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Decline in horizontal surface visibility over India (1961–2008) and its association with meteorological variables

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Abstract Horizontal surface visibility range, one of the simplest measures of local atmospheric pollution, is critical for aviation, surface transport besides long-term impact on human health and climate. Long-term observations from multiple stations (including airports) across the world show statistically significant decline in visibility. We have studied climatology and trends of morning poor visibility days (PVD, visibility <4 km) and afternoon good visibility days (GVD, visibility >10 km) based on 279 surface meteorological stations well distributed over India for the period 1961–2008. During last 5 decades, all India averaged range of annual morning PVD has increased from 6.7 to 27.3 % days, while the range of afternoon GVD has decreased from 76.1 to 30.6 % days. Annually, the morning PVD increased significantly at 3.3 % days per decade, and the afternoon GVD declined significantly at −8.6 % days per decade. Seasonally, the highest increase in morning PVD has occurred in winter (+4.3 % days per decade), while post-monsoon has the highest decrease in afternoon GVD (−9.2 % days per decade). In spatial distribution, visibility has decreased nationwide especially over Indo-Gangetic (IG) plains, central, east and northeast India which is due to increased wintertime fog, water vapor and aerosol loading. The IG plains suffer from increased fog or smog and aerosol loading during wintertime. Long-term visibility impairment over India is visible through increasing morning PVD (decreasing GVD) and decreasing afternoon GVD (increasing PVD) which are spatially well correlated with increasing relative humidity and decreasing wind speed (seasonal).

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1 Introduction

Visibility is an excellent indicator of air quality of a place because its impairment can be recognized easily by even laypersons. Visibility impairment occurs as a result of scattering and absorption of light by tiny particles and gases in the atmosphere. Increased biomass burning and anthropogenic emissions into the Earth's atmosphere have led to much debate with regard to greenhouse gases, carbon buildup and increases in aerosols. It is well known that atmospheric pollution can cause a decrease in visibility which is defined as the maximum distance at which the outlines of a target can be recognized against the horizon as background (Horvath 1994). Air moves across the oceans and land masses transporting and transforming pollutants as they move from their source to locations where they impair visibility. Thus, the basic relationship between atmospheric visibility and other meteorological variables is complex due to highly intercorrelated nature of variations in these variables. However, through analysis of visibility trends, major factors responsible for visibility impairment can be estimated.

Globally, long time series of visibility data are available at respective National Meteorological Services all over the world. It has been used in many previous studies (e.g., Green and Battan 1967; Miller et al. 1972; Lewis 1980; Malm et al. 1980; Naegele and Sellers 1981; Sloane 1982a, b, 1983, 1984; Gomez and Smith 1987; McTainsh et al. 1989; Goudie and Middleton 1992; Qin and Yang 2000; Dayan and Levy 2005; Tsai 2005; Chang et al. 2009; Wang et al. 2009). Miller et al. (1972) reported substantial declines in summer season visibility during 1960s at three non-urban airports in USA. Studying visibility trends of 18 cities in USA, Naegele and Sellers (1981) have found decreasing trends for 1958–1972 and increasing trends for 1973–1979. There is a growing interest among scientists all over the world in the use of atmospheric visibility measurements as a proxy for air pollution studies. Munn (1973) and Inhaber (1976) have found significant increase in haze over airport stations from the middle 1950s to the early 1970s over eastern Canada especially during the summer. Sloane (1982a, b) has examined the methods used to determine trends in visibility due to air pollution. Studies have shown that low visibility strongly implies air pollution by ambient pollutants (Bishoi et al. 2009), by particulate matter (Lin et al. 2008; Xu et al. 2008) or by gaseous species (Sequeria and Lai 1998). The effects of meteorological parameters on visibility trends have been examined by Sloane (1983, 1984). Investigating UK visibility data, Lee (1983, 1988, 1990, 1994) and Gomez and Smith (1984) found trends within these data which correlate with changing fuel consumption and changing meteorological conditions (Lee 1994). Chang and Koo (1986) investigated the variation in visibility in Hong Kong and found significant upward trend in reduction in visibility during the period 1975–1980. Malm (1999) has attributed decline in visibility, especially during the summer in the southeast parts of USA between the late 1940s and early 1980s, to increase in sulfur emissions. Qin and Yang (2000) and Chang et al. (2009) have found decreasing trend in visibility in Beijing during 1980–1994 and 1973–2007, respectively. Analyzing visibility trends, Tsai (2005) found that there is a negative correlation between visibility and the concentration of the pollutant in southern Taiwan. Scattering and absorption by aerosols, however, are strongly correlated with anthropogenic emissions and are the main contributors to visibility impairment (Seinfeld and Pandis 2006). Recently, Wang et al. (2009) have found decrease in clear sky visibility over land globally from 1973 to 2007.

Visibility measurements taken at Indian stations have been studied by many investigators (Chandiramani et al. 1975; Mukherjee et al. 1980; Padmanabhamurty 1984; De et al. 2001) who have attributed the decreasing trends in visibility to atmospheric pollutants. Chandiramani et al. (1975) have shown that visibility at Mumbai airport is closely correlated with the concentration of suspended particulate matter and is inversely proportional to the concentration of pollutants. Mukherjee et al. (1980) and Padmanabhamurty (1984) have attributed winter month's poor visibility at Mumbai airport to smoke and other particulate matter. De et al. (2001) have shown that most airports in India which are located close to the major urban centers show a decreasing trend in horizontal surface visibility. Using remote sensing data, Saraf et al. 2011 have attributed occurrence of winter fog over the Indo-Gangetic plains to increasing pollution conditions over the region. Numerous studies carried out all over the world indicate that visibility impairment is largely due to the light scattering of ambient aerosols. But there is hardly any study related to long-term spatial and temporal changes in horizontal surface visibility over India and its correlations with meteorological variables like relative humidity and surface wind speed. Therefore, the aim of the present study is to document the long-term spatial and temporal changes in horizontal surface visibility and its correlations with relative humidity and surface wind speed over India. The location of 279 stations selected and the synoptic hours for which data are used in this study are shown in Fig. 1.

2 Data and methodology

2.1 Horizontal surface visibility definitions

Horizontal surface visibility is the maximum distance at which an observer can see an object situated in essentially the same horizontal plane. In other words, atmospheric

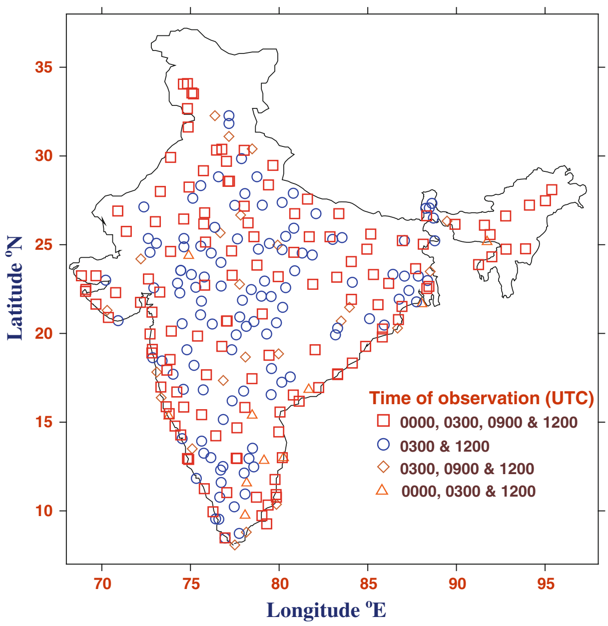


Fig. 1 Locations of 279 stations indicating data of synoptic hours used for the study

visibility is a standard of human visual perception of the environment. Horvath (1994) defined it as the maximum distance at which the outlines of a marker (generally mountains or other natural features) can be recognized against the horizon as a background. Shendrikar and Steinmetz (2003) define surface visibility as a human perception of a complex environmental situation that is primarily related to clarity of the air between the observer and the target that is being observed. Besides horizontal surface visibility, maximum visible range is defined as the furthest distance at which a dark object can be distinguished from the horizon which is about 300 km (Seinfeld and Pandis 2006) in a pristine environment at sea level.

2.2 Horizontal surface visibility classifications used in this study

While visibility data values estimated by trained observers are routinely recorded at most of the meteorological observatories all over the world, their reliability and accuracy have been questioned by many investigators (Sloane 1984; Hoffmann and Kuehnemann 1979). Regardless of its subjective nature, studies carried out all over the world have given ample evidence that visibility impairment is largely due to the light scattering of ambient aerosols whose concentrations are governed by the meteorological conditions.

In this study, we have used surface meteorological data for 0000, 0300, 0900 and 1200 hours UTC to classify morning and afternoon visibilities. Morning visibility denotes an average of 0000 (if available) and 0300 hours UTC (5:30 a.m. and 8:30 a.m., local time), and afternoon visibility denotes average of 0900 (if available) and 1200 hours UTC (2:30 p.m. and 5:30 p.m., local time). Furthermore, monthly percentage frequencies of days with morning visibility less than 4 km are defined as “poor visibility days” (PVD), while monthly percentage frequencies of days having afternoon visibility more than 10 km are defined as “good visibility days” (GVD). Gomez and Smith (1987) and Lee (1983) have used similar method to study the frequencies of “very good” visibility (>19 km) in United Kingdom. While visibility during morning is selected as a characteristic variable representing particle concentration in the boundary layer that could be aggravated by low mixing height and high relative humidity, visibility during afternoon is selected as a characteristic variable that could show the effects of fine particles emitted from vehicles, industries and other human activities on atmospheric visibility. According to Gomez and Smith (1987), this is a good indicator of the influence of long-range transport of air pollution.

2.3 Methodology

Visibility observations in India are recorded at surface weather stations under the network of India Meteorological Department (IMD) at every synoptic hour (at 3 hourly intervals) in codes ranging from 90 (<0.05 km) to 99 (≥50 km). Surface meteorological data for 0000, 0300, 0900, and 1200 UTC are used in characterizing morning and afternoon hour visibility. To facilitate comparison, monthly frequencies of visibility are expressed as a percentage of the total number of observations recorded at the station in the month. Monthly percentage frequencies of visibility in ranges <1 km and 1–4 km at 0000 and/or 0300 UTC are used for preparing mean morning poor visibility days (PVD), and monthly percentage frequencies of visibility in ranges 10–20 km and >20 km at 0900 and/or 1200 UTC are used in preparing mean good visibility days (GVD) data series. Similar to visibility, monthly means of relative humidity (RH) and wind speed (WSP) are also prepared for morning and afternoon hours. From the monthly means, annual and seasonal mean

Table 1 All India trends in poor visibility days (PVD) in percentage days per decade, good visibility days (GVD) in % days per decade, relative humidity (RH) % per decade and wind speed (WSP) in kmph per decade

	Morning trends			Afternoon trends		
	PVD	RH	WSP	GVD	RH	WSP
January	+4.7*	+1.3*	−0.4*	−8.6*	+1.2*	−0.4*
February	+4.1*	+1.6*	−0.4*	−8.9*	+1.4*	−0.5*
March	+3.0*	+1.7*	−0.5*	−8.4*	+1.3*	−0.6*
April	+2.1*	+1.0*	−0.6*	−7.9*	+0.7*	−0.7*
May	+2.2*	+1.1*	−0.7*	−8.1*	+1.0*	−0.9*
June	+2.6*	+0.6	−1.0*	−7.9*	+0.8	−1.0*
July	+3.0*	0.0	−0.9*	−8.3*	−0.1	−0.9*
August	+2.8*	0.0	−0.8*	−8.6*	−0.2	−0.8*
September	+2.8*	+0.2	−0.7*	−8.9*	0.0	−0.7*
October	+3.3*	+0.8*	−0.4*	−9.3*	+0.5	−0.5*
November	+4.2*	+1.0*	−0.4*	−9.0*	+0.7	−0.4*
December	+4.4*	+0.9*	−0.4*	−8.3*	+0.7	−0.4*
Annual	+3.3*	+0.8*	−0.6*	−8.6*	+0.7*	−0.7*
Winter	+4.3*	+1.3*	−0.4*	−8.6*	+1.1*	−0.5*
Summer	+2.4*	+1.3*	−0.6*	−8.1*	+1.0*	−0.8*
Monsoon	+2.8*	+0.2	−0.8*	−8.4*	+0.2	−0.8*
Post-monsoon	+3.8*	+0.9*	−0.4*	−9.2*	+0.6	−0.4*

Trends are based upon data from 279 surface meteorological stations for 1961–2008 and trends significant at 99 % level of confidence are marked by "*"

morning PVD, afternoon GVD, morning and afternoon RH and WSP are prepared for all 279 stations. The annual and four seasons are averages of January to December [annual], December (of previous year) to February [winter], March to May [summer], June to September [monsoon] and October to November [post-monsoon]. Data used in this study are taken from the archives of IMD located at National Data Centre (NDC), Pune, where all quality-controlled atmospheric data are archived.

From the monthly time series of 279 stations, India averaged monthly, annual and seasonal morning PVD, and afternoon GVD, RH and WSP data series are prepared for 1961–2008 to examine countrywide trends. The linear trend analysis is performed on these data series, and trends are tested for significance at 99 % level of significance using *t* test. All India averaged monthly, annual and seasonal trend values of morning PVD, RH and WSP and afternoon GVD, RH and WSP are given in Table 1. Monthly variations in all-India averaged means of morning PVD and afternoon GVD are shown in Fig. 2. Annual and seasonal temporal variations in India averaged morning PVD and afternoon GVD for 1961–2008 are shown in Fig. 3. The interannual variations in morning PVD and afternoon GVD all over India are compared by calculating standard deviation for all stations. The geographical distributions of annual and seasonal means and standard deviations of morning PVD and afternoon GVD are shown in Figs. 4 and 5, respectively, where patterns of standard deviation are shaded. Annual and seasonal trends in morning PVD and GVD and afternoon GVD and PVD are shown in Figs. 6 7, 8 and 9. Numbers of stations having decreasing/increasing trends in morning and afternoon PVD and GVD for annual and four

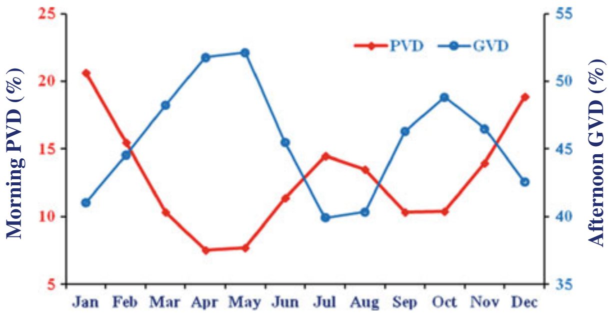


Fig. 2 Monthly variations in all India mean morning poor visibility days (PVD) and afternoon good visibility days (GVD) based upon data from 279 stations for 1961–2008

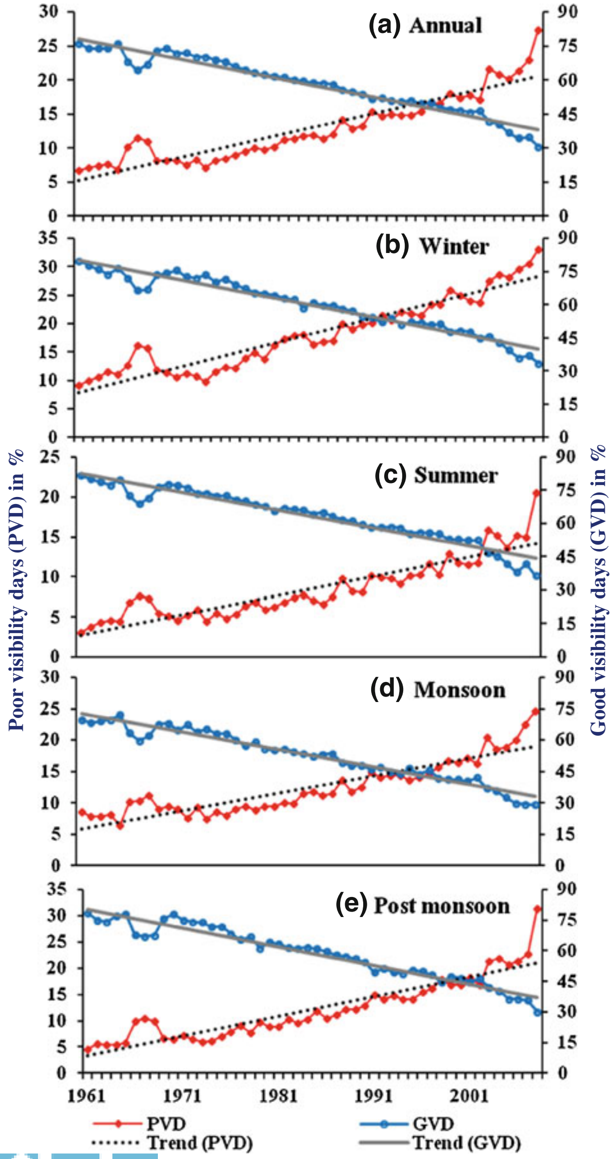


Fig. 3 Temporal variations in all India morning poor visibility days (PVD) and afternoon good visibility days (GVD) for 1961–2008

seasons are given in Table 2. Morning and afternoon RH and WSP trends and correlations with morning PVD and afternoon GVD are calculated, and their spatial patterns are shown for only annual (Figs. 10 and 11, respectively). Numbers of stations having negative or positive correlation between morning PVD and RH and morning PVD and WSP for annual and four seasons are given in Table 3. Similarly, numbers of stations having negative or positive correlation between afternoon GVD and RH and afternoon GVD and WSP are given in Table 4. The effects of population growth, increases in total numbers of vehicles, industrialization and urbanization in India are highlighted by showing the changes in rural–urban population ratio (Fig. 12a), growth of total numbers of vehicles (Fig. 12b) and increase in CO_2 emissions by vehicle exhaust (Fig. 12c).

3 Results and discussion

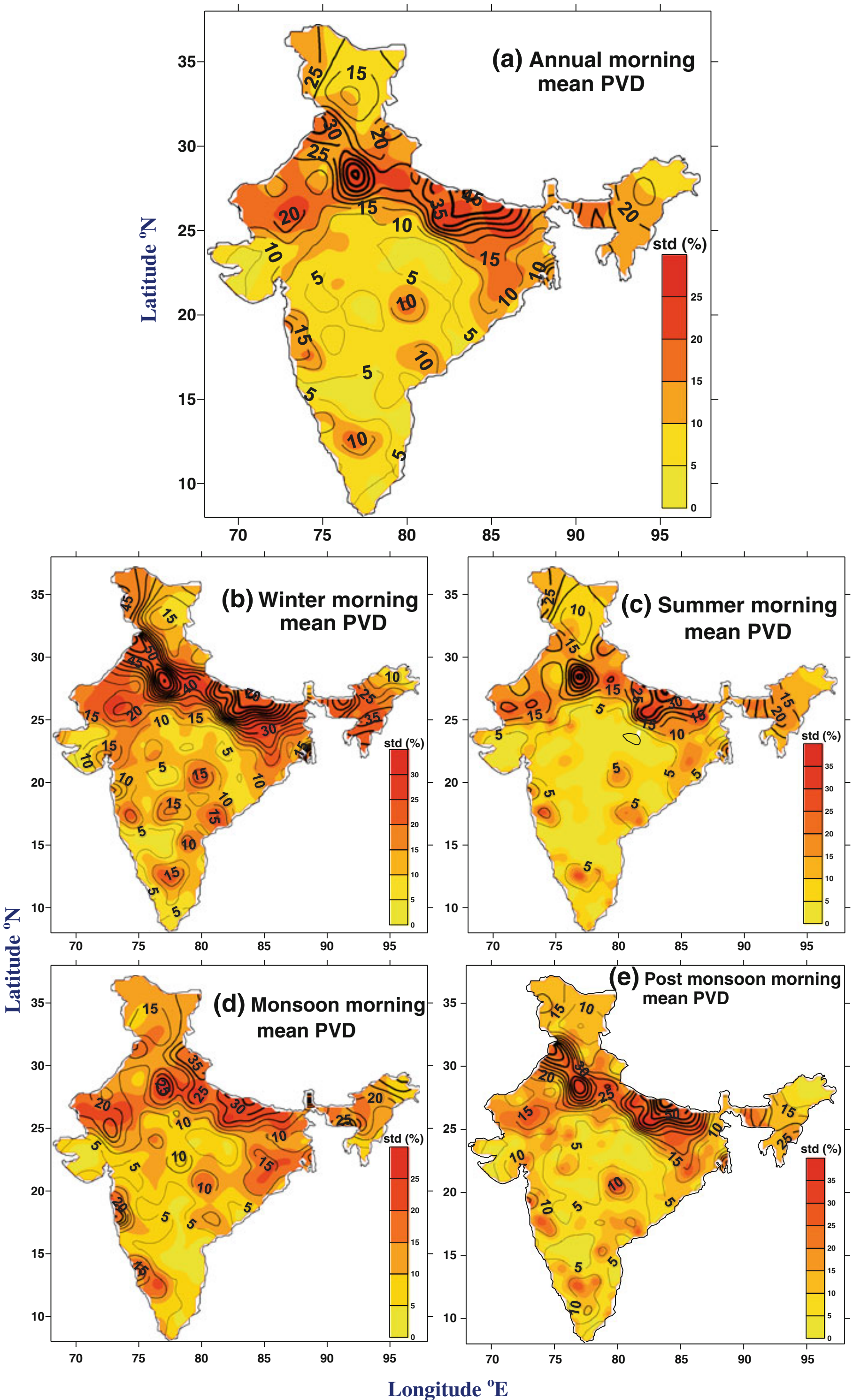
3.1 All India averaged means and trends

3.1.1 Monthly means of morning PVD and afternoon GVD

The transparency of the atmosphere is affected by the presence of hydrometeors (like rain, snow, mist and fog) or litho-meteors (like dust, smoke and other aerosols) which vary during the year all over India. The monthly time series of all India averaged morning PVD and afternoon GVD indicates complementary relationship as shown in Fig. 2. Mean morning PVD and afternoon GVD have two maxima and minima. All India averaged morning mean PVD is highest in January (20.6 %) and lowest in April (7.5 %). Similarly, all India averaged mean afternoon GVD is highest in May (52.1 %) and lowest in July (39.9 %). With southwest monsoon at its peak and with strong westerly surface winds, pollutants transported from Thar, Middle East and Sahara desert (Prasad et al. 2004 and Prasad et al. 2011) are well mixed, forming a uniform haze over many parts of India resulting in afternoon GVD minima in July. The secondary maxima and minima in morning PVD are obtained in July (14.5 %) and September (10.3 %), respectively. Afternoon GVD has secondary maxima and minima in October (48.9 %) and January (41 %), respectively. From October onward, there is an increase in morning PVD and decrease in afternoon GVD reaching their respective maxima and minima in January when atmosphere is stable.

3.1.2 Morning PVD and afternoon GVD, RH and WSP trends

All India monthly, annual and seasonal trends in morning PVD and afternoon GVD, RH and WSP are given in Table 1. The significantly increasing trends in morning PVD are in the range +2.4 to +4.3 % days per decade. Similarly, the decreasing afternoon GVD trends are in the range −8.1 to −9.2 % days per decade. Morning PVD trends are increasing significantly and afternoon GVD trends are decreasing significantly at 99 % level for all periods. On monthly scale, the highest increase in morning PVD is in January (+4.7 % days per decade), while the highest decrease in afternoon GVD is in October (−9.8 % days per decade). The increase in morning PVD and decrease in afternoon GVD are significant for annual as well as all the four seasons. Seasonally, the highest increase in morning PVD is for winter (+4.3 % days per decade), and the highest decrease in afternoon GVD is for post-monsoon (−9.6 % days per decade). All India morning mean monthly RH trends are significantly increasing for all months except June to September, in which trends are weak and non-significant. The highest increase in morning RH is in


(a) Annual morning mean PVD
(b) Winter morning mean PVD
(c) Summer morning mean PVD
(d) Monsoon morning mean PVD
(e) Post monsoon morning mean PVD
std (%)
Latitude °N
Longitude °E

◀**Fig. 4** Spatial variations of morning poor visibility days (PVD) over India for **a** annual, **b** winter, **c** summer, **d** monsoon and **e** post-monsoon. Means and standard deviations (*shaded*) of PVD are in percent

March (+1.7 % per decade). Afternoon RH trends are significantly increasing for January to May months with highest increase in February (+1.4 % per decade). Seasonally, morning RH trends are significantly increasing for all seasons except monsoon. Afternoon RH trends are significantly increasing for winter (+1.1 % per decade) and summer (+1.0 % per decade) seasons only. The RH trends all over India are similar to the trends reported by Jaswal and Koppar (2011). All India averaged WSP trends are significantly decreasing for all periods. The highest decrease in monthly morning and afternoon WSP is in June at −1.0 kmph per decade. Seasonally, the highest decrease in morning WSP is in monsoon (−0.8 kmph per decade), while highest decrease in afternoon WSP is in summer and monsoon (both at −0.8 kmph per decade). The decreasing WSP trends all over India are similar to the trends reported all over the world (Pirazzoli and Tomasin 2003; Tuller 2004; Pryor et al. 2009; McVicar et al. 2008; Guo et al. 2010).

3.1.3 Temporal variations in morning PVD and afternoon GVD

All India averaged annual and seasonal temporal variations in morning PVD and afternoon GVD for 1961–2008 are shown in Fig. 3. It is clearly evident from Fig. 3a–e that annual and seasonal morning PVD are increasing significantly while afternoon GVD are decreasing significantly. The increase (decrease) in morning PVD (afternoon GVD) is continuous during the period of study from 1961 to 2008. The range of annual morning PVD has increased from 6.7 % days in 1961 to 27.3 % days in 2008, while afternoon GVD has decreased from 76.1 % days in 1961 to 30.6 % days in 2008. This clearly indicates significant decline in atmospheric visibility all over India, which is similar to the reported decrease in range of annual visibility from more than 20 km in the early 1960s to 6–7 km during 2002–2003 all over Taiwan by Tsai (2005). Seasonally, the highest increase in morning PVD and afternoon GVD has occurred in post-monsoon. The range of post-monsoon morning PVD has increased from 4.5 % days in 1961 to 31.4 % days in 2008. On the other hand, range of afternoon GVD has declined from 78.5 % days in 1961 to 30.1 % days in 2008 for post-monsoon. The sharp increase in morning PVD and decrease in afternoon GVD during 1961–2008 (Fig. 3a–e) clearly indicates increase in atmospheric pollutants and aerosols during the period. As reported by many investigators, impaired visibility strongly implies the occurrence of ambient pollution (Dzubay et al. 1982; Sequeria and Lai 1998; Bishoi et al. 2009).

3.2 Annual and seasonal patterns of morning PVD and afternoon GVD means

3.2.1 Means of morning PVD

Figure 4 shows the geographical distribution of annual and seasonal means of morning PVD all over the country. Annual mean morning PVD are highest over north, northwest and northeast India. It is clear from Fig. 4a that stations in the Indo-Gangetic plains have the highest annual mean PVD. The highest mean morning PVD values obtained are 66.7 % days and 60.7 % days at New Delhi (Palam) and Kolkata (Dum Dum), respectively. The standard deviation of mean morning PVD is higher over northwest, northeast and Indo-Gangetic plains and lowest over central India and South Peninsula. Seasonal values of morning PVD are highest in winter (Fig. 4b) where large numbers of stations in Indo-

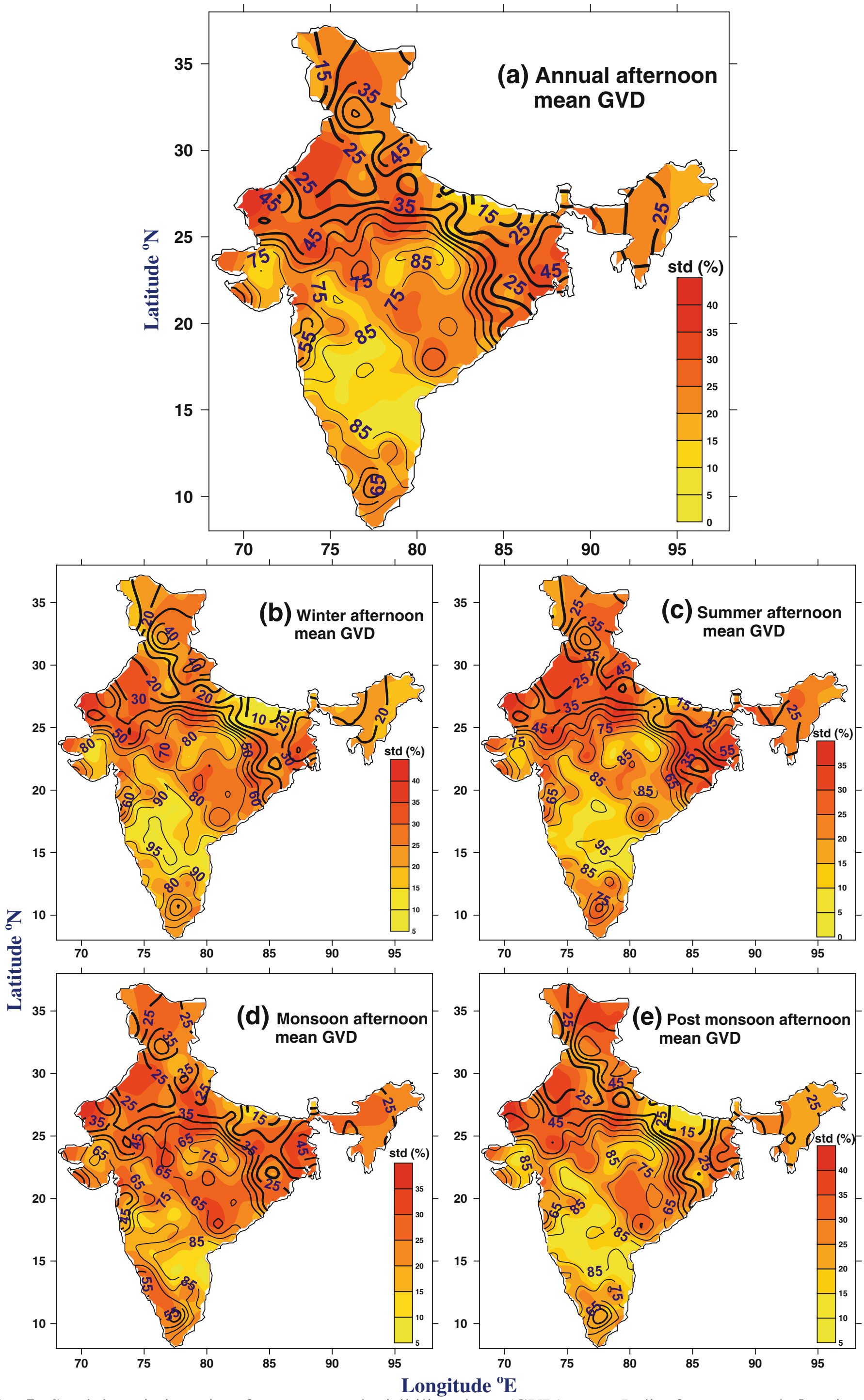


Fig. 5 Spatial variations in afternoon good visibility days (GVD) over India for **a** annual, **b** winter, **c** summer, **d** monsoon and **e** post-monsoon. Means and standard deviations (*shaded*) of GVD are in percent

Gangetic plains (New Delhi, Varanasi, Allahabad, Gorakhpur, Lucknow and Kolkata) are having morning PVD above 70 %. Except Indo-Gangetic plains and Rajasthan where dust storms are frequent during summer season, all other regions have lowest mean morning PVD as shown in Fig. 4c. For summer season, mean morning PVD are in the range 0.1 % days (Akola) to 67 % days (New Delhi). Spatial patterns of morning PVD for monsoon (Fig. 4d) show highest PVD over Rajasthan and Indo-Gangetic plains. Pockets over Western Ghats and northeast show higher mean PVD because of heavy southwest monsoon rainfall. Post-monsoon season has higher numbers of PVD over northwest India and in the Indo-Gangetic plains (Fig. 4e). The annual and seasonal spatial patterns as shown in Fig. 4 suggest Indo-Gangetic plains and Rajasthan as regions of highest morning PVD while central and south India have least morning PVD.

3.2.2 Means of afternoon GVD

Spatial patterns of annual mean afternoon GVD (Fig. 5a) indicate region of highest GVD over central India and South Peninsula where mean values are in the range 80–97 % days. Many stations in central and south India are having annual mean afternoon GVD more than 95 %. The standard deviation values of mean afternoon GVD are lowest at these stations as shown by the shaded regions in Fig. 5a. Seasonally, afternoon GVD are lowest over the northwest and northeast India and along the Indo-Gangetic plains with higher standard deviations as shown in Figs. 5b to 5e. It is clearly evident from Fig. 5 that central and south India have the highest mean afternoon GVD (70–95 % days) and northwest and northeast India and regions in the Indo-Gangetic plains have the lowest mean afternoon GVD (10–40 % days) for all periods. The standard deviation values of mean afternoon GVD are higher over northwest, northeast and central India and lowest over South Peninsula.

The distribution of morning PVD and afternoon GVD over India (Figs. 4 and 5) also shows similar distribution as obtained from satellite-derived mean seasonal aerosol loading by Prasad et al. 2004 and Prasad et al. 2011. This implies that the sources and distribution of aerosols over the IG plains have direct relationship with the PVD and GVD distribution and variability all over India.

3.3 Spatial patterns of trends in morning and afternoon PVD and GVD

3.3.1 Trends in morning PVD and GVD

Annual and seasonal morning PVD and GVD trends increasing or decreasing at 279 stations under study are given in Table 2. It is clearly evident from tendencies of these trends that PVD are increasing and GVD are decreasing at more than 75 % of the stations. These trends in morning PVD (Fig. 6a–e) and GVD (Fig. 7a–e) are more coherent over north, northwest, east, northeast India and along the Indo-Gangetic plains.

3.3.1.1 Annual Out of 279 stations in this study, annual trends in morning PVD are significantly increasing at 137 stations while morning GVD trends are significantly decreasing for 212 stations as given in Table 2. The annual PVD trends are between −6.3 % and +24.1 % days per decade. Stations showing higher increase in annual morning PVD (>15 % days per decade) are Allahabad, Mumbai, Varanasi, New Delhi, Kolkata, Bareilly and Rohtak. Annual GVD trends range between −35.3 % per decade at Mandya and +15.1 % at Dohad. Spatial patterns of annual mean PVD trends (Fig. 6a) and

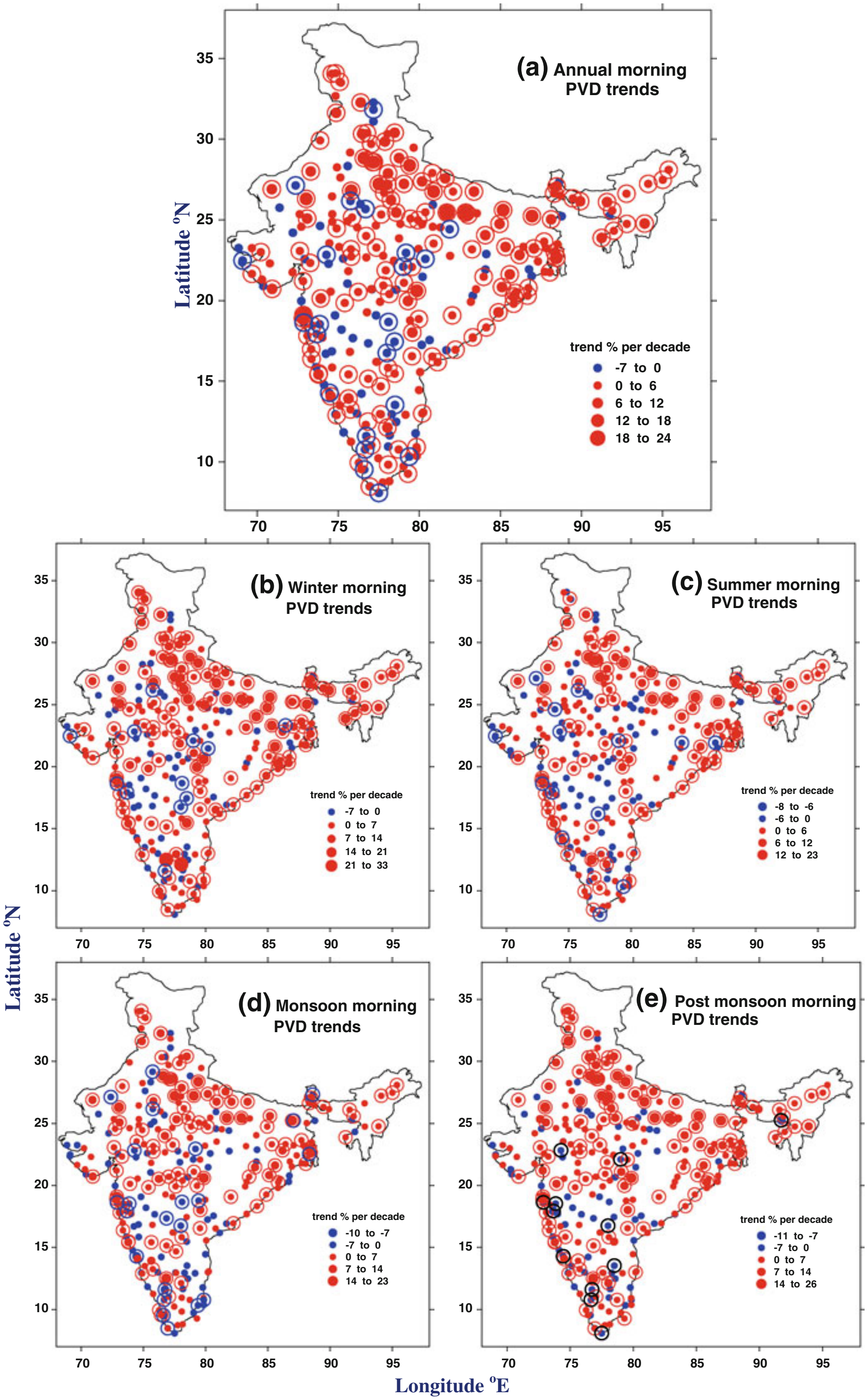

(a) Annual morning PVD trends
trend % per decade
-7 to 0
0 to 6
6 to 12
12 to 18
18 to 24
(b) Winter morning PVD trends
trend % per decade
-7 to 0
0 to 7
7 to 14
14 to 21
21 to 33
(c) Summer morning PVD trends
trend % per decade
-8 to -6
-6 to 0
0 to 6
6 to 12
12 to 23
(d) Monsoon morning PVD trends
trend % per decade
-10 to -7
-7 to 0
0 to 7
7 to 14
14 to 23
(e) Post monsoon morning PVD trends
trend % per decade
-11 to -7
-7 to 0
0 to 7
7 to 14
14 to 26
Latitude °N
Longitude °E

Fig. 6 Spatial variations of trends in morning poor visibility days (PVD) over India for **a** annual, **b** winter, **c** summer, **d** monsoon and **e** post-monsoon. Trend values are in % per decade, and outer circle at station indicates trends significant at 99 % level

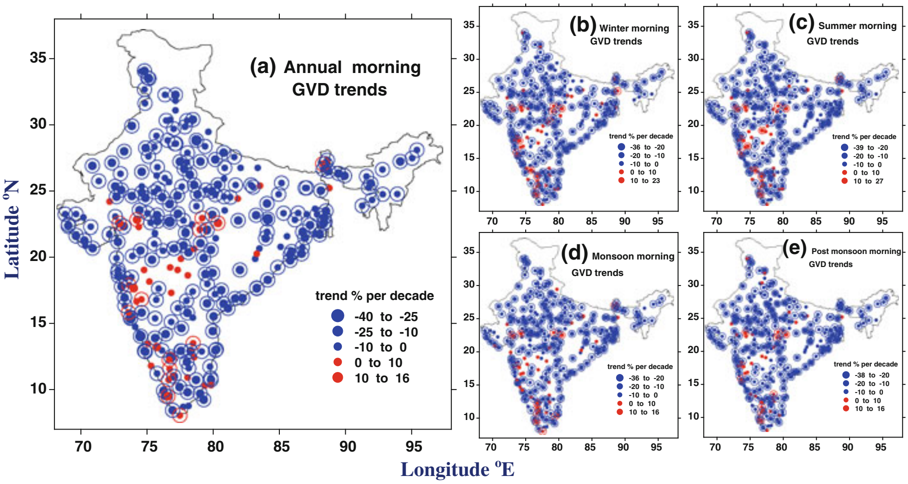


Fig. 7 Spatial variations of trends in morning good visibility days (GVD) over India for **a** annual, **b** winter, **c** summer, **d** monsoon and **e** post-monsoon. Trend values are in % per decade, and outer circle at station indicates trends significant at 99 % level

annual mean GVD trends (Fig. 7a) indicate significant decrease in horizontal surface visibility over large parts of the country.

3.3.1.2 Winter Winter morning PVD trends are significantly increasing at 127 stations, and GVD trends are significantly decreasing at 198 stations (Table 2). PVD trend values are between −6.6 and +32.7 % days per decade. Similarly, GVD trend values are between −36 % per decade and +22.5 % per decade. The spatial patterns of winter morning PVD trends (Fig. 6b) and GVD trends (Fig. 7b) indicate significant increase in PVD and decrease in GVD in all parts of the country but more coherently over west, north, northwest, east and northeast India. Most of the stations in the Indo-Gangetic plains are having significant increasing (decreasing) trends in winter morning PVD (GVD).

3.3.1.3 Summer Summer morning PVD are significantly increasing at 93 stations, and morning GVD are significantly decreasing at 198 stations (Table 2). Spatial patterns of summer morning PVD trends (Fig. 6c) and morning GVD trends (Fig. 7c) are more coherent over north, northwest and northeast India. The calculated trend values of PVD lie between −7.1 % days per decade and +22.4 % days per decade. Morning GVD trends lie between −38.4 % per decade and +26.3 % per decade.

3.3.1.4 Monsoon Monsoon morning PVD trends are significantly increasing at 103 stations, and morning GVD trends are significantly decreasing at 202 stations (Table 2). Spatial patterns of monsoon morning PVD and GVD trends are shown in Figs. 6d and 7d, respectively, which is almost similar to summer patterns.

Fig. 8 Spatial variations of trends in afternoon good visibility days (GVD) over India for **a** annual, **b** winter, **c** summer, **d** monsoon and **e** post-monsoon. Trend values are in % per decade, and outer circles at station indicate trends significant at 99 % level

3.3.1.5 Post-monsoon Post-monsoon morning PVD trends are significantly increasing at 115 stations and morning GVD trends are significantly decreasing at 200 stations as given in Table 2. Figs. 6e and 7e show patterns of morning PVD and GVD trends, respectively, for post-monsoon, indicating significant increase in PVD and decrease in GVD over all parts of the country but spatially more coherent over Indo-Gangetic plains, north, northwest, northeast and central India.

Annual and seasonal morning PVD and GVD trends clearly indicate sharp reduction in horizontal surface visibility over India, and the trends are similar to the observed trends over India (De et al. 2001) and China (Liang and Xia 2005).

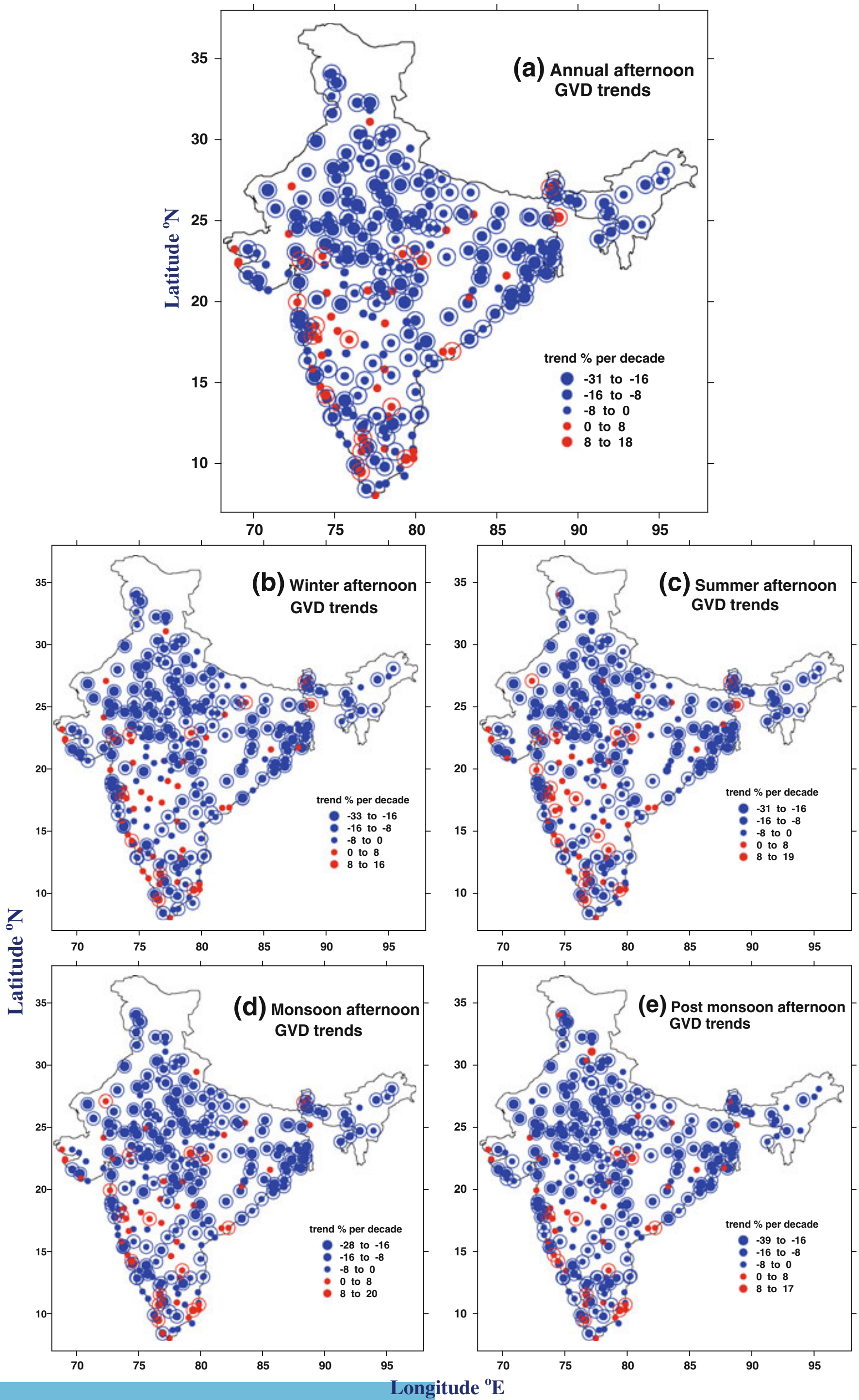
3.3.2 Trends in afternoon GVD and PVD

As given in Table 2, numbers of stations showing significant decreasing trends in afternoon GVD are 189, 176, 156, 178 and 179 for annual, winter, summer, monsoon and post-monsoon, respectively. Numbers of stations showing significant increasing trends in afternoon PVD are 121, 109, 57, 91 and 96 for annual, winter, summer, monsoon and post-monsoon, respectively. The spatial patterns of afternoon GVD (Fig. 8a–e) and PVD (Fig. 9a–e) indicate large-scale reduction in horizontal surface visibility, which is more coherent over north, northwest, east, northeast India and along the Indo-Gangetic plains.

Spatial patterns of afternoon annual mean GVD (Fig. 8a) and PVD (Fig. 9a) trends indicate significant decrease in good visibility days and increase in poor visibility days over all parts of the country. Except over some pockets in South Peninsula, the decreasing GVD (increasing PVD) trends are spatially coherent over all regions of the country. The range of annual afternoon GVD trends is between −30.2 and +17.6 % days per decade. Similarly, the calculated annual afternoon PVD trends lie between −7.1 % per decade and +23.3 % days per decade. Seasonal spatial patterns of winter (Fig. 8b), summer (Fig. 8c), monsoon (Fig. 8d) and post-monsoon (Fig. 8e) are almost similar to annual patterns except variations in magnitude of trends, suggesting all-round large-scale degradation of visibility for all periods. Seasonal trends in afternoon PVD are shown in Fig. 9b–e. Considerably, large numbers of stations are showing higher magnitude of decrease in afternoon GVD over the country. Some of the stations showing consistently higher decrease in afternoon GVD (more than 20 % days per decade) during all four seasons are Mumbai, Ahmedabad, Nagpur, Bhopal, Indore, Jhansi, Gwalior, Sriganganagar, Udaipur, Moradabad, Aurangabad, Baroda, Surat, Udaipur, Midnapore, Panjim, Coimbatore, Tirupattur and Kochi. Seasonal trend values are in the range −38.1 % days per decade (post-monsoon) and +19.1 % days per decade (monsoon). The decreasing trends in afternoon GVD and increasing trends in afternoon PVD imply increase in occurrence of haze over India.

3.4 Relationships with meteorological parameters

Meteorological factors such as wind, relative humidity, cloud cover, rain and temperature affect pollution. The rate at which pollutants are converted to other pollutants is determined by the availability of sunlight and the presence or absence of clouds. The heating of the Earth's surface and the vertical temperature profile of the atmosphere determine


(a) Annual afternoon GVD trends
trend % per decade
-31 to -16
-16 to -8
-8 to 0
0 to 8
8 to 18
(b) Winter afternoon GVD trends
trend % per decade
-33 to -16
-16 to -8
-8 to 0
0 to 8
8 to 16
(c) Summer afternoon GVD trends
trend % per decade
-31 to -16
-16 to -8
-8 to 0
0 to 8
8 to 19
(d) Monsoon afternoon GVD trends
trend % per decade
-28 to -16
-16 to -8
-8 to 0
0 to 8
8 to 20
(e) Post monsoon afternoon GVD trends
trend % per decade
-39 to -16
-16 to -8
-8 to 0
0 to 8
8 to 17
Latitude °N
Longitude °E

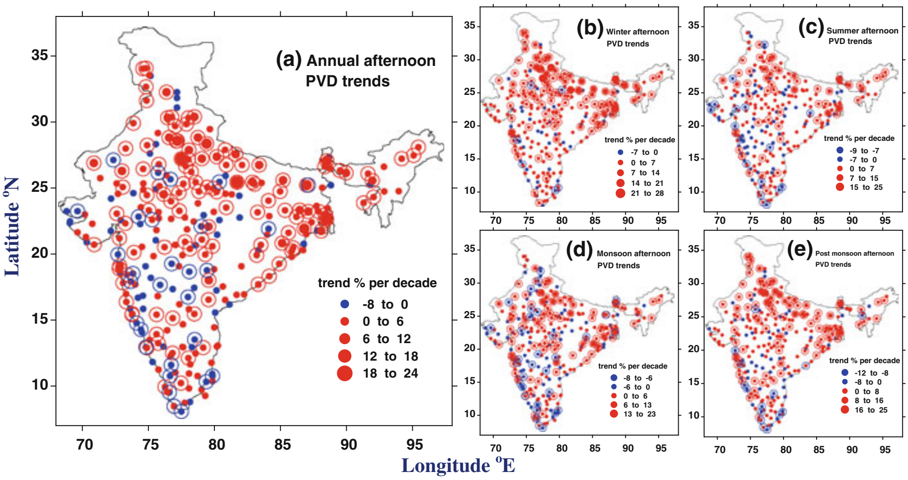


Fig. 9 Spatial variations of trends in afternoon poor visibility days (PVD) over India for **a** annual, **b** winter, **c** summer, **d** monsoon and **e** post-monsoon. Trend values are in % per decade, and outer circle at station indicates trends significant at 99 % level

Table 2 Numbers of stations having decreasing/increasing trends in morning and afternoon poor visibility days (PVD) and good visibility days (GVD) for annual and four seasons based upon data for 1961–2008

	PVD					GVD				
	ANN	WIN	SUM	MON	PMO	ANN	WIN	SUM	MON	PMO
Morning										
Decreasing	50	66	84	72	64	29	39	43	38	45
Significantly decreasing	23	12	14	22	12	212	198	198	202	200
Increasing	69	74	88	82	88	23	28	25	27	24
Significantly increasing	137	127	93	103	115	15	14	13	12	10
Afternoon										
Decreasing	61	67	86	75	67	44	55	72	51	57
Significantly decreasing	29	6	17	32	15	189	176	156	178	179
Increasing	68	97	119	81	101	29	37	32	34	31
Significantly increasing	121	109	57	91	96	17	11	19	16	12

whether the pollutants are mixed and diluted throughout the atmosphere or whether they are trapped under the lid of inversion. Pollutants emitted that are well mixed appear as a uniform haze impairing horizontal surface visibility. Regional- and synoptic-scale meteorological conditions also influence visibility as changing weather patterns can substantially alter the air transparency of a place at a given time (Sloane 1983, 1984; Lee 1983; Sequeria and Lai 1998; Dayan and Levy 2005; Tsai 2005).

3.4.1 *Relative humidity*

High relative humidity in the early morning hours leads to fog formation, which scatters visible light and thus reduces the atmospheric visibility. Annual morning RH trends are

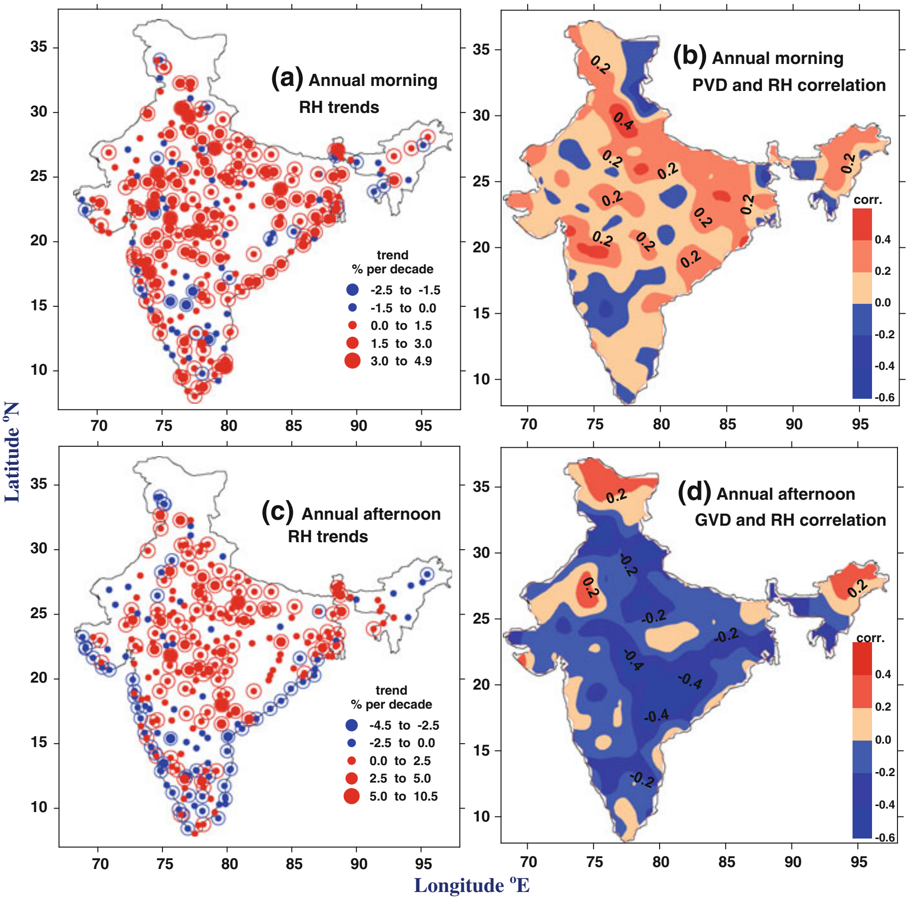


Fig. 10 Spatial variations of **a** annual morning relative humidity (RH) trends, **b** correlation between annual morning poor visibility days (PVD) and RH, **c** annual evening RH trends and **d** correlation between annual afternoon good visibility days (GVD) and RH over India based upon 279 stations for 1961–2008. Regions of positive correlation coefficients are *shaded*

significantly increasing at 143 stations and significantly decreasing at 23 stations. The trends in annual morning RH are in the range −2.5 to +4.8 % per decade.

3.4.1.1 Morning RH trend Spatial patterns of annual mean morning RH trends indicate significant increase over almost all parts but more coherently over Indo-Gangetic plains and southwest parts of the country as shown in Fig. 10a. Stations showing higher significant increasing trends in annual mean morning RH are Vedaranniyam, Khargone, Kalimpong and Amraoti, while Tirupattur, Alirajpur and Gadag are showing decreasing trends. As given in Table 3, 164 stations (61 %) are having positive correlation between annual morning PVD and RH. The correlation coefficients are between −0.7 and +0.8, and stations having higher positive correlations are Aurangabad, Karnal, Ozar and Varanasi.

Figure 10b shows the spatial patterns of correlation coefficients of annual morning PVD and RH, suggesting close relationship between increase in PVD and RH over large parts of

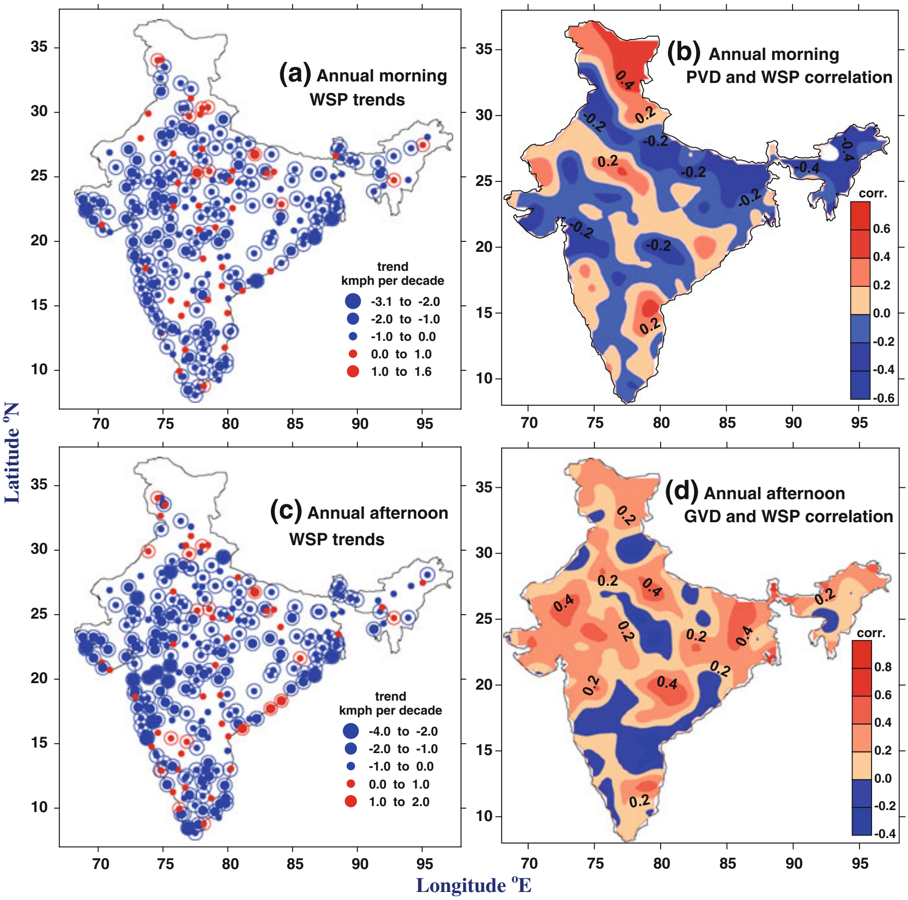


Fig. 11 Spatial variations of **a** annual morning wind speed (WSP) trends, **b** correlation between annual morning poor visibility days (PVD) and WSP, **c** annual evening WSP trends and **d** correlation between annual afternoon good visibility days (GVD) and WSP over India based upon 279 stations for 1961–2008. Regions of positive correlation coefficients are *shaded*

Table 3 Numbers of stations having negative or positive correlation between morning poor visibility days (PVD) and relative humidity (RH) and morning poor visibility days (PVD) and wind speed (WSP) for annual and four seasons based upon data for 1961–2008

	Morning PVD and RH					Morning PVD and WSP				
	ANN	WIN	SUM	MON	PMO	ANN	WIN	SUM	MON	PMO
Negative	84	60	87	82	45	143	131	123	144	136
Positive	164	187	165	161	183	115	113	117	113	104
No correlation	31	32	27	36	51	21	35	39	22	39

the country. Spatial patterns shown in Fig. 10a and b indicate regions of increasing annual morning RH trends have strong positive correlation with morning PVD. Inorganic salts, such as sulfates and nitrates, are the most common hygroscopic aerosol species. According

Table 4 Numbers of stations having negative or positive correlations between afternoon good visibility days (GVD) and relative humidity (RH) and afternoon good visibility days (GVD) and wind speed (WSP) for annual and four seasons based upon data for 1961–2008

	Afternoon PVD and RH					Afternoon PVD and WSP				
	ANN	WIN	SUM	MON	PMO	ANN	WIN	SUM	MON	PMO
Negative	164	165	168	158	174	85	87	94	86	90
Positive	83	73	73	78	63	162	161	155	164	165
No correlation	32	41	38	43	42	32	31	30	29	24

to Malm and Day (2001), at high humidity (above 90 %), these species can take up large amounts of water and greatly increase the total mass in the aerosol phase, resulting in increase in scattering by a factor of five or more. According to Doyale and Dorling (2002), visibility reduction is greatest at RH more than 90 %. The RH trends are significantly increasing over India, and the trends obtained are similar to RH trends over India reported by Jaswal and Koppar (2011).

3.4.1.2 Afternoon RH trend Annual mean afternoon RH trends are significantly increasing at 105 out of total 279 stations. The trend values are in the range −4.3 to +10.3 % per decade. Most of the coastal stations are showing significant decrease in annual afternoon RH. The spatial patterns of annual afternoon RH indicate overall increase except over coastal regions and extreme south peninsula as shown in Fig. 10c. Annual afternoon GVD and RH correlation coefficients are positive for 83 stations and negative for 164 stations which clearly indicate stronger role of increasing afternoon RH on afternoon visibility impairment. The correlation coefficients of annual afternoon GVD and RH are between −0.8 and +0.7.

As expected, spatial patterns of annual correlation coefficients of afternoon GVD and RH (Fig. 10d) are negative over large parts of the country. It is clearly evident from Fig. 10c and d that increase in annual afternoon RH has stronger role in the decrease in annual afternoon GVD. Seasonal numbers of stations having positive or negative correlations with morning and afternoon RH and morning PVD and afternoon GVD suggest stronger role of RH in increase in morning PVD and decrease in afternoon GVD.

3.4.2 Wind speed

In addition to relative humidity, wind (direction and speed) also plays an important role in the dispersion of aerosol particles and thus has influence on atmospheric visibility. When pollutants are emitted into a stable atmosphere, usually one of two things will happen, depending on whether there is surface wind or not. If a wind is present, the emitted pollutants usually form a plume and get transported. If there are no surface winds, a layer of haze forms near the ground and continues to build as long as the atmospheric stagnation condition persists. There are reports of reduction in wind speed over many countries such as Italy (Pirazzoli and Tomasin 2003), Canada (Tuller 2004), USA (Pryor et al. 2009), Australia (McVicar et al. 2008) and China (Guo et al. 2010).

3.4.2.1 Morning WSP trend Annual morning WSP trends are significantly decreasing at 183 out of total 279 stations. The significant deceasing annual mean WSP trends are

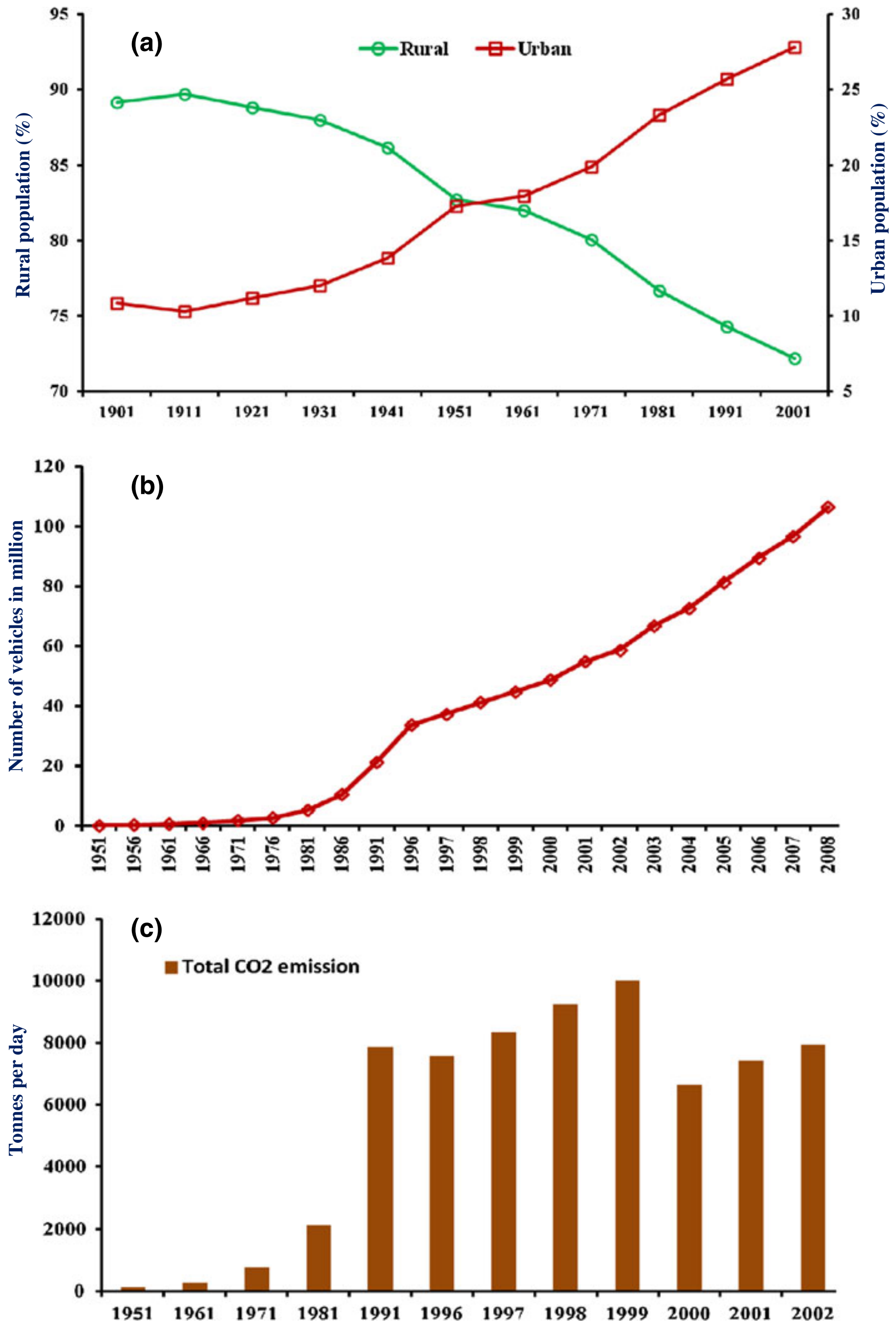


Fig. 12 **a** Changes in rural and urban population of India since 1901. Population data are in percentage of the total population. (Ref.:http://www.censusindia.gov.in). **b** Growth of total numbers of vehicles in India since 1951, **c** total emission of CO_2 from vehicular exhaust in tonnes/day in India

similar to the trends reported in many other countries. The trend values are in the range −3.1 to +1.5 kmph per decade. The spatial patterns of annual morning WSP trends (Fig. 11a) indicate overall decrease over all parts of the country. The highest decrease has occurred over coastal regions of Gujarat, West Bengal and Orissa. Stations showing highest significant decrease in annual morning WSP are Okha, Sagar Island, Paradip Port, Kakinada, Pilani and Jalgaon. Stations showing significant increase in annual morning WSP are Faizabad, Shivpuri and Tuticorin. Annual morning PVD and WSP correlations are negative at 143 stations and positive at 115 stations as given in Table 3. Spatial patterns of annual morning PVD and WSP correlations indicate regions of positive correlations over Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Rajasthan, coastal Andhra Pradesh and some pockets over other parts of the country as shown in Fig. 11b. Regions of negative correlations between annual morning PVD and WSP are more coherent over Indo-Gangetic plains, northeast, southwest and southeast parts of India. The correlation values are between −0.8 and +0.8. A comparison of spatial patterns given in Fig. 11a and b indicates close relations between regions of strong decrease in annual morning WSP and negative correlation between annual morning PVD and WSP particularly over Indo-Gangetic plains, southwest, southeast and northeast India.

3.4.2.2 Afternoon WSP trend Out of 279 stations, 177 stations are showing significant decreasing trends in annual afternoon WSP. The spatial patterns of annual afternoon WSP trends indicate decrease over all parts of the country as shown in Fig. 11c. The decreasing trends in annual afternoon WSP are more coherent over western and southern parts of the country. Almost all stations along western coast of India are showing significant decrease in annual afternoon WSP. The trend values are in the range −3.8 to +1.8 kmph per decade. Stations showing highest significant decrease in annual afternoon WSP are Paradip Port, Sagar Island, Okha, Kolhapur, Ozar, Mormugao and Malegaon. Figure 11d shows spatial patterns of afternoon GVD and WSP correlations. Out of 271 stations, 162 stations are showing positive correlation. The annual GVD and WSP correlation values are between −0.8 and +0.9. The spatial patterns shown in Fig. 11c and d indicate positive correlations between annual afternoon GVD and WSP correlations over the regions where significant decrease in WSP has occurred. This gives out an indication toward the role of decreasing afternoon WSP on decreasing GVD. Seasonal numbers of stations having positive or negative correlations with morning and afternoon WSP and morning PVD and afternoon GVD suggest stilling effect of decreasing WSP on visibility.

3.5 Other factors responsible for visibility impairment

Even though visibility is defined in various ways, basically it concerns the transparency of the atmosphere as related to human perception limited by atmospheric conditions. The transparency of the atmosphere is affected by the presence of hydrometeors (like rain, snow, mist and fog) or litho-meteors (like dust, smoke and other aerosols). Meteorological conditions largely determine the extent and speed with which pollutants disperse and thus have a major effect on atmospheric visibility. Further, the vertical temperature profile of the atmosphere determines whether the pollutants are mixed and diluted throughout the atmosphere (summer season) or whether they are trapped and thus accumulate below an inversion layer as happens in winter season. In India, suspended particulates form mainly as a result of human activities such as construction, vehicular traffic, burning of fossil-fuel, power generation, cooking (biofuel) and burning of vegetation (biomass or crop residue) with large influx of transported desert dust during the summer season (Prasad et al. 2006, 2007, 2011; Prasad and Singh 2007). As suspended particulates are carried and dispersed by the wind, reduced visibility is significantly influenced by meteorological factors such as wind direction, wind speed and atmospheric stability. Aerosol particles are responsible for light scattering properties of the atmosphere up to 99 % in an urban environment as compared to 90 % in a remote continental environment (Horvarth 1994). Visibility at a given location is controlled by the physical and chemical properties of the particulate matter and the relative humidity. Reduction in visibility is greatest at relative humidity more than 90 % when the cross-sectional area of scattering particles increases due to water absorption (Doyale and Dorling 2002).

In India, air pollution is widespread in urban areas (where vehicles are one of the major contributors) as well as in rural areas having high concentration of industries and thermal power plants (Prasad et al. 2006, 2012). The rapidly growing cities, increasing vehicular traffic, industrialization and higher levels of energy consumption during the last three decades have lead Indian cities toward air pollution (Prasad et al. 2006). Also, urbanization often causes an increase in suspended particulate matter in the atmosphere; as a result, there is a decrease in atmospheric visibility. The problem is further compounded by high influx of population from rural to urban areas as depicted in Fig. 12a. Between 1961 and 2001, the urban population has nearly tripled from 78.9 million to 286.2 million and its proportion has increased from 18.0 to 27.8 % as shown in Fig. 12a. Green and Battan (1967) have correlated population growth with visibility and found strong positive correlation of decline in visibility with population growth. This is primarily a result of drastic increase in number of motor vehicles leading to a significant increase in the CO_2 load from vehicular exhaust, which is amply evident from Fig. 12b and c, respectively. The total number of motor vehicles has increased from 0.3 million in 1951 to 89.6 million in 2006, while CO_2 load from vehicle exhaust increased from 132.56 tonnes/day in 1951 to 7917.8 tonnes/day in 2002 (Jana et al. 2008). Trijonis (1984) has conducted a study on impact of diesel vehicles on visibility in USA and has shown that heavy-duty diesel vehicles contribute 5–20 % to the reduction in visibility. Most of these motor vehicles are concentrated in major metropolitan cities in India, thus aggravating air pollution leading to visibility impairment.

Visibility degradation is a matter of growing concern in India. The current study, based on the spatial and temporal trends from 279 surface meteorological stations over India, clearly shows that horizontal surface visibility has significantly decreased over the country but more strongly along the Indo-Gangetic plains which is the region of maximum load of pollutants and other aerosols as reported by numerous investigators (Prasad et al. 2004; Singh et al. 2005; Ramanathan et al. 2005; Venkataraman et al. 2005; Sarkar et al. 2006; Biggs et al. 2007). Atmospheric aerosols have been widely linked to reduced air quality and visibility in many parts of the world. Sarkar et al. (2006) have concluded that aerosol loading over the major cities in India has increased significantly in recent years. Aerosol optical depth (AOD) in India is significant during summer months (Singh et al. 2005; Prasad and Singh 2007; Prasad et al. 2011; Srivastava et al. 2011), and the maximum is observed over the northern parts of India. Prasad et al. 2011 have shown that a large amount of dust particles are transported (between 0 and 7 km range) to Indo-Gangetic plains from the Thar, Middle East and Sahara deserts by the westerly winds which increases aerosol loading over the Indo-Gangetic basin. This accumulation of dust and other particles over north India presumably leads to significant increase in morning PVD and afternoon GVD over these regions. Aerosols from biomass burning are typically carbon dominated and can significantly contribute to total aerosol loading, especially during the wildfire and prescribed burning seasons (Malm et al. 2004). These carbon-containing aerosols can both scatter and absorb light and thus contribute to significant visibility reduction (Reid et al. 2005).

The significant increasing trends in morning RH over the country and its strong positive correlation with morning PVD suggest its close relationship with the morning visibility impairment. The significantly decreasing trends in morning WSP are further contributing toward morning visibility impairment by lesser mixing of the hygroscopic pollutants in the atmosphere which are abundantly available. The afternoon RH trends are also increasing, and its correlation with decreasing afternoon GVD is negative over large parts of the country especially over the Indo-Gangetic plains, suggesting a closer relationship between them. Afternoon WSP trends are significantly decreasing over large parts of the country, and its correlation with afternoon WSP is positive, suggesting a closer relationship between them. The decrease in WSP is not allowing mixing of pollutants and thereby leading to stagnation and accumulation of pollutants over various regions of the country. Increasing trend in visibility impairment over the country can also be related to urbanization, which appears to cause increased concentration of aerosols and stagnation of airflow. Emissions of aerosol precursors in South Asia have increased about six times since 1930 (Ramanathan et al. 2005), and atmospheric visual range has correspondingly decreased (Kaiser and Qian 2002). In addition to sharp decline in visibility over India, solar radiation (Padma Kumari et al. 2007), pan evaporation (Jaswal et al. 2008) and sunshine (Jaswal 2009) have also decreased which is attributed to increase in aerosols over the country. Concentrations of these pollutants and aerosols are governed by regional- and synoptic-scale meteorological conditions, study of which is beyond the scope of the present paper.

4 Conclusions

With massive population growth, increasing urbanization and rapid industrialization over the past three decades, poor air quality has become one of the major environmental concerns in India. The spatial and temporal trend analysis of horizontal surface visibility at 279 stations from 1961 to 2008 has clearly indicated the significant decline in visibility. The probable reason for this decline appears to be the increase in relative humidity, decrease in wind speed and increase in anthropogenic aerosols over the Indian subcontinent as reported by several investigators. Based upon this study, following conclusions are drawn:

(a) Geographical distribution of climatological means of morning poor visibility days (visibility <4 km) and afternoon good visibility days (visibility >10 km) suggest Indo-Gangetic plains and West Rajasthan as regions of higher morning poor visibility (>30 % days) and lower afternoon good visibility (<30 % days) throughout the year. At the same time, central and south India have the least numbers of mean morning poor visibility days (5–10 % days) and highest numbers of afternoon good visibility days (75–95 % days).

(b) The range of annual morning poor visibility days has increased from 6.7 % days in 1961 to 27.3 % days in 2008, while the range of afternoon good visibility days has decreased from 76.1 % days in 1961 to 30.6 % days in 2008.

(c) India averaged morning poor visibility days have significantly increased and afternoon good visibility days have significantly decreased for all months. Maximum increase in monthly morning poor visibility days has occurred in January (+4.7 %

day per decade) followed by December (+4.4 % days per decade). Simultaneously, highest decrease in monthly afternoon good visibility days has occurred in October (−9.3 % days per decade) followed by November (−9.0 % days per decade).

(d) Annually, the morning poor visibility days rose significantly at 3.3 % days per decade and the afternoon good visibility days declined significantly at a higher rate −8.6 % days per decade during 1961–2008. Seasonally, the highest increase in morning poor visibility days has occurred in winter (+4.3 % days per decade), while the decrease in afternoon good visibility days has occurred in post-monsoon (−9.2 % days per decade).

(e) Spatially, increasing relative humidity and decreasing wind speed have stronger relationship with visibility impairment over the country.

India is rich in scenic views all over the country which have great tourist attractions, but atmospheric pollution or haze can diminish the visual amenity by discoloration, loss of texture and by making it harder to distinguish features from a distance. Good visibility is an amenity which should not be ignored and one which need to be protected. A comprehensive policy of protecting ambient air quality in India is very much required.

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