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Visibility degradation during foggy period due to anthropogenic urban aerosol at Delhi, India

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ABSTRACT

Fog occurs more frequently over urban areas than rural areas. It may occur due to increased air pollution emanating from variety of sources in the urban areas. The increased pollution levels may lead to the atmospheric reactions resulting into the formation of secondary pollutants that may also lead to the needed cloud condensation nuclei. Northern regions of India experience severe foggy conditions during the winter period (November–January) each year. In this study, we have simultaneously measured the particulate mass concentration (0.23 µm to 20 µm), meteorological parameters and atmospheric visibility in Mega city Delhi during a winter month of the years 2007–2008 in order to have an improved understanding of their role in fog formation. The effects of aerosols on fog formation are discussed through an analysis of trends in fog frequency and comparison with meteorological parameters, and visibility as an indicator of aerosol load. This satisfies the precondition for using these relations. The association between the meteorological parameters (visibility, depression temperature) and air pollutants are examined. The Windows software SPSS (version 17.0) is used to fit a linear regression model. The model explained the variation in visibility due to depression temperature and aerosols load.

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1. Introduction

Fog is defined as an obscurity near the surface layer of the atmosphere which is caused by a suspension of water droplets and is associated with visibility less than 1 000 m. Atmospheric aerosols has been recognized for accelerating and intensifying the fog formation in the urban areas (Mircea et al., 2002) due to the fact that polluted clouds are capable of having eight times as many droplets of half the size, twice the surface area, twice the optical depth, and causing higher obscurity than natural clouds (Toon et al., 2000). Also, the formation of fog droplets at sub–saturated conditions is mainly because of water soluble ionic species present in the polluted environments (i.e., ammonium, nitrate and sulfate) take up water vapor and form highly concentrated liquid particles (Frank et al., 1998).

The characteristics of aerosols (number and mass concentration, size distribution, chemical composition) have a large impact on when and where a fog layer will form (Bott et al., 1990; Bergot and Guedalia, 1994; Stoelinga and Warner, 1999). Fog is more likely to form in an environment with large concentrations of aerosols characterized by a low activation supersaturation (level of supersaturation at which aerosol particles spontaneously grow to become cloud droplets). Organic compounds change the surface tension of pure water and can cause cloud condensation nuclei activation at lower relative humidity than it is possible in the unpolluted atmosphere (Brooks et al., 2009). Although in a large number of fogs, the distinction between unactivated and activated droplets is not as straightforward as for other cloud types (Hudson, 1980). Estimation of the water uptake by the organic and inorganic ions is very complex in an aerosols mixture. The organic portion enhances the water uptake of the $(NH_4)_2SO_4$ – organic aerosol systems by as much as a factor of 2–3 for particles consisting 80% of organic acids. Thus the hygroscopic growth interaction can be positive or negative depending on organic volume fraction and the type of salt (Cruz and Pandis, 2000; Zhang et al., 2007). The properties of aerosols in the ambient air thus play an important role in fog onset due to the activation of fog droplets. Laboratory experiments have indicated that pollution/aerosol has a strong effect for fog formation in favorable meteorological conditions. Frank et al. (1998) studied the effect of the aerosol mass present in the fog and varied it by a factor of 4 (25–100 µg/m^3). It was found that the aerosol mass load strongly influenced the microstructure of the fog.

Certain meteorological parameters alone or in combination with some air pollutants trigger fog formation in the urban areas. In a metropolitan city like Delhi, with over 15 million inhabitants contributing towards the anthropogenic aerosols, coupled with the desert dust aerosols from the northwestern region (Singh et al., 2005), a very high level of ambient aerosol loadings is always expected. During the past decade, Delhi has witnessed increased frequency of fog in winter season. Analysis of six years (1996–2001) of meteorological data for the winter season shows that occurrence of fog is more than 50% of the time in this mega–city (Mohan and Payra, 2009). The pollution levels in Delhi environment, especially respirable suspended particulate matter (RSPM) concentrations are significantly high and more than any other major cities of the world. Ali et al. (2004) reported that the anthropogenic species are higher during winter period, because people in and around Delhi burn coal, wood, kerosene oil, and plant leaves to protect themselves from cold. Despite of all the possible control measures Delhi has significant concentration of RSPM often exceeding national ambient air quality standards and therefore it is expected that increased aerosols would have an important role in the fog formation.

The main objective of the present study is to show how the increase in aerosol content and meteorological parameters influences fog formation during winter period in the northern part of India. The study is also aimed to critically examine the relationships between meteorological parameters, air quality and visibility over Delhi based on observations during winter (November to January) that included severe fog episodes.

2. Sampling Site and Techniques

Delhi (28˚35'N; 77˚12'E, 218 m asl), the capital of India, experiences a severe weather swing between different seasons: from hot and humid weather in summer (April–May), spring (February–March), monsoon (July–September) with rains and high humidity levels in air to cold and dry weather in winter (November–January). Fog in Delhi is a persistent winter phenomenon (Ali et al., 2004). The winter period (November–January) is dominated by cold, dry air and ground–based inversions with low wind conditions and average minimum temperatures of 7.82 to 6.67 ˚C respectively. The wind direction over Delhi is mostly northwest during summer, West during spring and southwest during winter. A significant proportion (43%) of wind velocities are calm conditions with almost 52% of wind speeds below 2.1 m/s (Mohan and Bhati, 2009). The entire northern part of India, especially the Indo–Gangetic Plain, experiences thick foggy weathers during winter and shows low boundary layer heights. During such conditions, pollutants could not be dispersed and mix with free troposphere. The impact of such conditions is discernible as poor visibility and high levels of pollutants in this region.

The ambient sampling of aerosols for this study was carried out at about 15 m above the ground level, on the rooftop of a building situated in the thoroughly urbanized central part of Delhi. The area is primarily a residential area, and no large pollutant source exists nearby which could have influenced the sampling site directly. Sampling location is given on the road map of Delhi in Figure 1.

The GRIMM Aerosol Monitor which is an optical particle counter (OPC, GRIMM Aerosol Technik, model 1.108), a 16 channel aerosol spectrometer was used to measure the total mass concentration of particles in 16 different size ranges between 0.23 to 20 µm (Sciare et al., 2007). Diameters were measured as optical diameters (Peters et al., 2006). Counting of aerosols is accomplished by light scattering with the help of a laser ray. Simultaneously, constant flow rate (1.2 liters/min) is maintained with air volume control system throughout the measurements. All meteorological data for this study (2007–2008) are taken from India Meteorological Department (IMD). The IMD measures visibility with the help of transmissometer with a 30 min temporal and 5 km spatial resolution. It works on the physical principal of inverse total extinction and operates by sending a narrow, collimated beam of energy (usually a laser) through the propagation medium at 550 nm. The aerosol concentrations data has been taken with 1 minute temporal resolution. An hourly averaged data is however used in the present analysis.

3. Results and Discussion

3.1. Aerosol mass concentration and meteorological parameters

The official definition of fog is a visibility of less than 1 000 meters. This limit is appropriate for aviation purposes. The reduction in visibility is due to tiny water droplets suspended in the air. The thickest fog tend to occur in urban/industrial areas where there are many pollutant particles acting as nuclei for the water droplets. In the subsequent sections we will show and analyze the trends in aerosol mass concentration and depression temperature with visibility observed over the sampling site during 2007 and 2008, respectively. The time used in all the figures reflects Indian Standard Time (IST).

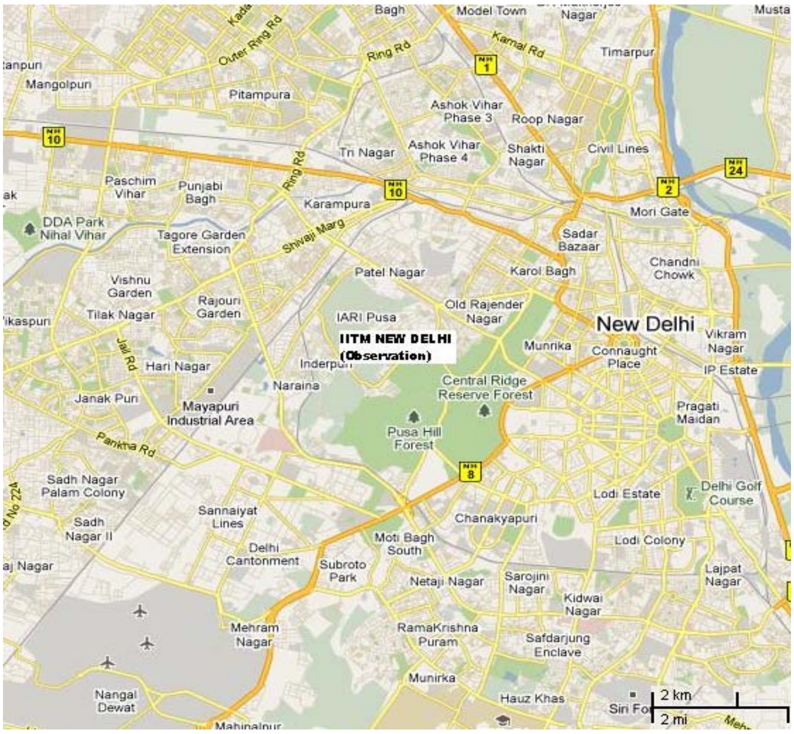

Figure 1. *Sampling location (IITM New Delhi) in road map of Delhi.*

3.2. Total aerosol mass concentrations and visibility

The hourly variations in total Aerosol Mass Concentration (AMC) for a weeklong data in November, 2007 along with the visibility are shown in Figure 2. The minimum and maximum values of hourly mean mass concentration of aerosols are 395 µg/m^3 (24th November, 4 p.m.) and 2 980 µg/m^3 (23rd November, 4 a.m.), respectively. The maximum and minimum concentrations are based on the summation of all channels of aerosol spectrometer. The corresponding visibilities are 2 700 m and 500 m, respectively. Minimum visibility is less than 300 m occurred on 28th November at 7 a.m. with a mass concentration of about 1 541 µg/m^3. The aerosol mass concentrations follow out of phase relationship with respect to visibility (Figure 2). The correlation between these two shows a negative value of –0.7 which infers that more the aerosols load, less will be the visibility.

Note that the term correlation referred above or elsewhere corresponds to the mean of Pearson correlation coefficient. Analyzing the sampling site data it can be concluded that aerosol loads are negatively correlated with daily mean visibility. This result is not surprising because of sampling site location, encountering almost all times foggy conditions with increasing aerosols concentration and lesser visibility during winter.

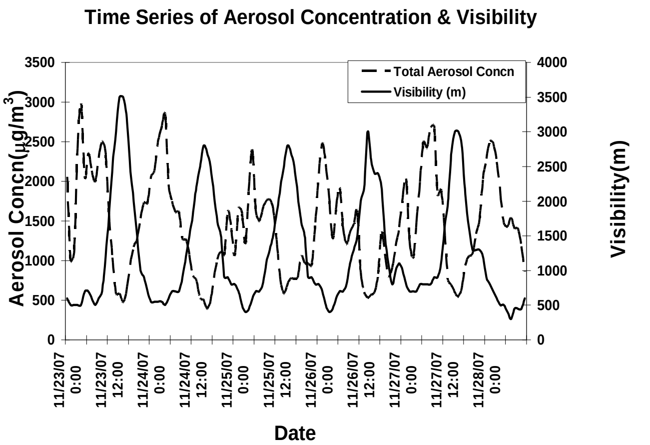

Figure 2. Time series of visibility and aerosol mass concentration (November, 2007).

Depression temperature is defined as the subtraction of dew point temperature from dry bulb temperature. Figure 3 shows the time series of depression temperature and visibility during November, 2007. Most of the pure meteorological models initially considered a depression temperature less than 1 degree as fog occurrence criteria. However, it is argued that if the pollution load increases rapidly then fog may occur with a depression temperature greater than 1 degree. This study clearly shows this synergic effect of pollution and meteorological conditions. The depression temperature and visibility parameter follow in–phase relationship. The minimum depression temperature (0.1) occurs on 28th November at 7 a.m. when the visibility is also lowest during this period (300 meter).

Hourly variations in Aerosol Mass Concentration for a week long data in January, 2008 along with the visibility are shown in Figure 4. The minimum and maximum values of hourly mean mass concentration of aerosols are 234 µg/m^3 (8th January 2008, 9 a.m.) and 3 419 µg/m^3 (6th January 2008., Midnight) respectively. The corresponding visibilities are 550 m and 700 m respectively. Minimum visibility is less than 50 m occurred on 7th January at 7 a.m. with a mass concentration 1 671 µg/m^3. Like November, 2007, the January, 2008 data also show a negative trend between aerosols concentration and visibility with a negative correlation. Thus the visibility trends in Figures 2 and 4 for a sampling location at Delhi clearly show that more aerosols loading is one of the important factors for fog formation.

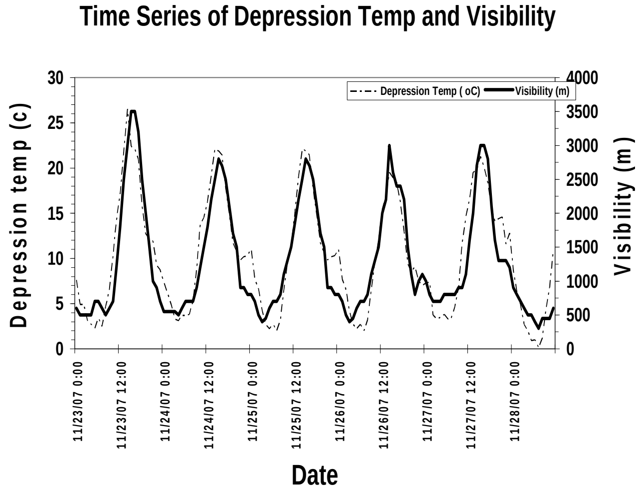

Figure 3. Time series of visibility and depression temperature (November, 2007).

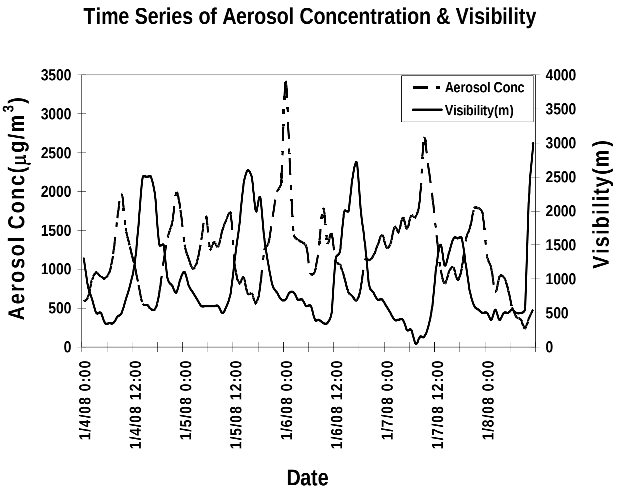

Figure 4. Time series of visibility and aerosol mass concentration (January, 2008).

The time series of depression temperature for January 2008 has been shown in Figure 5. The correlation of depression temperature with visibility is very high (0.87). The minimum depression temperature (0.9) occurs on 7th January at 7 a.m. when the visibility is also lowest (50 meter). The results from winter data shown in Figures 2 to 5, for 2007 and 2008, respectively clearly stems out that increase in pollution level (aerosol mass concentration) and less depression temperature are favorable for fog formation over the considered sampling site in Delhi.

3.3. Linear regression model for estimating fog

We investigate the fog formation criteria using hourly average data from 23rd to 28th November, 2007 to find linear regression amongst various parameters by due consideration of significance value. This satisfies the precondition for using these relations. The association between the meteorological parameters (visibility, depression temperature) and air pollutants was examined. Windows software SPSS (version 17.0) is used to fit a linear regression model. A model Equation (1) was derived to explain the variation in visibility due to depression temperature and aerosol mass concentration:

$$Visibility = 545.417 - 0.214 \times AMC + 103.082 \times DT \qquad (1)$$

where AMC is the total aerosol mass concentration, DT is the depression temperature (= Dry bulb – Dew point temperature).

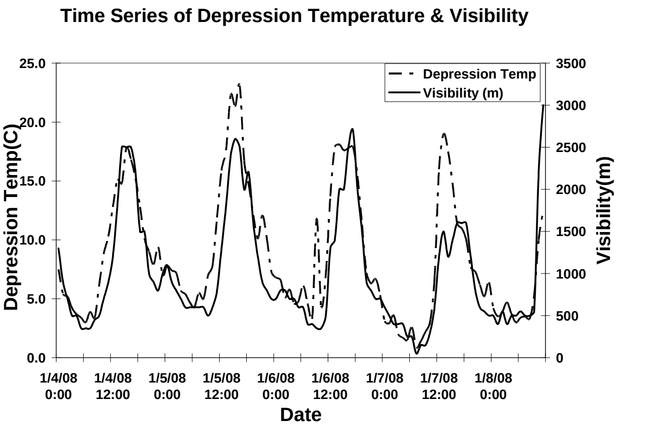

Figure 5. *Time series of visibility and depression temperature (January, 2008).*

The Equation (1) was used for 4th to 8th January, 2008 data for validation purpose. A visibility value of less than 1 000 meter is considered as fog occurrence criteria. The fog occurrence satisfies 88% of the cases.

The aerosol mass distribution data was further analyzed in detail to see the dependency of fog formation on different size ranges. The correlation is determined between different size ranges and visibility. The analysis shows that 0.65 µm size range is the most efficient attenuator in fog with a correlation value of –0.647. Thus, taking 0.65 µm as a reference, a regression Equation (2) was obtained:

$$Visibility = 470.830 - 2.333 \times AMC + 104.687 \times DT \qquad (2)$$

The fog occurrence satisfies 95.8% of the data. Thus better forecast is achieved using Equation (2). Therefore usage of 0.65 µm range results in better forecast. The predicted and observed fog occurrences are plotted in Figure 6.

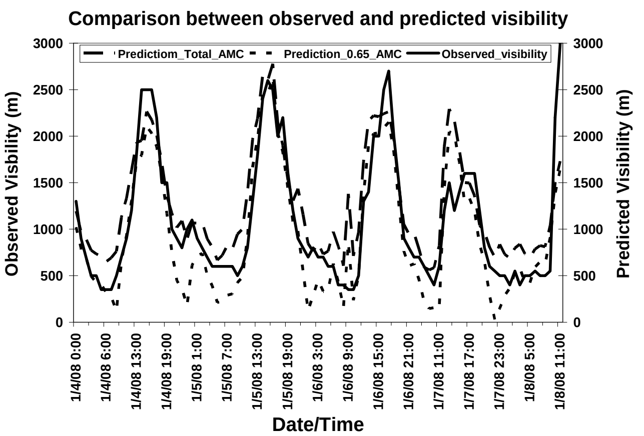

Figure 6. *Comparison between observed and predicted visibility.*

We carried out a comparison study to check whether taking aerosols mass concentrations into account in regression model improves visibility forecasting. For this, a linear regression model based only on depression temperature was derived:

$$Visibility = 90.437 + 117.505 \times DT \qquad (3)$$

The result of above equation is compared with Equation (2). A better correlation value is resulted when AMC is considered. The correlation between observed and predicted visibility by Equation (3) is 0.854 whereas with Equation (2) is 0.899 and Equation (3) is 0.885.

To provide a more quantitative measure of regression models performance, we have used the following standard statistical performance measures that characterize the agreement between model prediction (Vp) and observations (Vo) of visibility:

Root Mean Square Error:

$$(RMSE) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Vp_i - Vo_i\right)^2} \qquad (4)$$

Fractional Variance:

$$(FS) = \left(\sigma_o^2 - \sigma_p^2\right) \Big/ \left[0.5\left(\sigma_o^2 + \sigma_p^2\right)\right] \qquad (5)$$

where σ_p, σ_o are standard deviations of Vp and Vo respectively and N is the total number of measurements.

The statistical performance computed between observed and predicted visibility from Equations (1) – (3) are given in Table 1. The low RMSE and FS value of Equation (2) in comparison with Equation (1) verifies that usage of 0.65 µm size range of aerosols gives a better forecast (Table 1). Comparison of RMSE value from Equation (1) and (2) with Equation (3) further strengthen the relationship that a better forecast is resulted when AMC is considered in the model and thus, aerosols mass concentration is one of the important components in visibility forecasting.

Table 1. *Statistical performance measures for visibility by taking different regression models*

Statistical Measures	Equation (1)	Equation (2)	Equation (3)
RMSE	365.35	342.42	369.74
FS	0.34	0.0008	0.21

4. Conclusions

Delhi is a megacity with very high air pollution concentration levels. The increasing particulate pollution in urban areas is responsible for fog formation. The field experiments for the measurement of aerosol mass concentrations along with meteorological parameters and visibility were conducted and data analysis was performed in various ways. Our study over a sampling location at Delhi clearly shows that high aerosol load is one of the important factors for fog formation. The result of linear regression model depicts that increase in pollution level (aerosol mass concentration) and less depression temperature are favorable for fog formation over the sampling site in Delhi. The analysis with different size ranges and visibility show that 0.65 µm size range is most efficient attenuator for fog formation with a correlation value of –0.647. The linear regression performance analysis suggests that model with aerosols mass concentration gives better visibility forecasting, than with a model based only on depression temperature. Thus the aerosols mass concentration is one of the important components in visibility forecasting.

As the field measurements of fog are very rare, this is a novel approach for making a clear idea about the dependency of pollution in favorable meteorological conditions. The conclusions of this study can be used to substantiate the future campaigns at different sites and conditions.

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