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ARTICLE

Role of Atmospheric Boundary Layer (ABL) Height and Ventilation Coefficient on Urban Air Quality- A study based on Observations and NWP Model

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ABSTRACT

Air pollution is an issue of great concern in any urban region due to its serious health implications. The capital of India, New Delhi continues to be in the list of most polluted cities since 2014. The air quality of any region depends on the ability of dispersion of air pollutants. The height or depth of the atmospheric boundary layer (ABL) is one measure of dispersion of air pollutants. Ventilation coefficient is another crucial parameter in determining the air quality of any region. Both of these parameters are obtained over Delhi from the operational global numerical weather prediction (NWP) model of National Centre for Medium Range Weather forecasting (NCMRWF) known as NCMRWF Unified Model (NCUM). The height of ABL over Delhi, is also obtained from radiosonde observations using the parcel method. A good agreement is found between the observed and predicted values of ABL height. The maximum height of ABL is obtained during summer season and minimum is obtained in winter season. High values of air pollutants are found when the values of ABL height and ventilation coefficient are low.

1. Introduction

Air Pollution has become one of the major environmental issues in urban areas all over the world due to its adverse effects on human health [5]. The air quality of any region decreases due to emission from vehicular and industrial sources. In addition, the air quality also depends on the prevailing meteorological conditions. For example, when the pollutants are trapped below an inversion and there is no exchange between polluted and clean air the air quality of that region gets affected severely. The atmospheric boundary layer (ABL) is the lowest part of troposphere and plays a vital role in dispersion of air pollutants. The height of the atmospheric boundary layer is the height at which the maximum vertical mixing occurs and thus determines the ability of pollutants to disperse. The height of the boundary layer varies both in time and space ranging from hundreds of meters to few kilometres. The ventilation coefficient, is another significant parameter which gives the ability of atmosphere to dilute and disperse the pollutants over a region. It is a function of height of ABL and average wind speed within the ABL. A number of studies conducted in recent past has related ABL height and ventilation coefficient to air quality [8,12].

Delhi, the capital of India, is located at 28.5° N latitude and 77° E longitude at 216 m above mean sea level.

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It has Thar desert in the West, central hot plains in the South and hills in the North and the East. The city has a semi-arid climate with long summers from April to October with monsoon season in between and winters during October to January with a large number of fog events [1]. There has been increase in air pollutant emissions of particulate matter (PM), sulfur dioxide (SO2), nitrogen oxides (NOx), carbon monoxides (CO) and hydrocarbons due to rapid population growth. The increased level of pollutants in Delhi results in health and respiratory impacts and the city is characterized as the "asthma capital" of India [4].

The studies conducted in past [2,3,6,11,13] indicates that not a single factor but a number of sources including industries, power plants, domestic combustion of coal and biomass and transport are responsible for air pollution in Delhi. The contributions from different sources is also affected during summer and winter months. The pollution levels in Delhi are higher during winter season in the months of November to February. The events of smog and fog occur frequently over Delhi in winter season causing frequent delays and cancellations of flights [1]. A particulate matter source apportionment study for four seasons was conducted on measured PM2.5 concentration at various locations over Delhi by Chowdhary et al. [2]. The study indicated that average PM2.5 during winter months is higher than summer months.

While the previous studies helped us in understanding the sources of air pollution in Delhi, but the studies on association of ABL height and ventilation coefficient with pollution levels are limited. Keeping a view of this, the present study addresses the variation of boundary layer height and ventilation coefficient and their correlation with air pollution over Delhi. The focus of this study is to utilize the forecast of boundary layer height and ventilation coefficient of global operational numerical weather prediction model. The main objectives of the study is to obtain boundary layer height over Delhi from model and verify it against observation during 2017-2018 and to investigate the role of boundary layer height and ventilation coefficient on the dispersion of air pollutants.

2. Determination of Height of ABL and Ventilation Coefficient from NCUM

The Unified Model (UM) is the operational model of NCMRWF and is known as NCUM. The horizontal resolution of the model used in the present study is 17 km and it has 70 vertical levels spanning from ground up to around 80 km altitude. The hourly forecast of height of the ABL is available from NCUM and is used in the present study.

The height of the ABL in NCUM is based on parcel and bulk Richardson number method. Both of these methods are widely used to obtain the ABL height in convective conditions. The parcel method determines the height of the ABL in convective conditions as the height of intersection of actual potential temperature profile with the dry adiabatic lapse rate starting with the near surface temperature [7].

Another method used to determine ABL height is based on bulk Richardson number (R_{ib}) for boundary layer. This method defines the top of the ABL as the level at which R_{ib} exceeds a critical value. The critical value of R_{ib} is chosen as 0.25 [14]. The difference between ABL height obtained from parcel and bulk Richardson number method is negligible [7]. The height of the boundary layer in NCUM is computed by taking maximum height of the two methods- parcel and R_{ib} number method.

The bulk Richardson number at any level (h) is defined as:

$$R_{ib}(h) = \frac{gh}{\theta_{v1}} \frac{\theta_v(h) - \theta_{v1}}{U(h)^2 + V(h)^2} \tag{1}$$

Here θ_{v1} is the virtual potential temperature at the lowest vertical level and $\theta_v(h)$ is the same at height h. U and V are mean flow components at height h and g is the gravity of earth.

The ventilation coefficient (VC) in the model is computed as the product of ABL height and wind speed within the ABL. The wind speed within the ABL is the average of wind speed at surface and at the top of the ABL. Eq. (2) is used in the model to compute VC.

VC= (Height of the ABL x Wind speed within the ABL) (2)

The ABL height obtained over Delhi from NCUM is verified with the observed ABL height for a period of one year.

3. Materials and Methods

An attempt has been made in the study to correlate the air pollution over Delhi with ABL height and ventilation coefficient. The analysis is carried out for a period of one year and the values of Air Quality Index (AQI) are correlated with height of boundary layer. Air quality index is a tool that monitors air quality of any location at real time. It accurately reflects the extent of air pollution in region. The values of AQI at different locations across Delhi and National Capital Region (NCR) are available on website of Central Pollution Control Board (CPCB)[3] (https://

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app.cpcbccr.com/AQI_India/). The AQI is computed based on real time data of particulate matter (PM10 and PM2.5), sulphur dioxide, nitrogen dioxide, carbon monoxide, ozone, ammonia and benzene obtained from the number of air quality monitoring stations installed in different parts of Delhi. The real time pollution figures from these stations in the city are available on Delhi Pollution Control Committee (DPCC), System of Air Quality and Weather Forecasting and Research (SAFAR) and CPCB websites. The data from all these websites is used to calculate the overall AQI at different locations in Delhi and is displayed on website of CPCB. Six different categories of air pollution are identified depending on the values of AQI (Table 1).

Table 1. Classification of Air Quality

AQI	Category
0-50	Good
51-100	Satisfactory
101-200	Moderate
201-300	Poor
301-400	Very Poor
401-500	Severe

The height of the ABL from the model is obtained for convective conditions, thus the ABL height at 1200 UTC is correlated with air quality index at 1700 IST. The ABL height from the model is obtained for Indira Gandhi International (IGI) Airport (Latitude 28.57° N, Longitude 77.12° E) and thus AQI values of IGI are utilized in the present study.

The AQI of IGI airport in the present study is the concentration in micrograms/m3 of the primary pollutant from the five pollutants PM2.5, PM10, NO2, CO and Ozone. The value at any hour is the average of previous 24 hours. Figure 1. shows the primary pollutant at the site in different months during December 2017-November 2018. It is clear that PM2.5 is primary pollutant from October-February whereas from March-September majority of days have PM10 as primary pollutant at the selected site in the present study. The concentrations of NO2 and Ozone are zero for the entire study period and thus both of them are not included in the figure. The air quality is in moderate and satisfactory category for maximum number of days in pre-monsoon season (March, April and May) and monsoon season (June, July, August and September) respectively. Out of 299 days, there are only three days of good air quality one in the month of July and two days in the month of September. Similarly, there are only three days with severe air quality two observed in the month of June and one during the month of November. The air quality shifts from moderate category to poor and very poor category from the month of October. There are maximum number of days in poor and very poor category in the months of November, December, January and February (Figure 2).

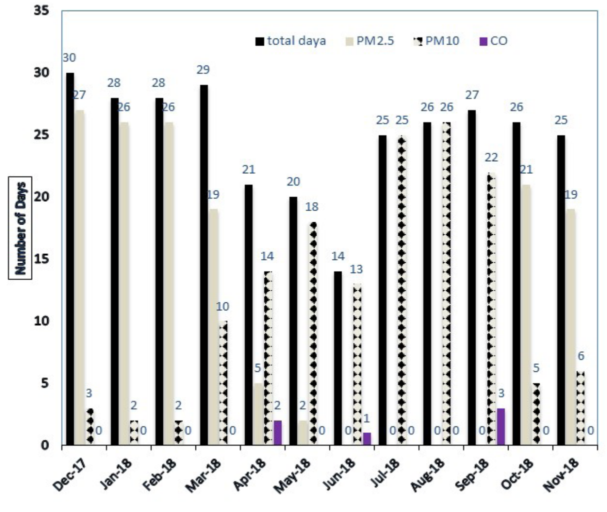

Figure 1. Primary pollutant from December 2017-November 2018

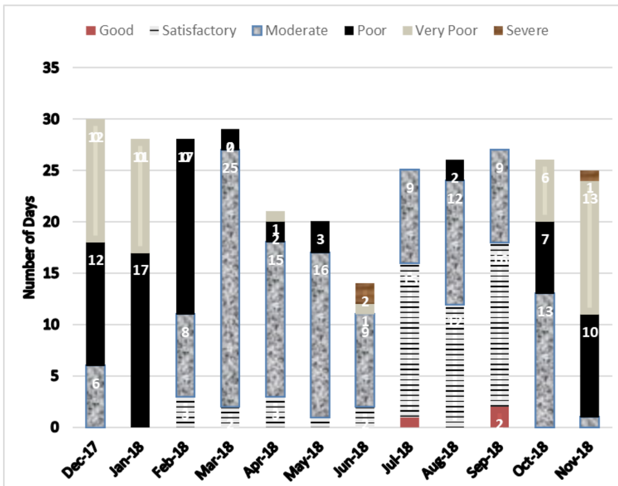

Figure 2. Air Quality Index (AQI) from December 2017-November 2018

The height of ABL and the ventilation coefficient (VC) is obtained from the operational global model NCUM at 12 UTC every day for a period of one year during 2017-2018. The observed ABL height, computed from radiosonde observations using the parcel method is utilized to verify the ABL height obtained from the model. The observed ABL height over Delhi is computed using the high-resolution radiosonde observations available from University of Wyoming site (http://weather.uwyo.edu/upperair). The radiosonde observations for Delhi (Station ID-42182, Latitude 28.58^0 N, Longitude 77.2^0 E) are available at 00 and 12 UTC, the present study utilizes the observations at 12 UTC

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to compute the ABL height. The traditional parcel method is utilized in present study to obtain ABL height over Delhi. The altitude (z) where the dry adiabatic line (DLR) intersects the temperature profile i.e. environmental lapse rate (ELR) is defined as the height of the ABL (Figure 3).

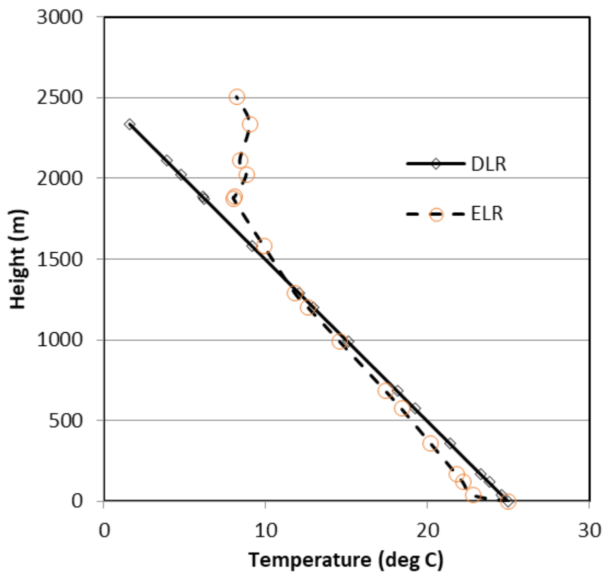


Figure 3. ABL Height determination using Parcel Method

4. Results and Discussions

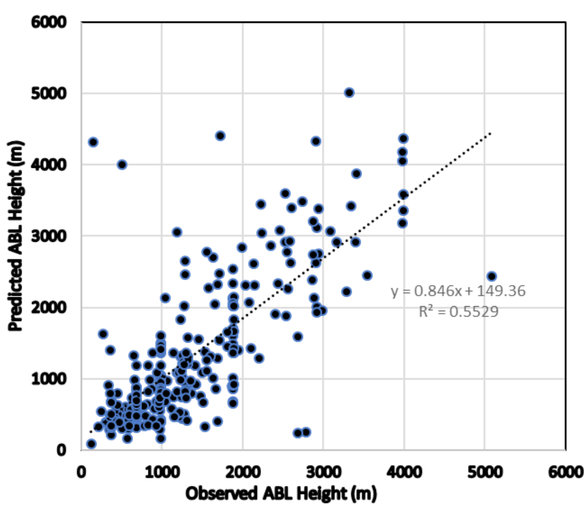


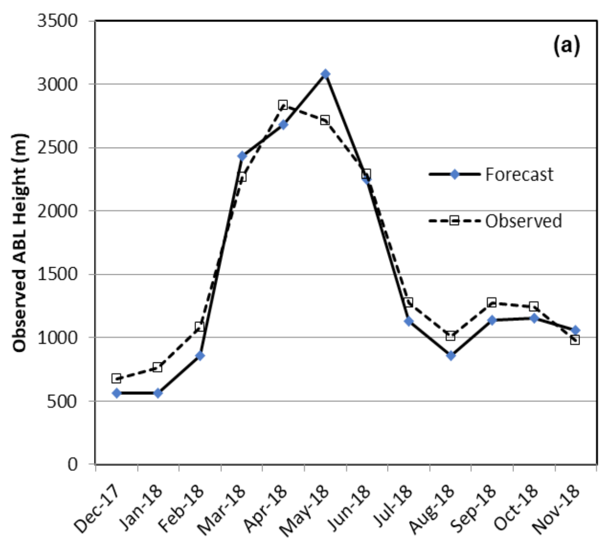
Figure 4. Observed and Predicted ABL Height during 2017-2018

The objective of the present study is to analyse the relationship of ABL height and ventilation coefficient obtained from NCUM with air pollution over Delhi. In view of this, the 36-hour forecast of ABL height from NCUM is verified against the observed ABL height over Delhi. The observed ABL height at 12 UTC correlates well with 36 hours forecast of ABL height from NCUM (Figure 4). The coefficient of determination (R^2) for ABL height is 0.55.

The monthly variations of ABL height are shown in Figure 5a, during the period from 2017-2018 at the study site. A gradual rise is noticed in ABL height from December to May and then sudden drop occurs in June. The higher values in the month of May are due to thermal convection processes during pre-monsoon season and the lowest values are in the month of December (winter season).

The monthly variations in VC are shown in Figure 5b. The highest value of VC is obtained in the month of May (pre-monsoon season) due to high values of ABL height and the lowest value is obtained in the month of November (post-monsoon season). The values of VC in December and January are higher in comparison to those obtained in the month of October and November. Although the height of ABL is higher (~1000 m) in the month of October and November than those obtained in the month of December and January (~500 m) Figure 5a., the higher values of VC in winter months (December and January may be due to higher wind speed within the boundary layer during these months. Thus, not only convection but mixing in the boundary layer also have significant role in dispersion of air pollutants in the lower atmosphere.

Figure 5c shows the variations of AQI over Delhi from 2017-2018. It is obvious that high values of AQI during winter and post monsoon season are due to low values of ABL height and VC during these months. It is found that AQI is in poor and very poor category in winter and post monsoon season due to low values VC, promoting the longer residence time of pollutants in the atmosphere during these seasons (Figure 5b). Figure 6 explains the correlation between AQI and VC and both are inversely related to each other in agreement with results reported earlier [9,10].



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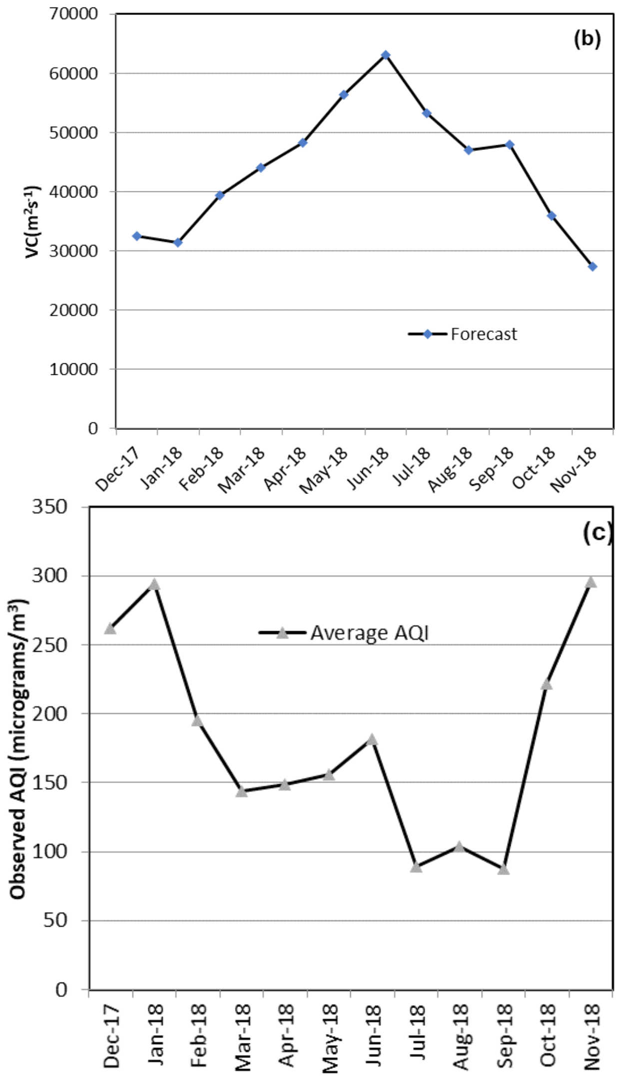

Figure 5. Variation of (a) Observed and Predicted ABL height (b) VC and (c) Average AQI over Delhi during 2017-2018

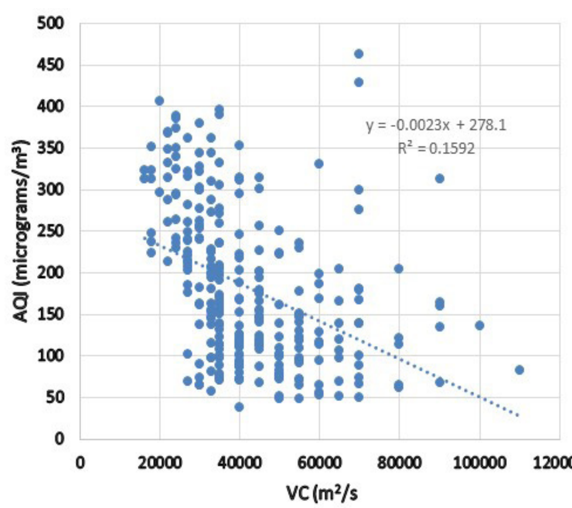

Figure 6. Scatter Plot between VC and AQI

The most significant meteorological parameters for dispersion of air pollutants are wind speed and ABL height, within which the pollutants are mixed. The results of the present study indicate that the model predicted values of ABL height and VC can be utilized to determine the dispersion of air pollutants as the higher values of AQI are found for low values of ABL height and VC.

5. Summary and Conclusions

The present study examines the role of ABL height and VC in dispersion of air pollutants over Delhi during 2017-2018. The ABL height and VC are obtained from global NWP model NCUM. The height of the ABL from NCUM is validated with observed ABL height obtained using radiosonde observations over Delhi. The main findings of the study include the following:

(1) The average monthly observed and predicted ABL height is maximum in pre-monsoon season due to strong convective activity and minimum in winter season in association with stable atmosphere. A good agreement is found between observed and predicted ABL height.

(2) VC is maximum in the month of May and minimum value is obtained during November. The value of VC is dependent on ABL height and wind speed within the boundary layer, thus despite of lower values of ABL height in December and January in comparison to those in October and November the values of VC are higher in these two months than October and November .

(3) Monthly variation of AQI shows minimum values in monsoon season and maximum values in winter and post-monsoon season. Due to low values of ABL height in winter and post monsoon season, the pollutants get trapped in stable layer and act as a capping to the mixed layer that leads to elevated ground level concentrations and thus higher values of AQI. The values of AQI are minimum in monsoon season although the values of VC are highest in pre-monsoon season. This may be due to the fact that in monsoon season the pollutant get washed out due to precipitation events leading low ground level concentrations. During pre-monsoon season Delhi and most parts of north west India experiences a number of dust storms which leads to high values of AQI.

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