped in the atmosphere; hence the trend in temperature is higher compared to Kolkata in the 850–500 hPa region. This shows that warming due to GHGs and other species is much stronger. Aerosol loading has been shown to increase at 2.4% per year over Thiruvananthapuram[21], which may also have an impact on the 850 hPa trends over the city of Thiruvananthapuram. However, long-term measurement data of GHGs and aerosols in the vertical are not available for Delhi and Kolkata.

Long-term temperature trends in different seasons

Since seasonality is observed in the dataset, these data are separated into four seasons: January and February (JF) for winter; March, April and May (MAM) for summer; June, July, August and September (JJAS) for monsoon, and October, November and December (OND) for post-monsoon/fall season. Occurrence of extreme low temperature in association with incursion of dry, cold winds from the north into the subcontinent (cold waves) is seen during winter (JF). North India and the adjoining plains are influenced by transient disturbances in the mid-latitude westerlies, which often have weak frontal characteristics. In particular, Delhi experiences severe winters with foggy conditions in the morning, which has been a growing concern. As winter season transforms into spring, thunderstorms and squally weather which are hazardous in nature, assume significance over both Delhi and Kolkata. During the JJAS period, both the stations experience southwest summer monsoon. Kolkata also experiences thunderstorms during the post-monsoon. Observations indicate occurrence of more extreme temperature events over the east coast of India. The decrease in the minimum temperature at the surface during summer monsoon and its increase during post-monsoon months have created a large difference of the order of 0.8°C in the seasonal temperature anomalies at the surface, which may have implications to seasonal changes in atmospheric circulation[22]. The estimated trends for the entire duration of records for different seasons over Delhi and Kolkata are shown in Figure 1. Whereas the general pattern of variability is similar to the annual profiles, the trends are different for different seasons. The variations over the two stations are discussed season-wise.

Long-term trends over Delhi become progressively greater from monsoon to post-monsoon, summer and winter at 850 hPa. During winter, both the stations experience northwesterly winds, which bring pollutants along their trajectories. Winter is the season when there is more static stability, implying a better accumulation of particles. In other words, better sustenance of warming in the lower and middle troposphere. Over Delhi, the winter trends are higher compared to all other seasons between 850 and 300 hPa, whereas the monsoon trend at 600 hPa is higher compared to the winter trend over Kolkata (Figure 1). It is seen that warming trend during winter over Delhi is quite pronounced and even at 300 hPa, a significant trend of 0.57°C/decade (significant at 95% CI) is observed. A haze over the IGP with as much as 10–15% of BC (by mass of total aerosols), is known to reduce the surface solar insolation by about 10% (–15 Wm^{-2}) and nearly double the lower atmospheric solar heating[23]. The average mass of BC aerosols measured over Delhi for a token year in 2000 was nearly 2.5 times higher during winter (19–27 $\mu g\ m^{-3}$) compared to the summer values (8–12 $\mu g\ m^{-3}$)[24]. BC acts to warm the atmosphere while cooling the surface. The seasonal and daily average reduction of solar radiation at the surface by the aerosols ranges from –10 to –30 Wm^{-2} between the equator and 25°N, and a heating of the aerosol layer (0–3 km) occurs by a similar amount[25]. An increasing trend in fog formation during the period 1989–2003 at the Delhi Airport with total rise of fog hours by 8.2 h/day was reported[26]. Additionally, winter temperatures being lower, warming effect appears more pronounced.

A significant warming of 0.36°C/decade during summer is observed at 850 hPa over Delhi (Figure 1). Analysis of tropospheric temperatures from the longest available record of microwave satellite measurements reveals widespread warming over the Himalayan–Gangetic region in the 4–7 km altitude range, especially in the pre-monsoon season due to high amount of dust mixed with soot from industrial/urban pollution over the IGP[9]. Figure 1 shows significant positive trends of 0.29°C/decade at both 500 and 400 hPa, and 0.34°C/decade at 200 hPa (significant at 95% CI) during summer over Delhi, when the wind pattern is westerly in the upper troposphere. Whereas the summer trends over Delhi continue to decrease till 600 hPa, the trends over Kolkata become more positive with increasing height till about 700 hPa, where the value is 0.21°C/decade. Overall, the summer profiles of temperature trends over the two stations do not exhibit much variation in the region between 850 and 200 hPa. Over Delhi, except at 300 hPa, the trends lie within a range of 0.15–0.40°C/decade, whereas over Kolkata they lie entirely between 0 and 0.2°C/decade.

The trend profiles during monsoon over both the stations exhibit almost similar patterns, with Kolkata showing slightly higher rate of warming than Delhi. Cloud cover data available from the IMD archive show a positive trend between 1980 and 2005 over both Delhi and Kolkata[27]. An interesting observation in Figure 1 is that temperature trends during monsoon increase with height above the ground. Thus, increasing cloud cover may have implications in reduced warming at the surface (reduction in solar radiation) and accelerating warming within and around the cloud layer. During this season, the wind pattern over Delhi is southwesterly whereas Kolkata experiences southeasterly winds. Further, Kolkata being closer to the sea is also more humid. A peak monsoon trend value of 0.34°C/decade occurs over Delhi at 600 hPa and ~0.35°C/decade at 500 hPa over Kolkata. These trends over both the places are significantly higher between 700 and 400 hPa. A conspicuous feature is the high warming rate at 600 hPa in comparison to other levels over both the stations during monsoon, while there is a dip in the altitudinal profile of trends at 600 hPa during winter and pre-monsoon. The aerosol burden is small during this period as a result of washout and scavenging by the summer-monsoon precipitation[23]. Apart from a warming at 700 hPa over Kolkata (0.4°C/deacde), post-monsoon trends are generally lower compared to other seasons. The post-monsoon trend over Delhi is conspicuously very low in the 600–200 hPa height region compared to other seasons.

Anomalies in temperature

Temperature anomalies at 850, 700, 500 and 300 hPa for Delhi and Kolkata during 1973–2008 are shown in Figure 2, along with the percentage departure in rainfall and solar radio flux values. The homogeneous monthly data for different regions over India during 1973–2008 have been used to calculate the percentage departure of rainfall over the Haryana–Chandigarh–Delhi region and Gangetic West Bengal region. These data have been taken from the website of the Indian Institute of Tropical Meteorology, Pune (www.tropmet.res.in) for the period 1973–2008. Adjusted solar radio flux values at 10.7 cm in solar flux units (1 s.f.u. = 10^{-22} Wm^{-2} Hz^{-1}) were obtained from the NOAA database (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/Penticton.txt). These are good indicators of solar flux values in the visible range also.

The amplitude of variation in the annually averaged temperature anomalies is about ± 1.5°C over both the places, with few values exceeding this limit. Temperature anomalies over both places seem to follow similar patterns, with positive values in early 1970s to large negative values in early 1980s. The values again peak around the end of 1980s and early 1990, then decrease and again peak just ahead of 2000. During the decade 1991–2000, a significant increase in the frequency, persistence and spatial coverage of heat wave/severe heat wave was observed in comparison to that during the earlier decades 1971–1980 and 1981–1990 (ref. 28), and this is also clearly visible in the temperature anomalies in Figure 2. There is a clear negative slope during 2000–2008 over Kolkata, which is not observed over Delhi. Solar flux values show a clear 11-year cycle with peaks around 1980, 1990 and 2001, whereas temperature anomalies show peaks around 1990 and 2000 but not in 1980.

Rainfall may change due to changes in air temperature and aerosol apart from other factors[2,29]. A significant reduction (5% level) in the strength of wind field (NCEP/NCAR reanalysed data) over peninsular India and the adjoining southern parts of the Bay of Bengal and the Arabian Sea has been observed[30]. However, the present results do not show any systematic departure in the rainfall pattern due to changes in temperature (Figure 2). Volcanic eruptions generally release large amounts of dust and sulphur dioxide into the stratosphere, causing a dip in temperature due to the scattering property of sulphate aerosols. The negative temperature anomalies in the initial part of 1980s and 1990s bear signatures of volcanic eruptions. Climate models estimate 0.2°C and 0.5°C reductions in global temperature due to the El Chichon and Mt. Pinatubo volcanoes respectively[31]. In fact, the temperature dropped dramatically for a year or so after each major eruption (El Chichon; 1982 and Mt. Pinatubo; 1991, which released about 7 and 20 million tonnes of SO_2 respectively) and took a few years to gradually recover[1,32]. At 300 hPa, the effect of the Mt. Pinatubo (June 1991) eruption is reflected by large negative anomaly over both Kolkata and Delhi (also reported over Thiruvananthapurum using a bistatic CW lidar[32]). This anomaly is seen for all the pressure levels in the upper troposphere. However, not all large eruptions are followed by temperature decreases, and not all historic temperature decreases are preceded by large eruptions. Changes in atmospheric circulation or modes of atmospheric variability (e.g. El Niño-Southern Oscillation, ENSO) can produce different temperature trends in the surface and aloft[33]. In fact, in both observations and climate models, variations in the ENSO have pronounced effects on surface and tropospheric temperatures. The negative anomalies in 1997 at all levels over both the stations may be related to a relatively strong ENSO event in that year, though effect of El-Niño towards weakening of the Indian monsoon and rising temperatures is still unclear. However, each ENSO event marked in Figure 2 is followed by a visible increase in temperature. The link between the heat wave in 1998 with El-Niño of 1997 has been documented[28] and is also visible in Figure 2. Reports indicate that 1998 was noted for severe heat wave and a larger number of deaths in different parts of the world.

Other effects and correlations

The annual and seasonal temperature data series over Delhi at different pressure levels has been compared to the corresponding values over Kolkata for the period 1973–2008 to find out whether there is a common factor governing the temperature variations over these urban stations. Correlation between mean temperatures over Delhi and Kolkata at different pressure levels is poor in the lower atmosphere (correlation coefficient values of 0.39 for 850 hPa), and moderate (0.71–0.79) between 700 and 150 hPa levels (Table 2). This is because with

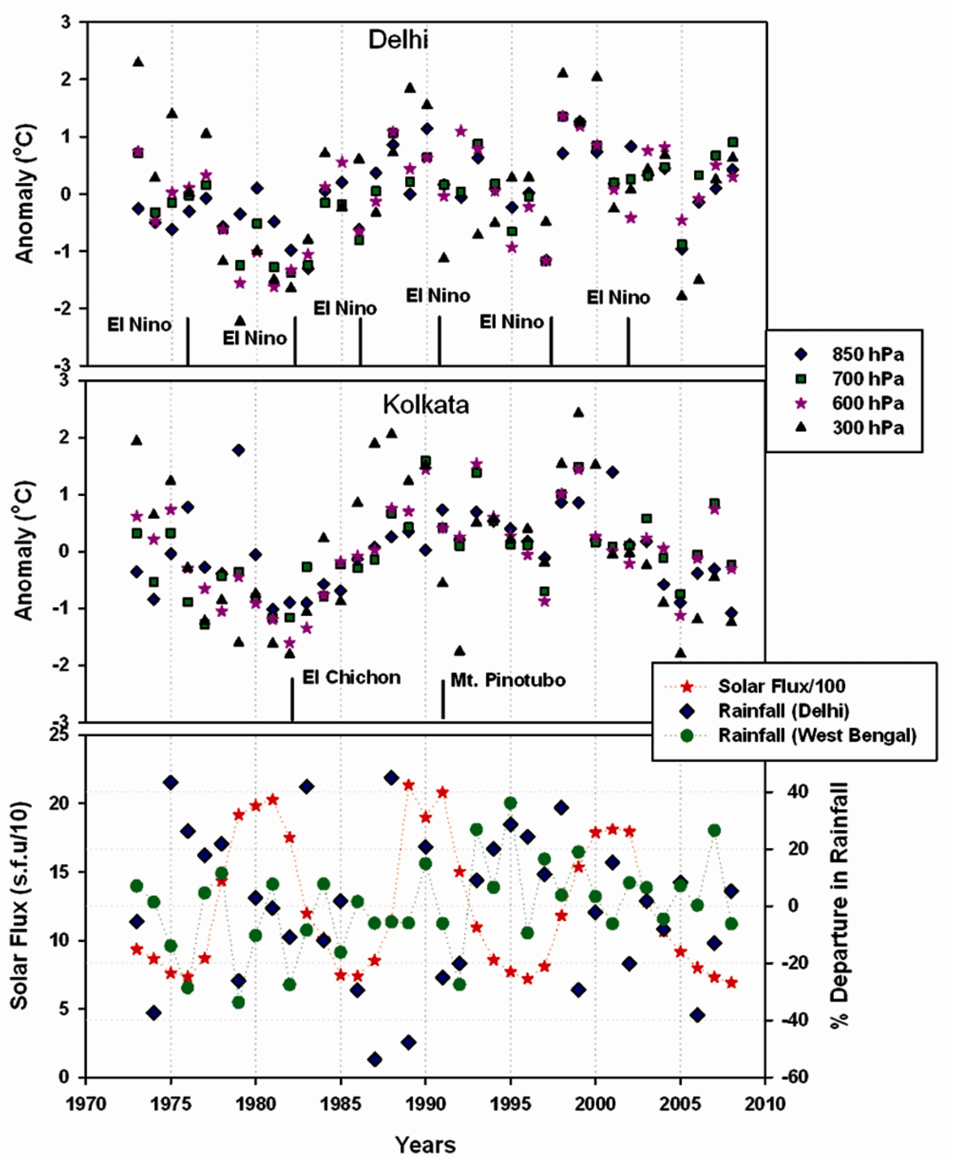

Figure 2. Temperature anomalies over Delhi and Kolkata for different pressure levels for the period 1973–2008. The third panel shows percentage departure of rainfall over the Haryana–Chandigarh–Delhi region and Gangetic West Bengal region using mean value of 1973–2008 and also yearly adjusted solar flux values.

Table 2. Correlation between Delhi and Kolkata temperatures at various pressure levels during 1973–2008

Pressure (hPa)	Annual	DJF	MAM	JJA	SON
850	0.39	0.54	0.36	0.60	0.51
700	0.72	0.59	0.74	0.69	0.50
600	0.73	0.49	0.79	0.73	0.46
500	0.76	0.67	0.54	0.75	0.60
400	0.71	0.65	0.57	0.69	0.57
300	0.75	0.55	0.76	0.76	0.63
250	0.77	0.53	0.77	0.81	0.70
200	0.78	0.57	0.66	0.78	0.70
150	0.77	0.29	0.55	0.70	0.58

DJF, December, January and February; MAM, March, April and May; JJA, June, July and August; SON, September, October and November.

increase in altitude, the local effects (microclimate) diminish and regional effects become predominant. It is also seen that while temperatures during the monsoon exhibit correlation values of the order of 0.6–0.8 at all levels, correlation coefficient values are lower for other seasons. This is related to particularly strong winds associated with the southwest monsoon that sweep the IGP during monsoon. This homogenizing effect is absent during the other seasons. Hence the effect of aerosols, trace gases and thermodynamics is more prone to reflect the local characteristics of the places. However, correlations of the order of 0.74 and 0.79 during summer at 700 and 600 hPa respectively are probably a consequence of long-range transport that causes northwest India and the IGP to be shrouded in dust.

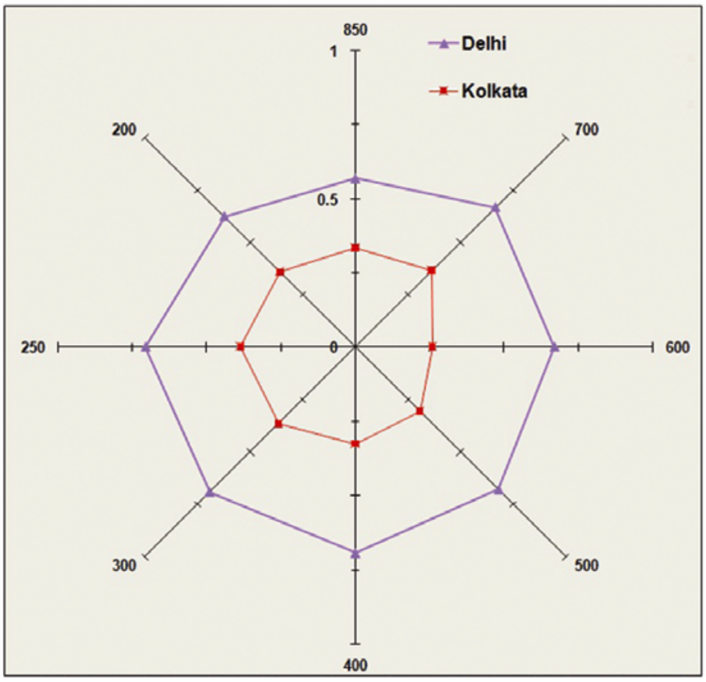

Figure 3. Correlations between aerosol optical depth at 550 nm obtained from MODIS–GOCART and temperature at various pressure levels during 2000–2007.

As aerosols are an integral part of the radiation budget and their distribution plays a pivotal role in determining temperature over a region, we have compared the tropospheric temperatures for the period 2000–2007 with the available monthly aerosol optical depth (AOD) at 550 nm from MODIS (http://daac.gsfc.nasa.gov/giovanni/). Delhi temperatures at 850 hPa showed a correlation value of 0.57 with AOD over Delhi (Figure 3). The temperature patterns at higher altitudes show better correlation with AOD over Delhi until 250 hPa. The corresponding correlation values over Kolkata are very low (Figure 3). This shows that Delhi temperatures are affected more by aerosol values than Kolkata temperatures. In fact, Delhi is often affected by high levels of pollution and dust from the nearby Thar Desert, whereas showers in different seasons, including pre-monsoon thunderstorms often cleanse Kolkata's atmosphere. It must be noted that these AOD data represent total columnar values, whereas temperature values are for individual altitudes.

Summary and conclusion

Long-term temperature trends over Delhi and Kolkata have been studied at different pressure levels in the troposphere based on radiosonde data for the period 1973–2008. Between 850 and 150 hPa, the maximum increase in temperature (0.27°C/decade for Kolkata and 0.29°C/decade for Delhi) occurred at 700 hPa during 1973–2008. Warming trends are seen until 400 hPa, whereas cooling trends are found to occur above this altitude. Long-term trends in different seasons reveal greater warming during winter until 300 hPa over Delhi and in lower altitudes over Kolkata. Trends during monsoon are the highest at altitudes above 500 hPa over Kolkata. The summer profiles of Delhi and Kolkata show contrasting characteristics in the lower atmosphere. A conspicuous observation is that while there is a dip in altitudinal profile of trends over both stations at 600 hPa during pre-monsoon and winter, there is a peak in trend at this level during monsoon. Seasonal trends in temperature are found to be the lowest during post-monsoon over most height regimes.

An important feature observed in the temperature trends over these two stations is the change from cooling during 1958–1985 to warming during 1973–2008. In an earlier study[12], a reduction in cooling trends during 1970–1985 compared to the 1958–1985 period was evident. However, the present study shows warming trends during 1973–2008. The recent period, i.e. 1971–2003 has also seen a relatively accelerated warming of 0.22°C/decade for all-India annual mean surface temperature. During the last three decades, there has been manifold increase in emissions from fossil fuels, petroleum burning and coal consumption due to rapid industrialization and urbanization. The distribution of aerosols, mainly BC and dust, has been shown to influence the temperature trends. Increasing concentration of GHGs also contributes in the lower and middle troposphere with respect to temperature trends. However, because of the lack of comprehensive long-term observations of vertical variations of these gases and aerosols, it is not possible to establish their role with respect to temperature trends. The rate of warming at different altitudes is a complex interplay of radiation, chemistry and dynamics, and needs to be disentangled by simultaneous analysis of trends in trace gases and aerosols.

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