Seasonal PM$_{10}$ dynamics in Kathmandu Valley

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Data on ambient PM$_{10}$ levels from six locations in the Kathmandu Valley recorded by means of continuous sampling using low volume air samplers from October 2002 to March 2007 were used to investigate PM$_{10}$ concentration dynamics in the valley. Monthly average data of the urban areas, which have much higher concentrations than the rural areas, even exceeded the daily standard level of PM$_{10}$ in Nepal, 120 $\mu$g m$^{-3}$. Repetitive peaks and troughs each year indicated annual patterns. Monthly average showed seasonal patterns are different between rural area and urban sites. The highest monthly average concentration was observed in February, the end of winter in urban areas whereas in rural found in spring, and the lowest concentration was observed in July (monsoon period). The continuous increase in PM$_{10}$ concentration from December to February in urban areas showed accumulation of PM$_{10}$ in the ambient air during the wintertime. Rainfall in June and September, during the monsoon period, caused a PM$_{10}$ concentration decrease, demonstrating that precipitation is effective in removing PM$_{10}$ from the valley. Cross correlation analyses among the PM$_{10}$ levels measured simultaneously at the sampling stations showed a poor relationship in winter; however, there were good relationships in the monsoon and post-monsoon seasons. Both the PM$_{10}$ concentration and the air-mixing environment in the valley were closely associated with the temperature and wind speed.

1. Introduction

Thoracic ambient particulate matter (PM$_{10}$) is defined as particles less than 10 $\mu$m in aerodynamic diameter. It is well-documented that increased exposure to thoracic PM is associated with various adverse health effects, such as respiratory diseases, cardiovascular mortality, morbidity, and probably, malignant lung diseases (Donaldson and MacNee, 2001; Kan and Chen, 2003; Chang et al., 2005; Goldberg et al., 2006; Ostro et al., 2006). Ambient PM$_{10}$ represents a complex mixture of anthropogenic and naturally occurring airborne particles. There is increased evidence that most of the harmful components in PM$_{10}$ are particles formed from incomplete combustion of fossil fuels and pyrolysis of organic materials. A plethora of chemicals has been identified in contaminated ambient air, including polycyclic aromatic hydrocarbons (PAHs) and their nitro- and oxy-derivatives, strong acids and toxic metals (Fang et al., 2000; Lin et al., 2005). There have been many studies of the association between the prevalence of different air pollutants and adverse human health outcomes. PM$_{10}$ appears to be one of the most useful single measures of air pollution in a given area (US EPA, 1996; Kunzli et al., 2000; Schwartz, 2001). Most PM$_{10}$ studies have been conducted

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in developed countries, with only a small number of studies conducted in Asia (Health Effects Institute, 2004). There is a need for studies in cities of developing countries, where outdoor air pollution characteristics, such as air pollution level, meteorological conditions and socio-demographic status of local residents, may be different from developed countries.

The accumulation of pollutants in any location is mainly defined by the existing sources, the surrounding geology and meteorology. Pollution levels and dispersion features within mountain regions are more complex (Banta et al., 1997; Rega et al., 2001; Jazcilevich et al., 2005). Mountain ranges surrounding valleys block or reroute prevailing winds and thus alter the atmospheric thermal structure, which may create local winds and change the meteorology within a short distance. To understand the influence of surrounding mountains, several studies have been conducted in valley cities throughout the world (Baumgardner et al., 2000; Clements et al., 2000; Chazette et al., 2005; Jazcilevich et al., 2005; Shaw et al., 2005). This research has shown that the accumulation and dispersion of pollutants are influenced by the complex and time-varying interplay of local and regional winds with temporal and spatial emission patterns.

The Kathmandu Valley in Nepal is completely surrounded by rather steep mountains and hills, ranging from 500 to 3000 m above the valley floor (Kitada and Regmi, 2003). Being surrounded by high hills and mountains, the horizontal movement of air pollutants without vertical dispersion is limited (Sapkota and Dhaubadel, 2002). According to a recent report by Regmi and Kitada (2003), 48% of the population living in the Kathmandu Valley is exposed to annual PM concentrations from 20 to 40 \( \mu g m^{-3} \), and 33% of the population experiences annual PM concentrations higher than 60 \( \mu g m^{-3} \). Based on their short term observation for 3 weeks using passive sampler, Regmi and Kitada reported that a significant number of patients suffer from respiratory symptoms related to high PM exposure. For example, our recent survey at 3 different hospitals in the valley during winter in 2007 showed increase of 25–30% in outpatient number related to respiratory problems. According to the report by Kitada and Regmi (2003), the total suspended particles in the valley originated from a long-range transport of 9%, industrial sources of 46%, domestic sources of 28% and resuspension of 17%. The aim of our research was to evaluate the longer term PM\(_{10}\) concentration in different locations of the Kathmandu Valley (rural, urban background and traffic hotspots) using continuous sampling, to assess seasonal characteristics, and to determine the influence of meteorological conditions on PM\(_{10}\) concentration.

2. Materials and methods

2.1. Study area

The Kathmandu Valley is an oval shaped tectonic basin located in the middle section of the Himalayan range and is surrounded by ranges of green mountains. The valley has two narrow river gorges in the southwest and northwest edges and low hills on the southwest edge, connecting the neighboring Banepa Valley (Fig. 1). The central part of the valley is flat, with an elevation of 1300 m above sea level. The valley winds usually enter from the southwest and northwest gorges and exit over the low southeastern hills to the neighboring valley. Kathmandu Valley experiences four distinct seasons during the year: pre-monsoon, monsoon, post-monsoon and winter. During the past three decades, the Kathmandu Valley’s population has increased greatly and become more urbanized. Sharp population increase with an annual average growth rate above 4.5% (Central Bureau of Statistics, Nepal, 2001) and associated activities in the valley has worsened the air pollution (Sharma, 1997; Sapkota and Dhaubadel, 2002).

2.2. Measurements

Recognizing the air quality deterioration in the valley, the Ministry of Population and Environment of Nepal installed air pollution monitoring stations at six different locations. Ambient PM\(_{10}\) data for a period of 4 years and 6 months, from October 2002 to March 2007, were obtained from six monitoring sites located within 15 km of one another.
(Fig. 1). The six sampling sites include two busy traffic urban areas (traffic hotspot), one residential area (urban background), two semi-urban areas, and one rural area. The two urban traffic hotspots (BTUA1 and BTUA2) are characterized by core commercial areas with higher traffic density. The urban residential area (URA) is located at the heart of the city, which is characterized by a commercial area with tourist attractions, where vehicles are restricted. Two semi-urban areas (SUA1 and SUA2) are located outside of the city and thus have relatively low traffic. The land near the semi-urban areas is mostly covered with agricultural fields. The rural area (RA) is largely agricultural with negligible traffic activities. The rural area also serves as a background of PM$_{10}$ in the valley. Daily PM$_{10}$ data, with some missing days, were measured by continuous sampling using low volume air samplers (Instrumatic, Denmark, 85-02) with flow rate of 2.3 m$^3$ h$^{-1}$. The PM$_{10}$ air-monitors, which fulfilled all requirements of EN12341, were custom designed specifically for use in the Kathmandu Air Quality Monitoring Program. The designed PM$_{10}$ monitors used a reference inlet according to the European Directive 1999/30/EG. The sampler was adjusted from 760 (sea level) to 645 Torr (Kathmandu Valley) for mass flow meter (MFM) adjustment before sampling. GF/F Whatman Microfibre QMA filters were used for daily PM$_{10}$ sample collection. The sampling filters were kept in desiccators for 48 h at laboratory temperature (22°C) to minimize the effect of moisture on filters before and after taking air samples. The measuring device contained 8 sampling heads containing the protective roof with an impactor for pre-separation of particles larger than 10 μm. Each holder contained sample filters. Magnetic valves regulated the opening and closing the suction flow. Only one valve is open at a time and after a user defined time interval (24 h), the open valve closed and the next value in the series 1–8 opened. The valve collected air samples for 24 h to get daily PM$_{10}$ samples. After the 8th valve, the cycle restarted again. The flow meter was regularly calibrated by means of the ABB flow meter every 3 days.

Fig. 2. Wind speed and direction observed in four seasons in Kathmandu Valley.
months and ABB flow meter was calibrated by Ritter Wet Gas Meter every year. The gravimetric analysis was carried out using a 5-digit microbalance (Mettler, Toledo AX105DR with a range of 0–110 g, readable down to 0.01 mg, repeatability of 0.03 mg and linearity of 0.2 mg) to measure the collected PM$_{10}$. Meteorological data (temperature, wind speed, wind direction, humidity, cloud cover, and precipitation) were collected from Tribhuvan International Airport (TIA), located 3–6 km from the sampling sites in the central area of the valley (Fig. 1). The TIA (airport) is the only meteorological observatory in the Kathmandu Valley. Good agreement between the TIA data and those of the other temporary station data (Regmi et al., 2003; Pandey, 2006) indicates that the TIA data would be representative of the valley. The daily average PM$_{10}$ data from the six stations were analyzed in a cluster analysis using the Ward method (SPSS Base 13) to determine the similarity of daily average PM$_{10}$ concentrations among the six locations.

3. Results and discussion

3.1. Meteorological characteristics analysis

Fig. 2 shows the relative frequency of wind direction and wind speed obtained based on wind direction and speed data measured every 3 h during the study period. Observation of windrose diagram shows that the valley experiences similar wind directions (west, west-west-south and south) for four seasons with additional easterly wind during the monsoon period. The wind direction of the prevailing winds for three seasons (pre-monsoon, post-monsoon, and winter) were west, however, they were south during the monsoon season. The pre-monsoon period had a much-increased proportion of strong winds with above 7.0 m s$^{-1}$ where as the winter experienced a lot of low wind speeds, such as 0.5–2.0 m s$^{-1}$, as compared other seasons.

Fig. 3 represents diurnal meteorological characteristics (temperature and wind) near the surface of the valley for the four seasons in year 2003 that extends up to February 2004 to picture the influence of seasons in PM$_{10}$. A diurnal variation of the observed winds is characterized by calm winds from 18:00 LST to 10:00 LST (the next day). Winds begin around 12:00 LST and continue until around 18:00 LST, while changing direction from westerly to north-westerly (Regmi et al., 2003). Average wind speeds during the daytime (around 11:00–19:00) under the pre-monsoon periods were much higher than those under other periods. Stratified calm winds and low temperature are observed in winter, while gusty winds, with high temperature, occur in pre-monsoon.

3.2. PM$_{10}$ dynamics

Table 1 summarizes minimums, maximums, averages with standard deviations of PM$_{10}$ concentrations measured in the valley for 4 years. Fig. 4 also shows the
PM$_{10}$ data with annual averages at the six air monitoring stations during the four-year measurement periods, 2003–2006. The highest annual average PM$_{10}$ concentrations were observed in the busy traffic urban areas (BTUA1 and BTUA2 with averages ranging from 202 to 230 µg m$^{-3}$ and from 170 to 202 µg m$^{-3}$, respectively) followed by the urban residential area (URA with averages ranging from 122 to 149 µg m$^{-3}$) and the semi-urban areas (SUA1 and SUA2 with averages ranging from 62 to 80 µg m$^{-3}$ and from 75 to 131 µg m$^{-3}$, respectively). The lowest annual average of PM$_{10}$ was observed in the rural area (RA with averages ranging from 42 to 56 µg m$^{-3}$).

The highest PM$_{10}$ values in the high-traffic urban areas are mainly due to local traffic emissions in the area, along with other emissions. The BTUA1 values were higher than BTUA2 because of higher traffic density in the BTUA1 area. The annual PM$_{10}$ average levels in the BTUA1, BUTA2 and URA exceeded the standard concentration based on even 24-h average in Nepal, 120 µg m$^{-3}$. The national ambient air quality standard in Nepal is very permissive compared to those of the neighboring countries, India (60 µg m$^{-3}$), China (100 µg m$^{-3}$), and Bangladesh (50 µg m$^{-3}$), and that of the World Health Organization (50 µg m$^{-3}$), based on 24-h average. Many people who live in the urban area of the Kathmandu Valley might be exposed to a much higher PM$_{10}$ level and consequently have higher rates of respiratory symptoms and mortality compared to people in more developed countries. Regmi and Kitada (2003) reported that a significant number of patients suffer from respiratory symptoms related to high PM$_{10}$ level exposure. As compared to Kitada and Regmi’s paper (2003), our research results showed much higher values of PM$_{10}$ in the valley. Thus the adverse health problems or symptoms associated with PM$_{10}$ exposure would be more severe than the results reported earlier by Kitada and Regmi. The possible reasons for the discrepancy in PM$_{10}$ concentrations between two different studies might be due to the difference in (i) sampling locations, (ii) sampling methods, and (iii) measurement period. The study by Kitada and Regmi was based on a short term period of 3 weeks by using passive air sampler which they extrapolated in simulation using extended version of the chemical transport model (Kitada et al., 1983, 1993). Our study was based on a long-term measurement with continuous monitoring using active samplers at 6 different places.

Fig. 5 shows dynamics on PM$_{10}$ concentrations in the valley for the sampling period (2002–2007). Similar highs and lows observed annually indicate repetitive seasonal cycles of PM$_{10}$ in the valley. Seasonal trends for PM$_{10}$ levels showed the minimum levels during the summer monsoon (June–September) and the maximum ones during winter (December–February) in all sites except for the rural area (RA) where maximum peak shifted to spring (April and May). Thus these seasonal patterns seem to be highly dependent upon the meteorological characteristics such as temperature, humidity, rainfall and wind.

### 3.3. Monthly variation of PM$_{10}$ concentrations

Fig. 6 shows the monthly variation of average PM$_{10}$ levels at six monitoring locations in 2003 as an illustrative example. The data missing in the graph shows no data were
PM$_{10}$ values are not available during the month due to instrumental problems. The PM$_{10}$ average levels changes greatly with month. The monthly variation of PM$_{10}$ levels showed similar seasonal patterns in most study locations (SUA2, URA, BTUA1 and BTUA2) except in RA. Much higher PM$_{10}$ values were identified in all locations (except RA) in winter periods (December–February). However, the average PM$_{10}$ values in spring were higher those in winter periods in RA. The PM$_{10}$ concentration reached a minimum in monsoon periods (July–September) in all locations and started to increase again in the post-monsoon periods (October–November). The high and low PM$_{10}$ values indicate a strong seasonal influence. During winter, energy uses increase with decreasing air temperature, leading to more air pollutants, such as PM$_{10}$, NO$_x$ and SO$_x$, which could form secondary particulate matter. Low air temperature, combined with calm winds during the winter, reduces ambient ventilation (Figs. 2 and 3). The increased air emissions and reduced ambient ventilations could cause increased PM$_{10}$ concentrations in the valley air during winter.

Even though the energy uses decreases with increasing air temperature during the transition from winter to spring, the PM$_{10}$ concentrations do not change greatly. This is probably because (i) the ambient ventilation may not be sufficient to sweep out the PM$_{10}$ from the valley in the beginning of spring and (ii) the dry spring weather produces more fugitive emissions and pollens in April and May that also contribute to PM$_{10}$ levels. The two months (April and May) also experience strong gusty winds. Such
winds may lift surface particles in the atmosphere, and then add PM$_{10}$ components to the air emissions. The latter effect could be clearly seen in the RA and the SUA1 compared to other highly urbanized areas, where the greenery and open space areas are much higher compared to the other measuring sites. As summer develops, the air temperature increases, resulting in lower energy uses and thus lower air emissions. Summer also includes monsoon periods which have lots of rainfall. Eighty percent of the total annual precipitation occurs during monsoon season. The increase in average air temperature during summer periods generates upward movement of the air in the valley, resulting in an increase of the ambient ventilation in the valley. Furthermore, large amounts of PM$_{10}$ components are removed by rainfall activities during monsoon periods and are diluted by the increased ambient ventilation during summer.

Fig. 7 shows the relationship between daily average PM$_{10}$ levels and daily precipitation (mm) from pre-monsoon to monsoon periods (total number of data $N = 152$). With every precipitation, the concentration of PM$_{10}$ largely reduced in the atmosphere. Dotted arrows (vertical) show the rainfall and its effect on PM$_{10}$ concentration (only few are shown). Sharp dropping of the PM$_{10}$ concentration, from about 400 to 100 $\mu$g m$^{-3}$ in BTUA1 and 300 to 100 $\mu$g m$^{-3}$ in BTUA2, was observed in the monsoon period (June–September). In conclusion, low air emissions combined with the removal mechanism minimized the PM$_{10}$ concentration during the summer. As the temperature starts to drop again (following late
September), energy use increases and PM$_{10}$ values start to rise.

3.4. Correlation

Fig. 8 shows the dendrogram plot obtained from daily average PM$_{10}$ concentrations at six stations for 2003–2004, using the cluster analysis with Z-score normalization. Z-score normalization changes the rate of attributes, and thus they have same mean and variance \(Z = (s-\mu)/\sigma\) where: ‘z’ refers to the z-score, ‘\(\mu\)’ is the estimate of the sample’s mean, ‘\(\sigma\)’ is the estimate of the sample’s standard deviation, and ‘\(s\)’ is an individual score within the distribution having mean \(\mu\) and variance \(\sigma\). Among the six stations, the rural area (RA) had the lowest PM$_{10}$, likely due to the low influence of traffic activities compared to other stations. Among the remaining, URA and BTUA1 were similar due to the short distance between them (1.5 km). The close relationship among the SUA1 and SUA2 and BTUA2 cannot be explained at this moment.

Fig. 9 shows the interrelationships among seasonal PM$_{10}$ concentrations in 2003–2004. Table 2 also shows the cross correlation coefficient \(R^2\) among the PM$_{10}$ levels measured at the stations in seasons 2003–2004. The relationship between the stations is considered a good correlation if \(R^2 > 0.5\). The coefficient of determination \(R^2\) among the stations for PM$_{10}$ data showed a poor relationship in winter; however, there were good relationships in the monsoon and post-monsoon seasons. During winter, the Kathmandu Valley experiences a strongly stable and stratified cold air pond. The air in the valley becomes stagnant or temperature inversion occurs at night. The temperature inversion extends almost down to the ground, suggesting that the vertical mixing is strongly suppressed at the elevation where the pollution was emitted (Regmi et al., 2003). Small temperature and wind speed increases for relatively short periods in the afternoon helped to mix pollutants generated during the day. It is estimated that such increase of temperatures and wind speeds is not sufficient to greatly disperse and mix the localized pollutants, and thus resulting in restriction of PM$_{10}$ components.

Fig. 7. Effect of rainfall (mm) on daily average PM$_{10}$ concentration in two traffic hotspots (BTUA1 and BTUA2) in Kathmandu Valley (\(N = 152\)). Note, Dotted arrows (vertical) show the rainfall and its reduction effect on PM10 concentration (only few are shown).
in the limited area or boundary layer. Good PM$_{10}$ interrelationships among the stations were observed in monsoon and post-monsoon seasons. Higher surface air temperature and higher wind speed in post-monsoon might have helped to create a good mixing environment for the PM$_{10}$ in the valley (Fig. 3). The authors also conclude that the frequent monsoon precipitation helped to remove accumulated PM$_{10}$ and create a good mixing environment for freshly emitted PM$_{10}$. The pre-monsoon season, in between the monsoon and winter periods, acts as a transition period. This season experiences increases in temperatures and wind speeds at the early stage of the season, and the increase continues until the end of May. The increase of temperatures and wind speeds might have helped to mix the pollutants in the valley and resulted in the better interrelationship among the stations.

4. Conclusion

The seasonal patterns of daily average PM$_{10}$ concentrations measured in Kathmandu Valley during a period of four and a half years were analyzed and discussed. The authors reached to the following conclusions:

- Urban high-traffic areas in the valley were seriously polluted by PM$_{10}$. Monthly PM$_{10}$ concentration averages at urban traffic and residential areas greatly exceeded the daily ambient air quality standard in Nepal, 120 $\mu$m$^3$.m$^{-3}$.
- Low temperature and low wind speed in winter caused accumulation of PM$_{10}$ in the emission source vicinity of the valley.
- Higher temperatures and wind speeds in the pre-monsoon and post-monsoon seasons provided a good mixing environment for dilution and increased ambient ventilation for dispersion of air pollutants in the valley.
- Precipitation in the monsoon period also effectively removed PM$_{10}$ from the valley.
- The cross correlation coefficients ($R^2$) among the PM$_{10}$ data among the air monitoring stations data showed a poor relationship in winter; however, there were good relationships in the monsoon and post-monsoon seasons.
### Table 2

Cross correlation coefficients ($R^2$ value) among the PM$_{10}$ levels measured at the stations in four seasons in year 2003–2004

| Season          | RA  | SUA1 | SUA2 | URA  | BTUA1 | BTUA2 |
|-----------------|-----|------|------|------|-------|-------|
| Winter (Dec.–Feb.) | RA  | 0.56 | 0.28 | 0.01 | 0.02  | 0.09  |
|                 | SUA1| 0.68 | 0.72 | 0.03 | 0.34  |       |
|                 | SUA2| 0.23 | 0.04 | 0.45 |       |       |
|                 | URA | 0.59 | 0.54 | 0.54 |       |       |
|                 | BTUA1| 1   | 0.64 | 0.41 | 0.41  | 0.41  |
|                 | BTUA2| 1   | 0.25 | 0.34 | 0.34  | 0.34  |
| Pre-monsoon (Mar.–May) | RA  | 0.51 | 0.56 | 0.54 | 0.54  | 0.54  |
|                 | SUA1| 0.74 | 0.64 | 0.64 | 0.64  | 0.64  |
|                 | SUA2| 0.62 | 0.64 | 0.64 | 0.64  | 0.64  |
|                 | URA | 0.54 | 0.54 | 0.54 | 0.54  | 0.54  |
|                 | BTUA1| 1   | 0.44 | 0.44 | 0.44  | 0.44  |
|                 | BTUA2| 1   |       |       |       |       |
| Monsoon (June–Sept.) | RA  | 0.94 | 0.88 | 0.80 | 0.80  | 0.80  |
|                 | SUA1| 0.92 | 0.65 | 0.65 | 0.65  | 0.65  |
|                 | SUA2| 0.74 | 0.65 | 0.65 | 0.65  | 0.65  |
|                 | URA | 0.70 | 0.70 | 0.70 | 0.70  | 0.70  |
|                 | BTUA1| 1   | 0.54 | 0.54 | 0.54  | 0.54  |
|                 | BTUA2| 1   |       |       |       |       |
| Post-monsoon (Oct.–Nov.) | RA  | 0.84 | 0.70 | 0.65 | 0.65  | 0.65  |
|                 | SUA1| 0.58 | 0.58 | 0.73 | 0.73  | 0.73  |
|                 | SUA2| 0.88 | 0.78 | 0.78 | 0.78  | 0.78  |
|                 | URA | 0.82 | 0.82 | 0.82 | 0.82  | 0.82  |
|                 | BTUA1| 1   | 0.69 | 0.69 | 0.69  | 0.69  |
|                 | BTUA2| 1   |       |       |       |       |

Note: RA = rural area, SUA = sub-urban area, URA = urban residential area, BTUA = busy traffic urban area.

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