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RESEARCH ARTICLE

Comparison of predicted vehicular pollution concentration with air quality standards for different time periods

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Abstract Air pollution is caused by variety of sources such as industries, vehicles, cremation, bakeries, and open burning. These sources have variation in emission with different time scales. Industry and bakeries have variation in emission with day or week, rest of the sources like vehicles and domestic sector have variation with time in a day. In fact, vehicles have a large variation in emission with time period of the day. The average concentration of 24 h is much less than hourly concentration of peak time when there is heavy vehicular emissions. The hourly concentration of off-peak time or lean time is very low due to low emission for that period. The air quality standards of India are prescribed for 24-h average concentration with which the predicted average concentration from models is compared. However, the peak time concentration may be much higher than the standard. In the peak time, outdoor concentration is more and since a large proportion of the population is out the exposure is also very high and can cause severe health effect. In this paper, vehicular pollution modeling has been carried out using AERMOD with simulated meteorology by Weather Research and Forecasting model. NO_x and PM concentrations were 3.6 and 1.45 times higher in peak time than off-peak and evening peak, respectively. Lean time has higher concentration for both NO_x and PM than off-peak and evening peak. It shows the misleading concept of comparing average predicted concentration of 24 h with standards for vehicles.

Keywords Vehicular emission · Hourly concentration · WRF model · AERMOD

Introduction

With the increasing population of India, air pollution has become a serious problem in major metropolitan cities (Sivacoumar et al. 2001a, b). There are many sources of air pollution in urban region including vehicular and industrial sources. Most of the metropolitan cities of the world have heavy transportation load to meet the needs of the people. This load is increasing continuously as the population is increasing (CTS 2008). This increasing transportation load is making it difficult to manage the health and safety of society (Pawar and Patil 2015). Long-term exposure to air pollution leads to a variety of adverse health effects including respiratory, cardiovascular, developmental, reproductive, gastrointestinal, and neurological health outcomes (Bertazzon et al. 2015). Vehicular sources have severe effect on human health and environment as these are ground level source (Amundsen et al. 2008; Cheng et al. 2013; Fan et al. 2012; Fenger 2009; Kumar et al. 2016a; Nagendra and Khare 2002; Neema and Jahan 2014; Province et al. 2013; Sharma et al. 2004; Sivacoumar and Thanasekaran 1999). These vehicular emissions are diverse at different times of day. Industry, bakeries, and other sources have variation in emission with day or week or month. Vehicular sources have variation with time of the day as vehicular sources are at ground level and they are maximum in urban region where there is an abundance of canopy. Therefore, building effect and canyon effect have been attempted by many researchers (Aquilina

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and Micallef 2004; Assael et al. 2008; Berkowicz 2000; Berkowicz et al. 2008; Kakosimos et al. 2010; Ketzel et al. 2012; Kukkonen et al. 2001; Manning et al. 2000; Thaker and Gokhale 2015). However, effect of peak and off-peak hour of vehicular emission have not yet been studied specially in India. It is well known that peak near-source concentrations can be elevated over 24-h standards. However, it is the degree to which they are elevated and in the spatial extent that is important. The theme of the paper is the role of models in helping to determine this. Concentration of air pollutant is directly proportional to emission (Barnes et al. 2014). This concentration varies a lot in hour of the day. It causes maximum concentration at peak hours. In India, air quality monitoring is done on the basis of collection of 24-h sample, as Central Pollution Control Board (CPCB) prescribed 24-h and annual standards as presented in Table 1. Hourly concentration is not monitored as concentration varies considerably with hour of the day because of vehicular pollution. Peak hours cause interruption and congestion on the road and generate more emission (Choudhary and Gokhale 2016). Morning peak (Peak 1) and evening peak (Peak 2) have maximum emission and causes maximum concentration in the day (Gokhale 2011, 2012; Shukla and Alam 2010) when maximum population is supposed to be in outdoor environment. This peak hour concentration of pollutants has severe impact on public health due to high exposure (Namdeo and Stringer 2008; Sonawane et al. 2012). Therefore, proper and rational air quality management requires hourly concentration profile to analyze health impacts in a better way.

In view of the above, in this paper, the concentrations of pollutants for peak and off-peak time are studied. Hourly concentration of air pollutants can be either monitored or estimated by using modeling technique. Hourly kerbside air quality monitoring data are not available in Mumbai as they follow CPCB guidelines and their permissible limit is for 24 h. Also, the values of monitoring data include all urban/local sources such as vehicular, industrial, and domestic and regional sources. Variation in source is difficult to identify. So, a unique tool "Air Quality Model" was used to predict concentration for vehicular sources for peak and off-peak hours. It is also used for various purposes like to predict future pollutant concentrations from multiple sources and control scenarios after the implementation of a new regulatory program in order to estimate the effectiveness of the program in reducing harmful exposures to humans and the environment.

Table 1 Concentration (μg/m^3) of national ambient air quality standard prescribed by CPCB

NO_2		PM_{10}	
24 h	Annual	24 h	Annual
80	40	100	60

Air quality modeling is the mathematical tool for estimation of ambient concentrations of air pollution based on meteorological and emission data. They are designed to characterize primary pollutants which are emitted directly into the atmosphere and, in some cases, secondary pollutants that are formed as a result of complex chemical reactions within the atmosphere. There are many models to estimate concentration of vehicular pollution. The most widely used are Gaussian based, viz. CALINE3 model, EPA's HIWAY-2 model, and GM model (Benson 1979; Petersen 1980; Chock 1978). A model was developed by Csanady for a finite line source which is applicable for any orientation of wind with roadways (Csanady 1972). United State Environmental Protection Agency (USEPA) and American Meteorological Society (AMS) developed a regulatory air quality model viz. AERMOD in 1991 in order to design goal of initiating current planetary boundary layer (PBL) concepts into regulatory dispersion models in 1991 (Cimorelli et al. 2004). AERMOD is a steady state Gaussian plume model which can be used for computation of point, area and line sources (Kesarkar et al. 2007; Kumar et al. 2015). It can be used for simple and complex terrain for receptors within 50 km of a modeled source (Mokhtar et al. 2014). All dispersion models require two kinds of input data namely meteorological data and emission data. The schematic data flow of AERMOD is given in Fig. 1. Emission inventory is prepared based on air pollution sources and meteorological data is processed to make concentration profile in air quality model. Meteorological model Weather Research and Forecasting (WRF) was used to generate meteorological data to provide input in AERMOD which is given below.

Meteorological model

Meteorological data are either collected from a meteorological station or generated using meteorological model.

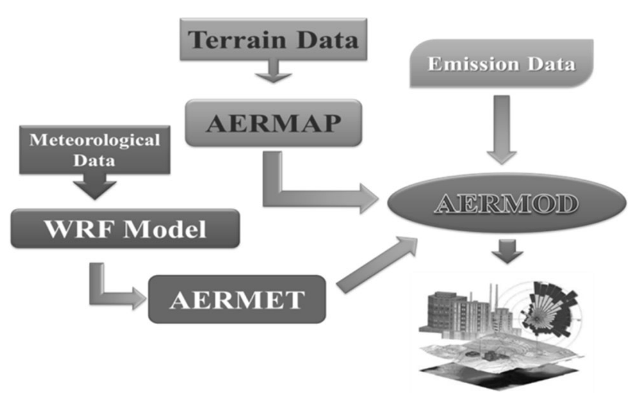

Fig. 1 Data Flow in the AERMOD Modeling System (Cimorelli et al. 2004)

Fig. 2 Study area Chembur

Very few meteorological stations exist in India. Generally, meteorological data are collected from nearby meteorological station and used for air quality modeling. However, in this study onsite meteorological data from an advanced meteorological model WRF generated. The meteorological model systems are in the field of weather forecasting and simulation. Research and development in the field of air quality include methods for forecasting atmospheric dispersion, decay and deposition of pollutant and methods for smog, ozone forecasting, and pollen forecasting (NCAR 2012). Fully revised resource for researchers and practitioners in the growing field of meteorological modeling is known as the second edition of Mesoscale Meteorological modeling at the mesoscale. This next-generation mesoscale numerical weather prediction system is WRF Model which is designed to serve both atmospheric research and operational forecasting needs (Henmi et al. 2005). WRF is the most recent numerical program model to be adopted by NOAA's National Weather Service as well as the U.S. military and private meteorological services. The capability of this model is to simulate and forecast then produce meteorological profile reflecting either real data or ideal data of atmospheric condition.

Two dynamical cores, a data assimilation system and a software architecture allowing for parallel computation and system extensibility are configured by WRF model. From meters to thousands of kilometers is the wide range of scaling which can be obtained in the meteorological field using this model. It includes idealized simulations (e.g., convection, baroclinic waves), parameterization research, data assimilation research, forecast research, real-time national weather service and coupled-model application. WRF provides operational forecasting a flexible and computationally efficient platform, while offering advances in physics, numeric, and data assimilation contributed by many research community developers.

The Chembur region of the Mumbai city was selected for this study. Vehicular pollution modeling was done using USEPA model AERMOD for morning and evening peak, off-peak and lean time of the day for the year 2011. It can help in understanding variation and comparison amongst the concentration of morning and evening peak, off-peak and lean time.

Fig. 3 Emission rate for roads and pollutants

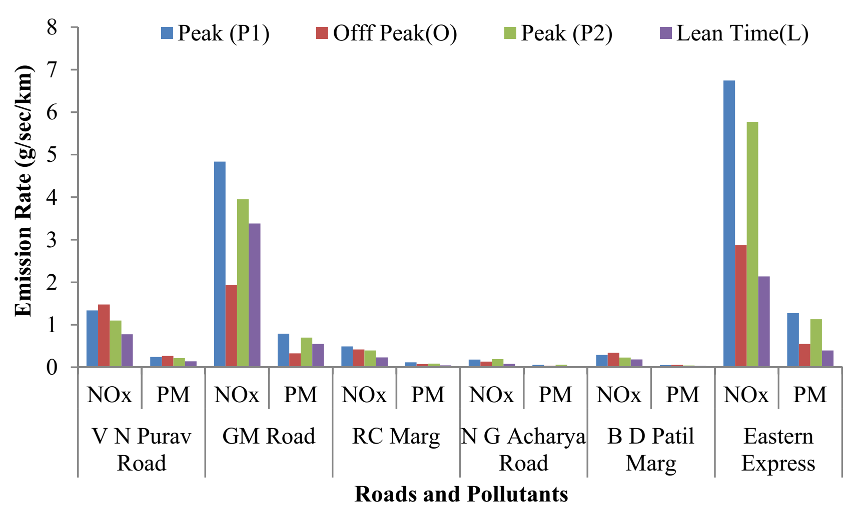

Table 2 Morning and evening peak, off-peak and lean time of the day

Morning peak (Peak 1)	8.00 am–12.00 am
Evening peak (Peak 2)	5.00 pm–9.00 pm
Off-peak	12.00–5.00 pm
	9.00 pm–11.00 pm
Lean time	11.00 pm–8.00 am

Study area

Chembur is a highly polluted region due to a high concentration of industries as well as vehicles. Its latitude and longitude are 19.05°N and 72.89°E, respectively. The study area is 6.5 km east-to-west and 8.45 kilometers north-to-south as shown in Fig. 2. It contains heavy duty vehicles on Port Trust Road, Mahul Road and Ramakrishna Chemburkar Marg. Due to continuous movement of heavy vehicles, road conditions are getting worse. It has four major industries such as two refineries (BPCL and HPCL), a fertilizer (RCFL), and a power plant (TPCL). Weather Research and Forecasting (WRF) model was used to derive onsite meteorology for input in air quality model. Nine parameters on meteorology were generated using WRF model and fed in AERMET which is a preprocessor of AERMOD. This region has considerable variation in official and commercial activity with time in a day. Population goes to office to work in morning and comes back in evening. This causes congestion and interruption on traffic and generates high emissions in peak time on the road when maximum population is in outdoor environment.

Methodology

Air quality model requires two kinds of input data viz. emission data and meteorological data. Emission inventory was prepared using actual number of vehicles, respective emission factors, and vehicle kilometer traveled (vkt). Hourly vehicle counting for each category was done for six roads of Chembur. Emission inventory for NOx and PM was assembled with the help of emission factor of air quality monitoring project-Indian clean air programme, ARAI, Pune (India: ARAI 2007). The emission factor was available for PM only and not available for PM_{10} and $PM_{2.5}$ thereby emission rate was prepared for PM only. The emission inventory has been prepared for morning and evening peak, off-peak and lean time of the day as shown in Fig. 3. This emission inventory has been prepared based on Indian driving cycle (IDC) of vehicles. So, congestion effect in emission has not been considered separately because it has been already considered in IDC. The peak, off-peak and lean time hour vary with locations and type of the road. So, the peak, off-peak and lean time hour is selected based on field traffic data. The morning and evening peak, off-peak and lean time of the day have been given in actual time of the day in Table 2.

Hourly onsite meteorological data were generated using Weather Research and Forecasting (WRF) model for the

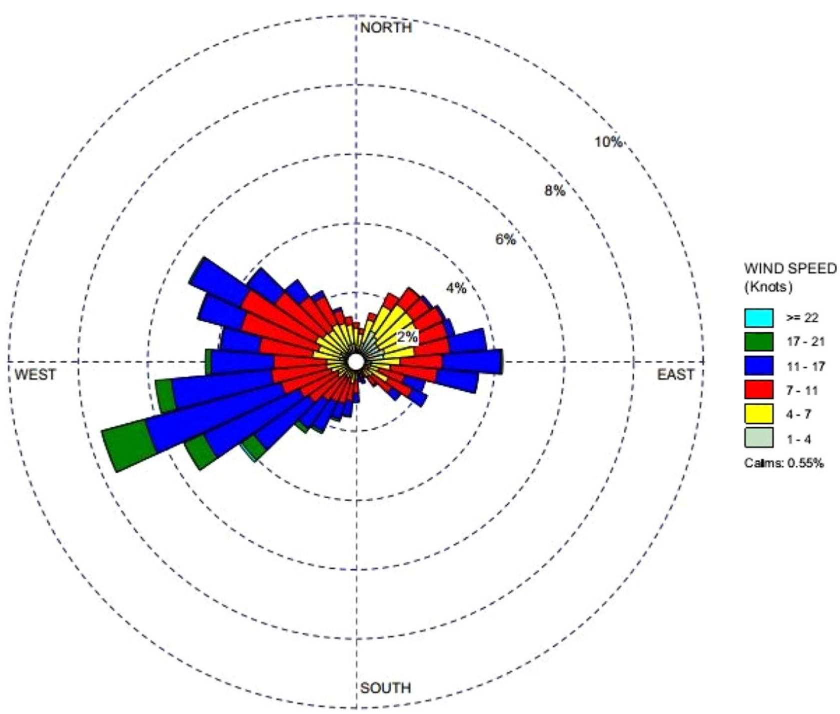

Fig. 4 Annual Wind Rose Simulated by WRF (Legend in m/s)

year 2011, which saved time and resources. National Centers for Environmental Prediction (NCEP) FNL (Final) Operational Global Analysis data were used as input of WRF whose resolution was at 1.0 × 1.0 degree grids, prepared operationally for every 6 h. This product is from the Global Data Assimilation System (GDAS), which continuously collects observational data from the Global Telecommunications System (GTS), for many analyses. These meteorological data from output of WRF model were prepared in spread sheet and were fed in AERMET that is the preprocessor of AERMOD. Later, AERMOD model was used for prediction of NO_x and PM concentration from traffic emission for the six roads of Chembur.

Results and discussion

WRF run was used to simulate the model from January 1st to December 31st, 2011. Hourly nine meteorological parameters such as wind speed, wind direction, rain fall, temperature, humidity, pressure, ceiling height, global horizontal radiation, and cloud cover were generated using

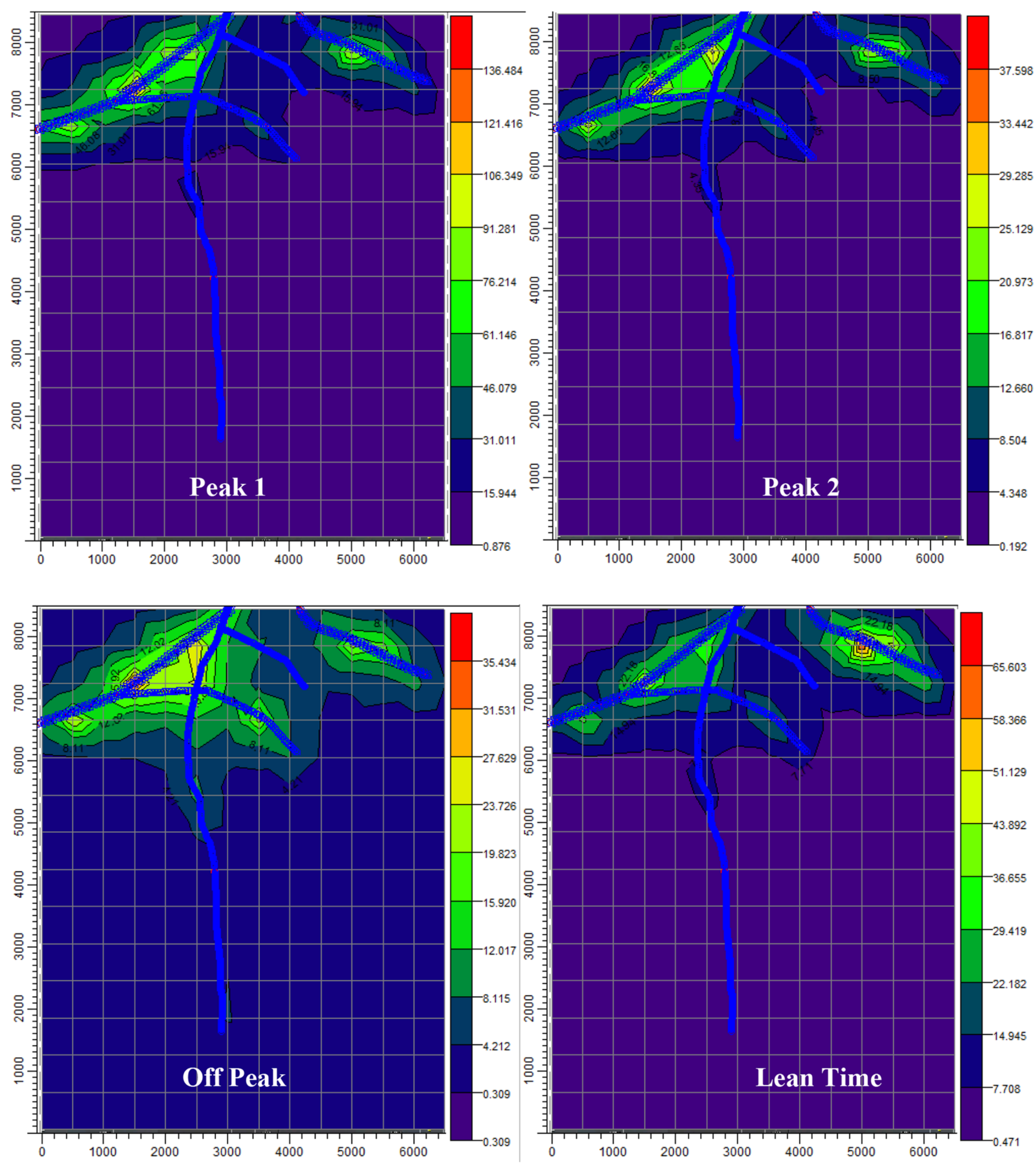

Fig. 5 NO_x concentration plot for morning and evening peak, off-peak and lean time

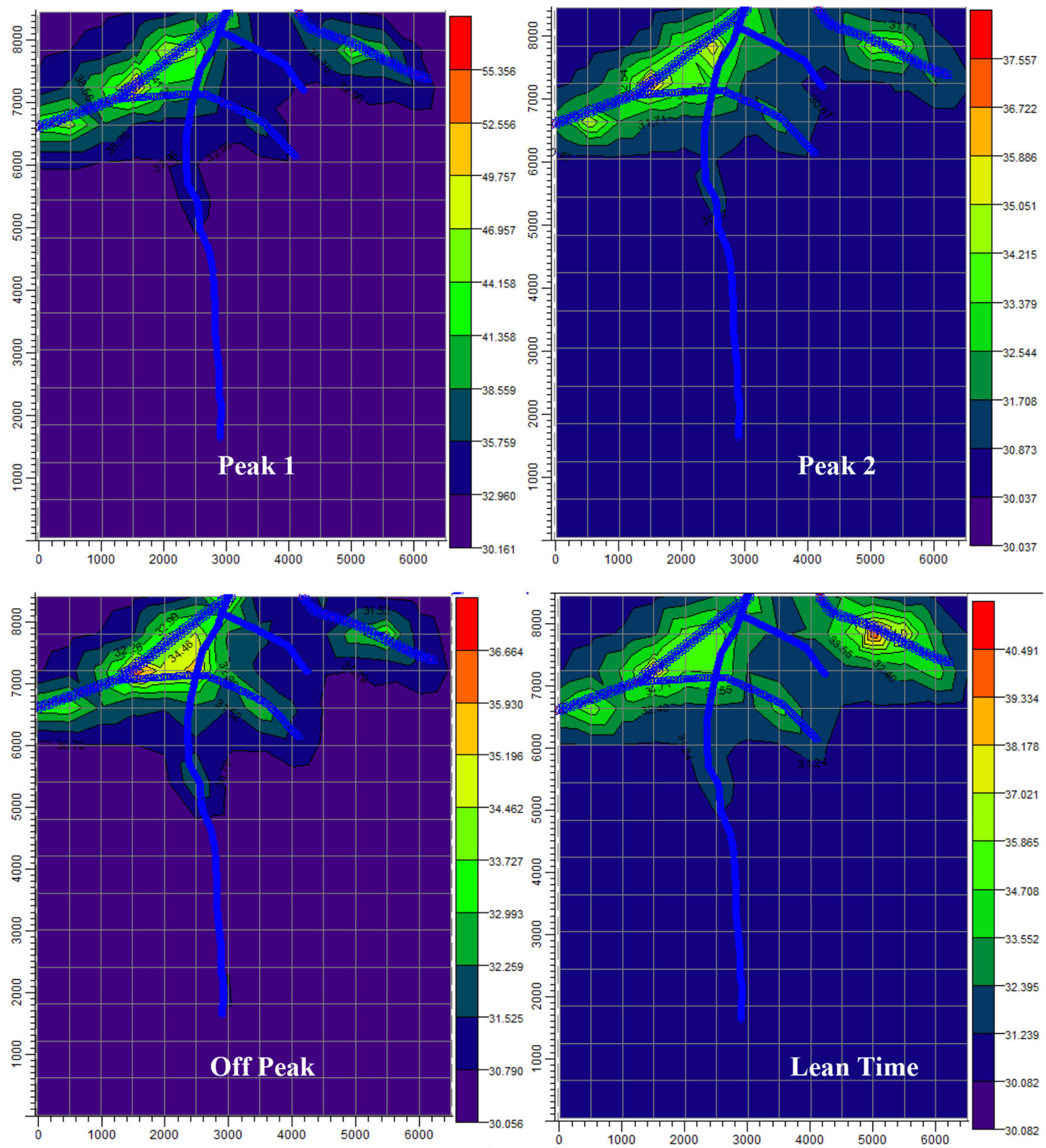

Fig. 6 PM concentration plot for morning and evening peak, off-peak and lean time

WRF model at 25 km resolution. The generated temperature and wind were compared with observed values because they are more significant for air modeling (Kumar et al. 2016b). The output meteorological data from WRF were incorporated in air quality model AERMOD. Figure 4 shows annual wind rose which has been plotted from WRF outputs. Wind roses have some differentiation in the terms of wind speeds as well as wind directions. The variation in topography and land use may be responsible for differentiation. The wind roses for morning and evening peak, off-peak and lean time of the day, have been plotted to investigate meteorological influence in air quality modeling as shown in Fig. A1 in "Appendix" section. Calm conditions for each period were estimated as 1 m/s was threshold. It was found to be 5.3, 0.3, 2.7, and 5.5 % for morning and evening peak, off-peak and lean time of the day, respectively. Morning time and Lean time (night time) were more calm condition as this period has stable boundary layer condition.

Since the emission factors of vehicles are available for PM only and not available for $PM_{2.5}$ and PM_{10}, vehicular pollution modeling was carried out for PM only. NO_x and

PM emissions have been modeled for the morning and evening peak, off-peak and lean time of the day of the entire year 2011 to see this effect of variation in air quality. Measurements of air quality by industries are carried out in south region and not in North region of study area (Fig. 1). Also, hourly measurement of ambient concentration for air pollutants is not carried out at road side so that the effect of peak and off-peak hour can be compared with model results. The continuous ambient air quality monitoring data were collected at sites HPCL and BPCL at 3.66 m (12ft) for NO_x and PM_{10}. AERMOD was run for all the sources in the region for the whole year of 2011 and concentration was predicted at ground level for NO_x and PM. The model results of NO_x and PM were compared with observed value of concentration and observed concentration includes all the sources. This is given in Table A1 in "Appendix" section. Model results of NO_x were in good agreement with observed concentration at both the locations. Model results of PM were compared with observed concentration of PM_{10} because vehicles emit fine particle only. Here, 30 μg/m^3 was background concentration which was estimated from the study of same region using all emission inventories in Kumar et al. (2015). This might be caused by missing sources like resuspension of dust in emission inventory. Vehicles emit less PM from tail pipe. The model results of PM were in good agreement with observed concentration at BPCL with incorporation of 30 μg/m^3 background concentration. However, modeled concentration for PM at HPCL is 50.3 μg/m^3 while observed concentration was 88.2 μg/m^3. At this location, model was underestimating as compared with observed value of concentration. It may be because, resuspension of particulate matter might be more or some emission sources like fugitive were missed in emission inventory which was used to run this model. It is also well known that models are underestimating for PM in air quality modeling study (Mohan et al. 2011; Rood 2014).

The NO_x concentration plot for morning and evening peak, off-peak, and lean time of the day of the entire year 2011 is shown in Fig. 5. NO_x concentration is maximum (136 μg/m^3) at Eastern Express Highway in peak 1 time. CPCB prescribed limit is 80 μg/m^3 for NO_x for 24-h average. Peak 2 and off-peak have almost same pattern and minimum concentration. Concentration was found more than off-peak and peak 2 in lean time because heavy duty diesel vehicles run in that time. In the morning time, the atmospheric state exhibits stagnant wind conditions, compressed atmospheric boundary layers (ABL), and or inversions. So, even though the source term for early morning rush hour is just ramping up, the impact before the boundary layer lifts can be very significant. This may be one of the reason for maximum concentration in morning peak (8.00 am–12.00 am). The daily average calculation of concentration can meet CPCB limit but during peak time, population are in outdoor environment and exposed to maximum concentration.

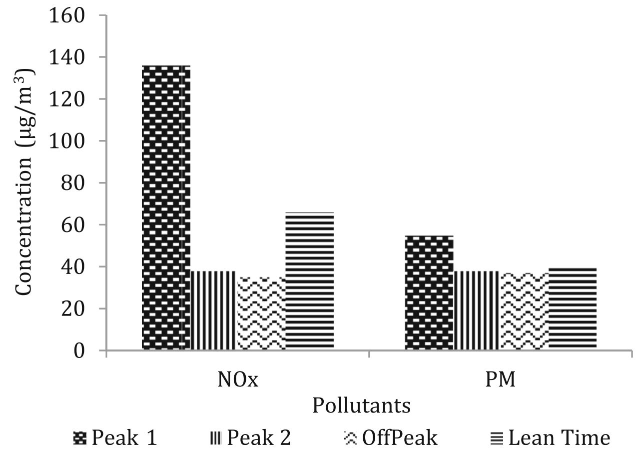

Fig. 7 Maximum concentration for Peak 1, Peak 2, Peak 3 and Peak 4 in the region

Similarly, PM concentrations have been modeled for the morning and evening peak, off-peak and lean time of the day of the entire year 2011 in Fig. 6. The maximum PM concentration was on Eastern Express Highway in peak 1. Peak 2 and off-peak have minimum and similar concentration pattern. Lean time has concentration more than off-peak and peak 2. The heavy duty diesel vehicles are operated in lean time in Eastern Express Highway and Ghatkopar-Mankhurd Road. Also, maximum concentration was seen for peak 1, peak 2, peak 3, and peak 4 in the region for both pollutants and shown in Fig. 7. Here, maximum concentration of NO_x can be seen as worst in morning peak (peak 1). NO_x concentration was 3.6 times higher in peak time than off-peak and evening peak. PM concentration was 1.45 times more in peak time than off-peak and evening peak. Lean time has more concentration for NO_x and PM than off-peak and evening peak. So, peak time may have severe health impact.

Conclusions

Central Pollution Control Board (CPCB) has prescribed concentration limit for air pollutants for 24 h and annual average. Vehicular emission varies with time of the day i.e., morning peak, evening peak, off-peak, and lean peak. So, vehicular emission modeling has been done to see variation in concentration of air pollutant in various time of the day. It is seen that the average of peak, off-peak, and lean time can meet the daily prescribed limit of CPCB but maximum concentration is in peak time when maximum population are in outdoor environment causing severe health impact. Morning peak time has maximum emission and causes maximum concentration. It might be also caused by low atmospheric boundary layers in morning time. This study shows that comparing daily average concentration with CPCB daily standard for vehicles can mislead in terms of health effects. Hence, the standard should also be prescribed for shorter time period like three hours for a day. This will help in ensuring improved public health. Hourly ambient air concentration should be monitored at road side so that variation in hourly ambient concentration can be seen. Further, health impact assessment can be carried out to formulate hourly ambient standard. Also, WRF model has been used to generate meteorological parameters where predicted wind speed by WRF was higher than observed, which causes low ambient concentration. It can be improved by including canopy effect in WRF model.

Appendix

See Table A1 and Fig. A1.

Table A1 Comparison of simulated concentration with ambient observed concentration

Pollutant	Location	Simulated conc. (μg/m^3)	Observed conc. (μg/m^3)
NO_x	BPCL	22.7	26.2
	HPCL	21.7	21.3
PM	BPCL	49.6	52.9
	HPCL	50.3	88.2

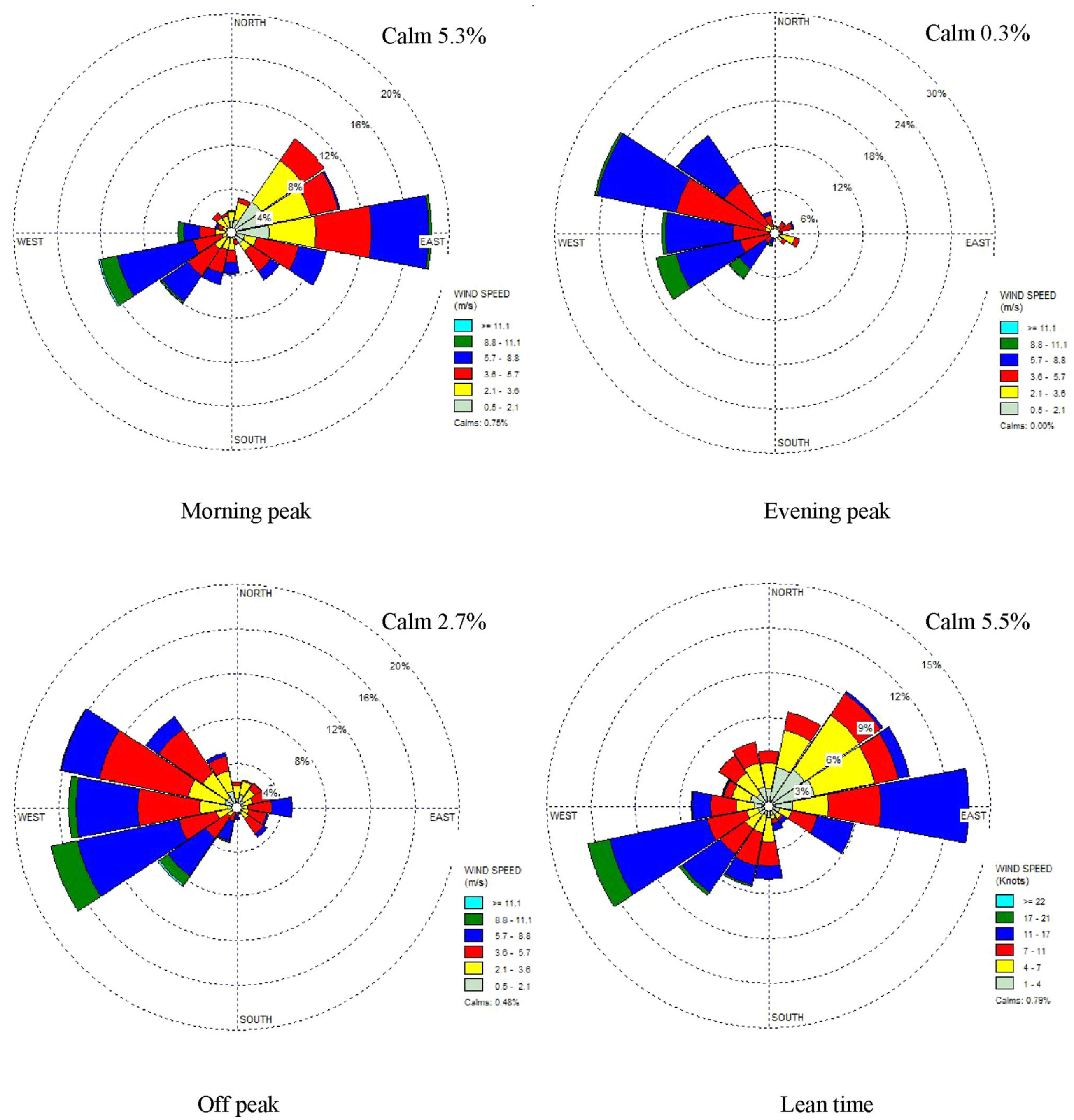

Fig. A1 Wind roses for morning and evening peak, off-peak, and lean time of the day

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