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Lidar-derived aerosol concentration and their relationship with horizontal winds over an urban location

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सार - इस शोध-पत्र में वायुमंडल के निचले भाग के ऐरोसॉल संबंधी अभिलक्षणों के क्षैतिजीय पवनों पर पडनें वाले प्रभाव की जाँच करने के लिए भारत मौसम विज्ञान विभाग, पुणे स्थित एक निम्न अंक्षाश उष्णकटिबंध केन्द्र से 10 वर्षों (1987-96) के दौरान लगभग 535 दिनों की अवधि में लिडार से व्युत्पन्न ऐरोसॉल उर्ध्वाधर प्रोफाईलों सहित समकालिक पवन सूचक गुब्बारा पवन (गति और दिशा) आँकड़ों का उपयोग किया गया है। जब पुणे शहर के प्रमुख शहरी और औद्योगिक क्षेत्रों से पवनें चलती है उस समय लिडार क्षेत्र के वायुमंडलीय परिसीमा सतह (भूतल के ऊपर 1100 मी. तक की सतह) में और धरातल (50 मी.) स्तर पर ऐरोसॉल स्तंभ के घनत्व में विद्यमान ऐरोसॉल समूहों के लिडार क्षेत्र में अपेक्षाकृत उच्चतर मानों का पता चला है। शीत ऋतु के दौरान यह प्रभाव अधिक सुस्पष्ट रूप में देखा गया है। संवर्धित ऐरोसॉल भारण पवन गतियाँ भी सुसंगत पाई गई है किन्तु यह स्थिति चुनी हुई उच्च पवन गति की घटनाओं के समय ही देखी गई है। इस प्रकार से इस अध्ययन से यह पता चला है कि प्रेक्षण के स्थान पर ऐरोसॉल की सांद्रता/भारण में अल्प और दीर्घ अवधि वृद्धि धरातल स्तरों में क्षैतिज पवनों द्वारा विस्तृत रूप से प्रभावित होती है जिसके परिणामस्वरूप कई वर्षों तक लिडार स्थल के आस-पास संवर्धित मानवोचित/शहरी गतिविधि देखी जा सकती है।

ABSTRACT. Lidar-derived aerosol vertical profiles obtained at Pune, a low latitude tropical station, on about 535 days during a ten-year period (1987 – 96) along with simultaneous pilot-balloon wind (speed and direction) data of India Meteorological Department, Pune have been used in the study to investigate the influence of horizontal winds on the aerosol characteristics in the lower atmosphere. Aerosol column content in the atmospheric boundary layer (surface to 1100 m altitude above ground-level) as well as aerosol number density at the surface level (at 50 m) showed relatively higher values over the lidar site whenever the winds were blowing from the main urban and industrial regions of the city of Pune. This effect was found to be more pronounced during the winter season. Wind speeds also correlate well with increased aerosol loading, but only during selected high wind speed episodes. Thus the study shows that the short- and long-term increases in aerosol concentration/loading over the observation site are, to a large extent, influenced by horizontal winds in the surface layers and this in turn, can be attributed to the increasing human/urban activity around the lidar site over the years.

Key words – Lidar, Aerosol number density, Aerosol loading.

1. Introduction

Aerosols form an important atmospheric constituent and their spatio-temporal distributions influence various geosphere-biosphere phenomena. Widespread surface and spatial sources are the two major sources of atmospheric aerosols (Jaenicke, 1993). The former includes biogenic sources, volcanoes, oceans and fresh water, crustal aerosols and biomass burning. Spatial source refers to particles produced in the atmosphere itself through gas-to-particle conversion (secondary aerosols). Airborne particulate matter is known to have adverse impacts on human health, materials and visibility. Atmospheric aerosols play a pivotal role in acid deposition also. Among atmospheric aerosols of all sizes, particles in the accumulation mode (0.1 – 2.5 m diameter) are the most critical with respect to health, visibility and acid precipitation. Most of the mass of the secondary aerosols tends to reside in this range. Further, the role of aerosols in modifying the Earth's climate on various time scales has been a topic of scientific discussion for many decades. In recent years greater importance is being given to the fact that the anthropogenic component of the particulate matter can cause a direct negative (*i.e.* cooling) radiative forcing in the short-wave, which is comparable but of opposite sign to the positive long-wave forcing of several trace gases (Charlson *et al*., 1992; IPCC, 1992; Harshvardhan, 1993).

Because of the dominant influence of anthropogenic emissions from industries, domestic heating/cooking systems and vehicular traffic, the aerosols in cities and human settlements have a special character and only a few observational measurements exist (Jaenicke and Junge, 1967; Whitby, 1978). Urban air pollution is comprised of a highly complex mixture of gaseous and particulate components (Seinfield, 1986). Mobilization, transportation and deposition of particulate pollutants is a concern of several disciplines like climatology, ecology and geology and there is overwhelming evidence that lower atmospheric aerosols can be transported over large distances, even intercontinentally (Hobbs *et al*., 1971). Urban areas ordinarily have more than one source of particulate pollutants and the dispersion/transportation from these sources is related to the topography, wind speed and direction and to the vertical temperature profile. The wind itself is a natural source of particulates in the atmosphere (Eagleman, 1991).

Most quantitative determinations of aerosols have until now been made by local point source measurements. Optical remote sensing techniques like Lidar (laser radar) have shown excellent capabilities in monitoring space-time variations in both particulate and gaseous pollutants (Killinger and Mooradian, 1983; Measures, 1984; Grant, 1987; Killinger and Menyuk, 1987). One of the earliest and important achievements of lidar technique has been its ability to measure remotely atmospheric aerosols (Fiocco and Smullin, 1963; Carswell, 1983). A program of measuring vertical profiles of atmospheric aerosols in the lower troposphere using a bistatic Argon ion lidar system has been in progress at the Indian Institute of Tropical Meteorology (IITM), Pune (18° 32′ N, 73°51′ E, 559 m AMSL) since October 1986. Continuous lidar aerosol observations over a period of nine years at Pune, a fast changing/growing tropical urban city have shown (Ernest Raj *et al*., 1997) that there is a significant increasing trend in the aerosol loading over this location which was attributed to be mainly due to the increase in human activity (commonly called urbanization) in and around the lidar site. In this context, it is felt that it would be worthwhile to examine the possible source of these observed increase in aerosol concentration over the lidar site. Winds are known to influence the distribution of aerosol concentrations in the atmosphere through various dynamical processes. Particles can be transported from emission sources to different locations depending on the existing wind speed and direction. The aim of the present study, is therefore, to examine the effect of wind speed and direction on the lidar-derived aerosol concentrations at a place almost on the edge of an urban locality and to find out whether the observed short-term/long-term variations in aerosol concentrations are in any way influenced by or related to the changing urban activity.

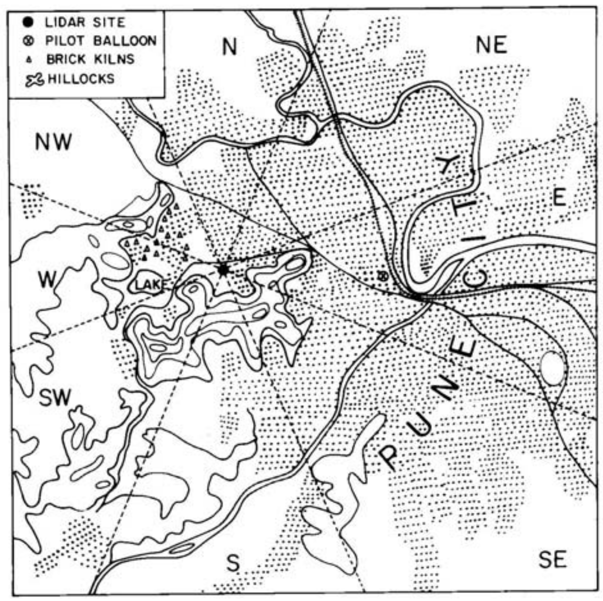
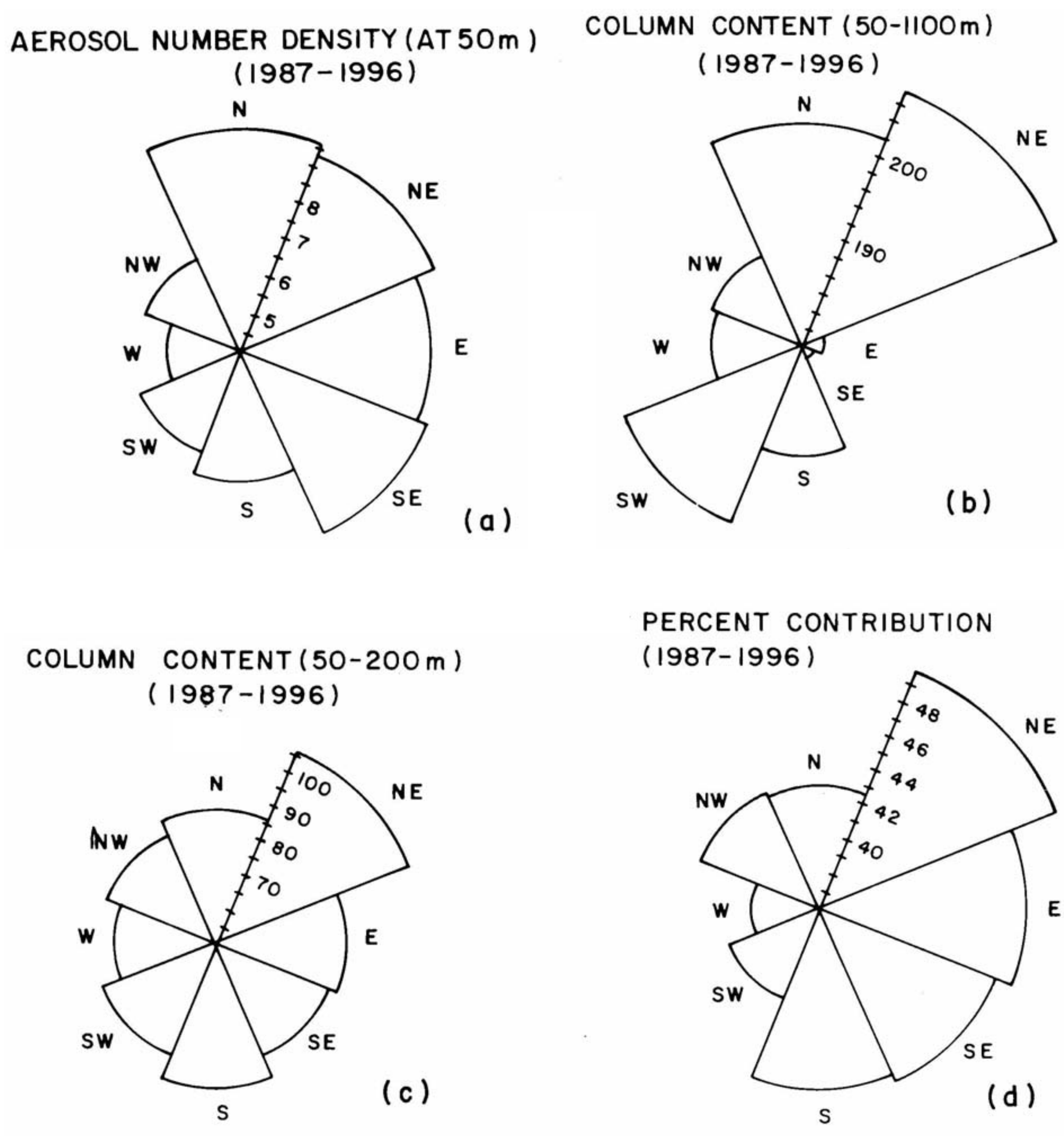


Fig. 1. Map showing the location of the lidar site with respect to the major urban areas (dotted) of the city of Pune

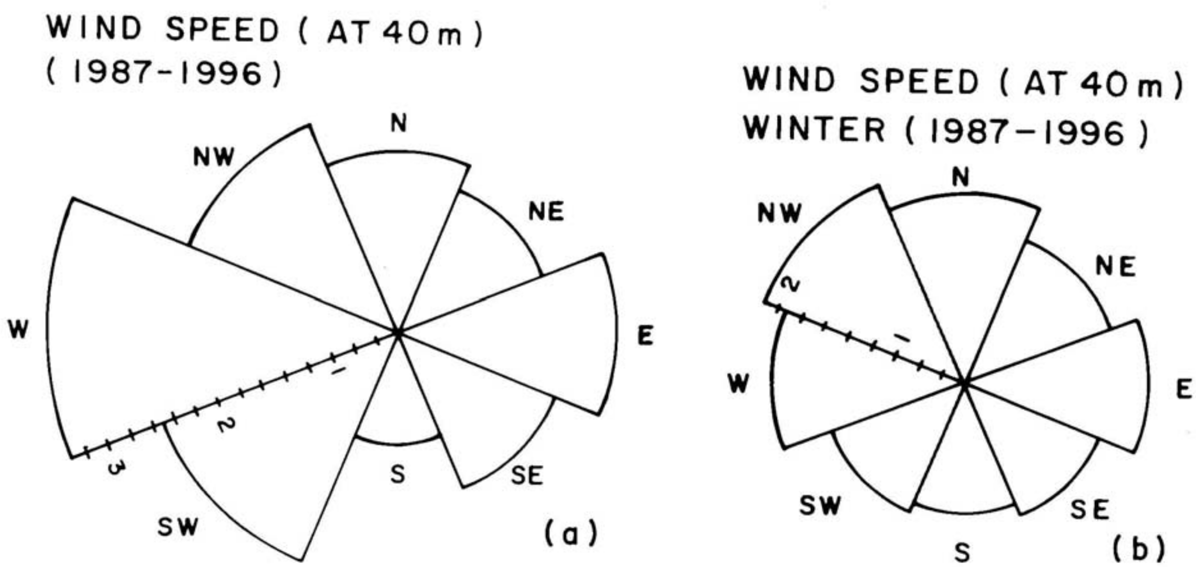
2. Experimental location, system description and data

The experimental station, Pune is about 100 km inland from the west coast of India and is located on the lee-side of the Western Ghats. The airflow in the lower troposphere over this location is predominantly westerly during the summer season (March-May), southwesterly in the monsoon season (June-September) and either the westerlies/southwesterlies weaken or even a weak easterly flow sets-in from October onwards. The lidar site (IITM campus) is itself located almost on the western edge of the city of Pune. Fig. 1 shows the location of the lidar site and its surroundings. The dotted/hashed regions in the figure



Figs. 2(a-d). Average values of (a) Aerosol concentration ($\times 10^3$ cm^{-3}) at 50 m altitude, (b) Aerosol column content ($\times 10^6$ cm^{-2}) in the 50-1100 m layer, (c) Aerosol column content in the 50-20 m layer, and (d) Percentage contribution of the lower layer, in different wind directions for the data during the period 1987-96

indicate the residential/commercial areas of the city. The lidar site is at an elevation of 570 m above the mean sea level and it is surrounded by several hillocks as high as 760 m (shown in the figure as contours). The region shown in the figure is divided into sight geographical directions of North, Northeast, East, Southeast, South, Southwest, West and Northwest, with respect to the lidar site. Thus it can be noted that the major urban and industrial activity is located on the North, Northeast, East and Southeast directions of the site. Here it may be mentioned that a few major automobile industries and the Pune-Mumbai and Mumbai-Bangalore National Highways



Figs. 3(a&b). Average wind speed (ms^{-1}) at 40 m altitude in different wind directions for (a) complete data and (b) winter data

are located to the North-Northeast and North-Northwest of the lidar site. Also, the city of Pune has a very large number of motorized vehicles on its roads. The regions in the other directions with respect to lidar site are sparsely populated with some isolated villages among undulating low-level hillocks. There are some open-air brick baking kilns close to the site (1 to 2 km away) on the Western side and Northwestern sides. Thick smoke emanates from these brick kilns, especially during the summer (March-May) and winter (December-February) seasons when these kilns are 'active', may be contributing to the observed particle concentrations in the lower atmosphere.

A bistatic, continuous-wave Argon ion lidar system (at the laser wavelength of 514.5 nm) has been in regular operation at this location in Pune since October 1986. The system basically consists of a 4-Watt CW Argon ion laser as the transmitter and a 25 cm Newtonian telescope-photo multiplier assembly as the receiver. The system is operated in the bistatic mode with a transmitter-receiver separation of about 60 m in the same horizontal plane. The system has been made completely computer-controlled in 1992 and the real-time profile of scattered signal strength at different pre-determined scattering angles is obtained during the experiments which is later inverted to obtain the vertical profile aerosol number density (cm^{-3}). As part of our regular observational program, lidar aerosol profiles from 50 m to about 6800 m are being collected at different altitudes during the post-sunset hours on every wednesday and alternate Thursdays. The detailed description of the lidar system at Pune and the method of extraction of aerosol vertical distributions from lidar return signals are given in our earlier publications (Devara and Ernest Raj, 1987; 1993; Ernest Raj and Devara, 1989; Ernest Raj *et al*., 1997).

About 535 days of lidar observations made during the 10-year period from 1987 to 1996 have been used for this study. Some of the aerosol parameters representative of the aerosol characteristics and their spatio-temporal variations in the lower atmosphere have been selected for a detailed investigation from the observed lidar data. They are (a) aerosol concentration (cm^{-3}) at 50 m altitude, (b) aerosol column content (cm^{-2}) in the 50-1100 m layer (obtained from integration of the vertical aerosol concentration profile over 12 height intervals in the 50-1100 m altitude range), (c) aerosol column content in the 50-200 m layer, and (d) percentage contribution of the lower layer (50-200 m) to the total column content (50-1100 m). The aerosol column content in the 50-1100 m layer is assumed to fairly represent the aerosol/particulate loading in the nocturnal boundary layer over the observing station. Along with the above mentioned lidar observations, simultaneous pilot balloon wind observations (speed and direction) of the late evening ascents on the days of lidar experiment, have been collected from the India Meteorological Department

(IMD), Pune observation station which is located at about 5 km in the eastern direction to the lidar site (Fig. 1). The wind speed and direction information at 40 m altitude (the first observation above the ground-level in the pilot balloon ascent data) have been considered for the analysis here. The results obtained are presented and discussed in the following section.

3. Results and discussion

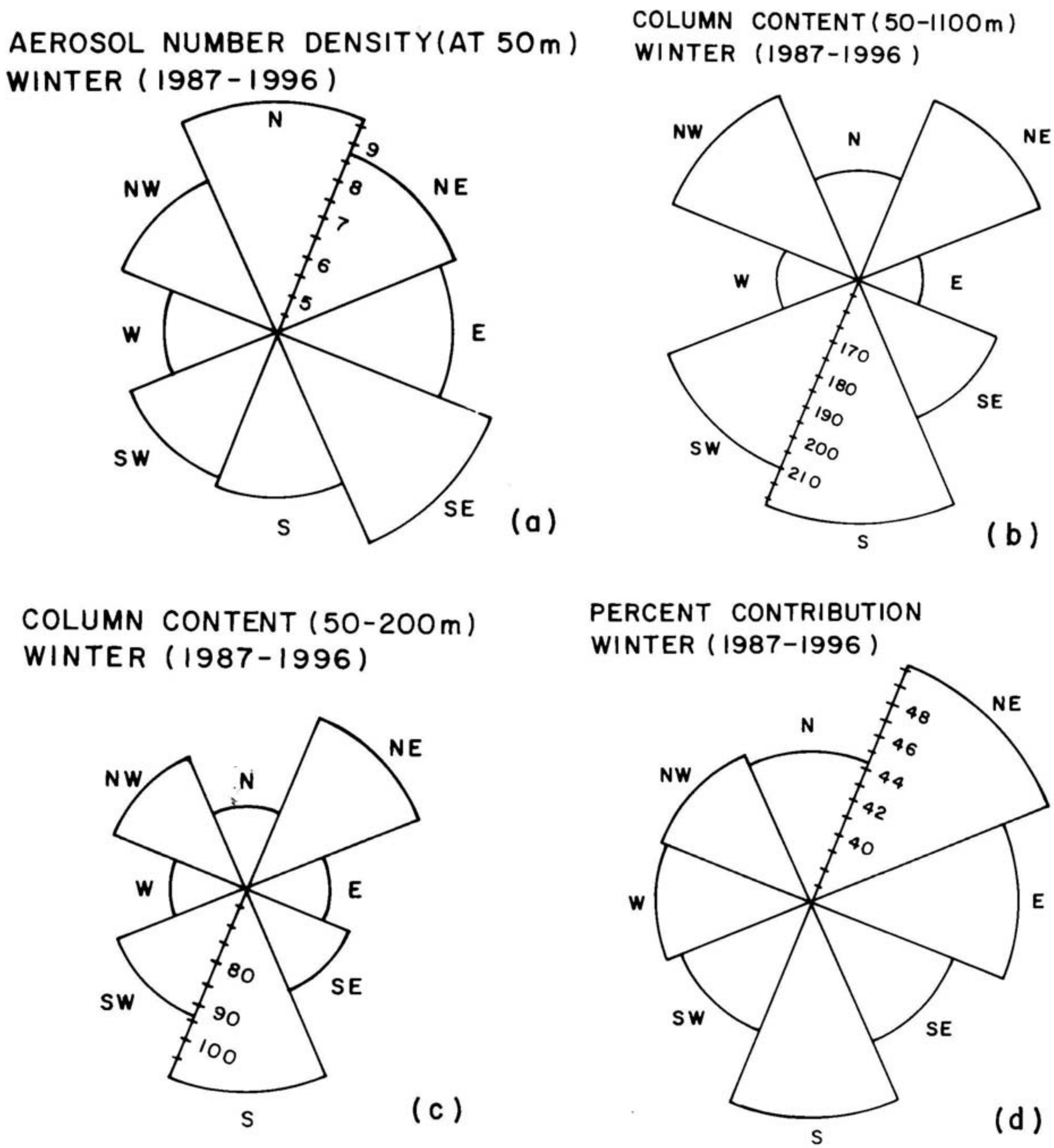
The entire 535 days data of aerosol concentration at 50 m altitude, aerosol column content in the 50-1100 m layer, aerosol column content in the 50-200 m layer, and percentage contribution of the lower layer and also the simultaneous data of wind speed at 40 m altitude has been separated and grouped into the eight standard wind directions of North, Northeast, East, Southeast, South, Southwest, West and Northwest depending on the observed prevailing wind direction at 40 m altitude on the corresponding day of observation. The average value of each of the above five parameters in the eight geographical directions for the ten-year period (1987-96) has been computed.

It is to be mentioned here that the lidar observational days are fairly spread out in all the months of the year. The total number of lidar observational days in each month over the ten-year period ranged from 35 to 50. Thus any bias towards a particular month or season is minimum. From the above analysis, the frequency distribution of wind direction shows that the winds over Pune are westerly and southwesterly on more than 70 % of the days.

The overall average aerosol number density (cm^{-3}) at 50 m altitude in the eight wind directions in shown in Fig. 2(a). It is seen that whenever the winds are blowing from the North, Northeast, East and Southeast, the aerosol concentrations are relatively higher and they are smaller in magnitude in other directions. Average aerosol column content (cm^{-2}) in the 50-1100 m atmospheric layer values are very high when the wind direction is from North and Northeast as seen in Fig. 2(b). Similarly, aerosol column content in the lowest layer (50-200 m) is largest whenever the winds are from Northeast [Fig. 2(c)]. [Fig. 2(d)] shows the average percentage contribution of the lower layer to the total content in the 50-1100 m layer in the eight wind directions. It is noticed that percentage contribution of the lower layer to the aerosol loading is also higher whenever the winds are from Northeast, East, Southeast and even from South. The Figs. 2(a-d) show higher values whenever the winds blow from North and Northeast and also when they are from East or Southeast directions. The data show that winds are not the highest in magnitude in North and Northeast directions. The average wind speed (at 40 m altitude) in the eight directions for entire 10-year period (1987-96) is shown in Fig. 3(a). It can be seen that, in fact, winds are the strongest when they are in the form Westerlies. Thus it is evident that even moderate winds can carry particulate pollutants over shorter distances of a few kilometers. The 10-year lidar aerosol data thus shows that there is a strong possibility of the influence of human/urban activity on the observed aerosol concentrations over the site in view of its location with respect to the major urban/industrial areas of the city of Pune.

In our earlier lidar studies at Pune (Ernest Raj and Devara, 1992), the vertical profiles of aerosol number density have been used to derive mixing depths/inversion layer heights over the site and also to compute ventilation coefficient. The ventilation coefficient represents the rate at which air within the mixed layer is transported or dispersed. It has been reported in the above publication that late winter evenings at a place like Pune tend to have a higher pollution potential. The temperature profile is of particular importance because it determines whether the atmosphere is stable or unstable. If a temperature inversion exists in the surface layer, very little mixing of pollutants occurs (Eagleman, 1991). Strong temperature inversions are times of air stagnation and higher concentration of particles of all sizes resulting in poor air quality. For example, the results of Mathai *et al.* (1980) show that the urban pollution levels increase substantially during inversion conditions. Further, the wind speed is an additional factor in the dispersion of pollutants. Nocturnal inversions are more frequent during winter at Pune and also the wind speeds are relatively smaller during this season. It means broadly that larger amounts of particulate or gaseous pollutants released into the atmosphere from surface sources during winter season have a greater chance of being confined to the lowest layers of the atmosphere for longer period without much dispersion and can cause adverse impacts on human health, materials and even visibility in the surface layer. With this aspect in view, lidar data recorded on 124 days during the winter season (December-February) has been examined separately in this study. Fig. 3(b) shows that during winter season the wind speeds are nearly equal in magnitude in all the wind directions and are relatively even smaller in magnitude when in North and Northeast directions. Further, the variations in low ventilation coefficients (low air quality) during winter season over Pune are mainly due to the variation in concentration of aerosols and precursor gases as a result of anthropogenic activities in and around the observation site (Devara, 2000).

The winter data of aerosol concentration at 50 m altitude, aerosol column content in the 50-1100 m and 50-



Figs. 4(a-d). Same as Fig. 2 but in wind directions for the winter season data during the period 1987-96

200 m layers, and percentage contribution of the latter to the former have been, separated and grouped into the eight wind directions according to the pilot balloon wind information. The average values of the each of the four parameters mentioned above during the winter season alone are shown in Figs. 4(a-d). Aerosol number density at 50 m altitude is higher in magnitude when winds at 40 m altitude are Northerly, Northeasterly and Southeasterly. Aerosol column content (50-1100 m) during winter season shows a different but an interesting aspect. It is higher in magnitude when winds are from Northeast, South, Southwest and also when they are from Northwest. During winter, Northwesterlies are relatively stronger as seen in Fig. 3(b). As shown in Fig. 1, within about 1 to 2 km distance of the lidar site in the Northwestern and Western directions there exist some brick baking kilns and

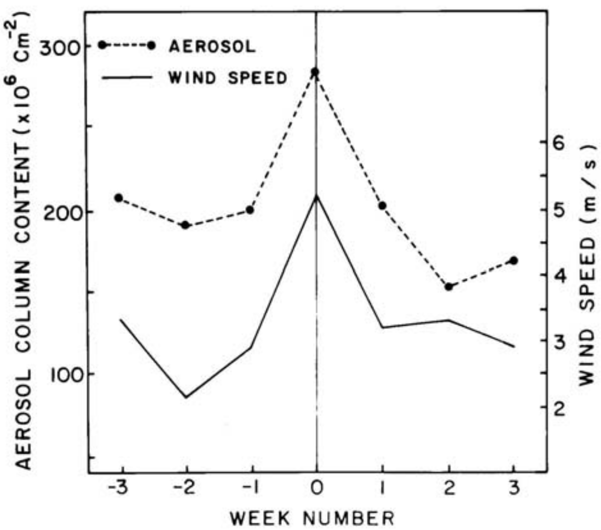


Fig. 5. Simultaneous mean values of wind speed and aerosol column content on days of higher wind speed (week 0), up to three weeks before and three weeks after

some villages also where some traditional method of domestic cooking and biomass burning is followed. The brick kilns are actively burning almost throughout the winter season when Pune receives practically no rainfall. Visual observation showed that thick smoke emanating from these kilns and village hutments especially during winter season, tends to move horizontally slowly without dispersing easily and quickly over the observing region. As this particulate-laden smoke spreads around, being confined to the lower/surface layers of the atmosphere, it could possibly become one of the reasons for higher aerosol column content during winter season whenever winds are from Northwest apart from the formation of close-to-ground inversion layers over the station. Column content in the 50-200 m layer and its percentage contribution, Figs. 4 (c&d), again show higher values when winds are Northeasterly. Thus winter data show greater influence of human/urban activities on the observed aerosol distributions at the lidar site.

Increased wind speeds at the ground can raise particles of soil origin from the Earth's surface. Some empirical relations have been given to express the generation rate of desert and maritime aerosols as a function of wind speed (WCP, 1983). However, wind speeds are not always directly/linearly correlated with observed increases or decreases in aerosol concentration. This is because winds can either add particulate matter from other locations to the site through transport or even help to remove the particulate load from a site. Thus day-to-day variations in aerosol concentration are not very well correlated with the day's corresponding wind speed magnitude. But in the above 10-year simultaneous lidar and pilot balloon wind data set there were some isolated episodes when winds showed a sudden increase in speed on a particular day with calm conditions on days before and after the episode. Such episodes have been identified and aerosol column content (50-1100 m) and wind speed data of these episodes alone have been averaged to examine the influence of wind speed on aerosol distribution at the lidar site. As the lidar data is obtained once in a week, the value of aerosol column content on the days of high wind speed is taken as central point and data obtained on 3 weeks before and 3 weeks after the episode day are also taken and averaged. Simultaneous values of wind speed are also averaged. Fig. 5 shows the superposed epoch analysis of wind speed and aerosol column content averaged for 19-selected higher wind speed episodes during the above period of observations. From the observed well-correlated variations between wind speed and column content a linear relationship (of the form $Y = 34.29X + 88.42$) can be established. It shows that during isolated episodic increases of wind speed, there is a marked increase in the aerosol concentration mainly of the surface origin. As the residence time of surface and lower tropospheric aerosols is only a few days, maximum being about one week (WCP, 1983), higher concentrations are seen only on the days of higher wind speeds. On days about or more than a week before and after the episodic situation, aerosol concentrations are observed to be normal when wind speeds are smaller. Though the data set of only 19 episodes may be a small data set to draw a conclusion, the present study enables us to suggest an linear empirical relationship which provides an observational evidence for a correspondence between wind speed and aerosol concentration in the lower troposphere that can be improved upon with the on-going lidar and pilot balloon observations at the station.

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