Journal of Hazardous Materials 168 (2009) 732–738

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Dynamics of $PM_{2.5}$ concentrations in Kathmandu Valley, Nepal

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ARTICLE INFO

Article history:
Received 25 August 2008
Received in revised form 5 December 2008
Accepted 17 February 2009
Available online 25 February 2009

Keywords:
Diurnal cycle
Dynamics
Kathmandu Valley
Inversion
$PM_{2.5}$

ABSTRACT

This study analyzed daily patterns and dynamics of $PM_{2.5}$ concentrations in the Kathmandu Valley during three winters. The $PM_{2.5}$ data showed a daily repetitive cycle which represents influence of local air flow and dispersion and accumulation of air pollutants in the valley. Two concentration peaks were observed in the morning and in the evening periods, and they fell down during the daytime and the nighttime periods. This indicates local emission sources as major contributors in the valley. The more pronounced morning peak compared to the evening peak showed that the upslope wind in the morning helped to move the polluted inversion layer downward, subsequently adding to freshly emitted pollutants and causing a sharp pollutant concentration rise in the morning. Katabatic wind and rise of temperature in the basin during the day helped the pollutant upflow and dilution, resulting in a sharp $PM_{2.5}$ concentration decline. Through the afternoon, the decrease in air temperature followed by decrease in wind speed caused to lower $PM_{2.5}$ peaks in the evening. Also, higher morning peaks of $PM_{2.5}$ concentrations compared to the evening indicated pollution from the previous day is added to the fresh emission. The valley had increased $PM_{2.5}$ from the beginning of October which continued till the first week of February. The increase in $PM_{2.5}$ peak fit the logistic equation $y = [k/(1 + \exp(p - qx)] + a\sin(bx)$ where k, p, q, a, and b are constants.

1. Introduction

$PM_{2.5}$, particulate matter less than 2.5 μm in an aerodynamic diameter, is generally referred to as fine particles and has been implicated in human health problems. The accumulation of $PM_{2.5}$ in any location is mainly affected by the existing sources, meteorological conditions and geological conditions. High mountains surrounding valleys create topographic complexity and thus the variety of physicogeographic characteristics in the basin can induce local circulations, such as anabatic/katabatic flows [1], valley winds [2] and cold pool formation in the basin [3]. Such local circulations may change meteorology within a very short distance and also change atmospheric dispersion patterns and pollution levels in a small basins or valleys. To understand the influence of surrounding mountains, several studies have been carried out in valley cities throughout the world [4–10]. These show that the accumulation and dispersion of pollutants in each valley are influenced by a complex and time-varying interplay of local and regional winds with temporal and spatial emission patterns. In developed countries many complex numerical simulations have been carried out in valleys. However, many developing countries are still struggling to gain a clear understanding of pollutant dynamics even at a basic level.

Over the last three decades the population of the Kathmandu Valley has increased greatly along with urbanization, and thus the valley has suffered from major air quality problems. Sharma [11] reported a high concentration of SO_2 (202 μg/cm^3) and NO_2 (126 μg/cm^3) in the valley. Similarly, Sapkota and Dhaubadel [12] recorded an Angstrom coefficient greater than 0.2 in the Kathmandu Valley and categorized it as a heavily polluted area. Ramana et al. [13] reported aerosol optical depth 0.34 in winter 2003, which is a typical for the polluted areas.

The aim of this research is to help to understand the diurnal dynamics of $PM_{2.5}$ in the Kathmandu Valley based on the recorded pollutant and meteorological data.

2. Methods

2.1. Study area

The oval shaped tectonic basin of the Kathmandu Valley is located in the middle section of the Himalayan range and is

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0304-3894/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.jhazmat.2009.02.086

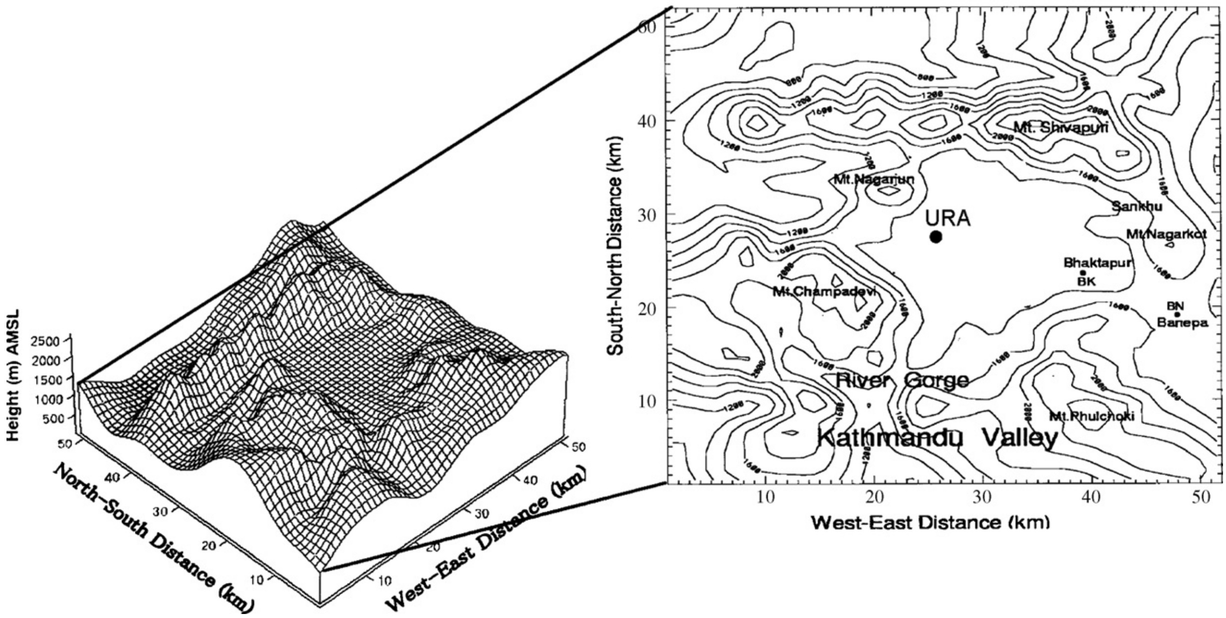

Fig. 1. 3-D topographic view of Kathmandu Valley (adopted from Ref. [14]) and $PM_{2.5}$ monitoring stations (right).

surrounded by tier upon tier of green mountains. The Kathmandu Valley experiences four distinct seasons: pre-monsoon, monsoon, post-monsoon and winter. The central part of the valley is flat at an elevation of 1300 m above sea level. The valley is completely surrounded by rather steep rising mountains and hills ranging from 500 m to 3000 m above the valley floor [13]. The valley has two narrow river gorges in the southwest and northwest edges and low lying hills on the southeast edge separate the Kathmandu Valley from the neighboring Banepa Valley (shown in Fig. 1). Winds usually enter into the valley through the southwest or northwest gorges and exit through the southeast hills. As the valley is surrounded by high hills and mountains, horizontal dilution of the air emissions from the valley area is restricted or limited especially with low temperature and calm winds. The air pollutants become trapped and accumulate in the valley without dilution by vertical dispersion [12].

2.2. Data collection

In order to analyze seasonal trends of $PM_{2.5}$ concentrations, daily $PM_{2.5}$ measurements were conducted during four seasons in a whole year 2006–2007 at a highly urbanized residential area (URA), Thamel, located at the heart of the Kathmandu Valley, with latitude and longitude 27°42′21″ N and 85°19′20″ E, situated above 1314 m from the sea level (Fig. 1). Also, daily average of $PM_{2.5}$ concentrations based on every 6 h measurement during three winters (October–February) in years 2003–2004, 2004–2005, and 2006–2007 were obtained at the URA, Thamel. For analysis of a sort of diurnal cycle patterns of $PM_{2.5}$ concentrations during the winter periods, daily measurement data of $PM_{2.5}$ concentrations were categorized as four groups such as morning (06:00–12:00), afternoon (12:00–18:00), evening (18:00–24:00), and night (00:00–06). The $PM_{2.5}$ concentrations were measured using a low volume air samplers (Model 85-02, Instrumatic Denmark) and $PM_{2.5}$ air-monitors. The $PM_{2.5}$-monitors, which fulfilled all requirements of EN12341, were custom designed specifically for use in the Kathmandu Air Quality Monitoring Program. The designed $PM_{2.5}$ monitors used a reference inlet according to the European Directive 1999/30/EG. The sampler was adjusted from 760 Torr (sea level) to 645 Torr (Kathmandu Valley) for mass flow meter (MFM) adjustment before sampling. The data set collected contained some missing days. GF/F Whatman Microfibre QMA filters were used for daily $PM_{2.5}$ 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 flow meter was regularly calibrated by means of the ABB flow meter every 3 months and ABB flow meter was calibrated by Ritter Wet Gas Meter every year. The gravimetric analysis was carried out using a five-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 $PM_{2.5}$. Meteorological data (temperature, wind speed, wind direction, humidity, cloud coverage, and precipitation) were collected from the Tribhuvan International Airport (TIA) which is located 3 km away from the sampling site.

2.3. Meteorological characteristics

Fig. 2 shows the average diurnal temperature and wind speed profiles in the Kathmandu Valley during winter (December 2006–February 2007). The diurnal temperature and wind profiles were very similar from day to day and allowed generalization of the results. The diurnal temperature profile shows that the temperature sharply rises during the day and reaches its peak value at around 14:00 LST. Temperature drops slowly after 14:00 LST and reaches the lowest value in the morning at 5:00 LST. Similarly, surface wind in the valley is calm from 18:00 LST to 10:00 LST. The wind speed also increases throughout the daytime period and peaks at around 14:00–15:00 LST. The wind speed is strongly correlated with temperature.

Owing to temperature and wind features, the Kathmandu Valley experiences a strongly stable and stratified cold air pond at night during winter (December–February). According to Regmi et al. [14] and Pandey [15] the cool air pond is about 400–600 m deep with long-calm conditions during the night and early morning hours, and thus the air in the valley stagnates and creates a temperature inversion. The inversion extends almost down to the ground, suggesting that vertical mixing is strongly suppressed at the elevation where pollution emission takes place. However, the air in the valley is mixed during the day after breaking the temperature inversion or with time progress of day. The afternoon increase in wind

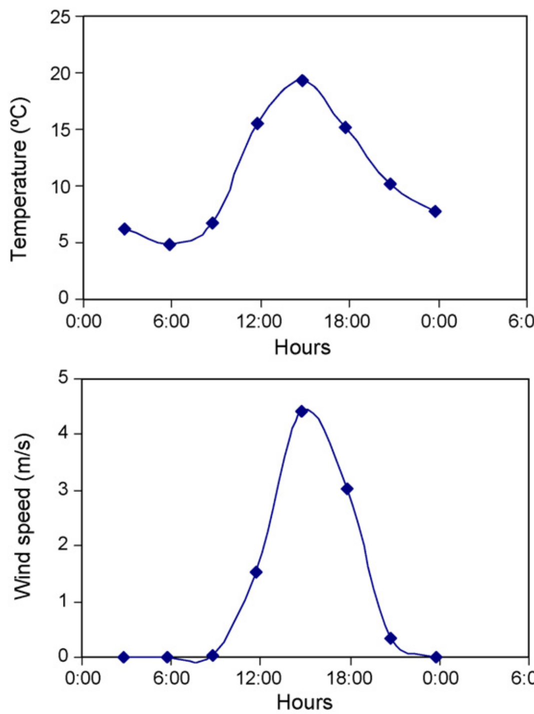

Fig. 2. Average wind speed and temperature profile of Kathmandu Valley in winter (December 2006 to February 2007).

speed causes an intrusion of local flows from outside of the valley. A SODAR measurement study conducted by Regmi et al. [14] reported high wind speeds at the lower layer below 200 m. Ramana et al. [13] reported that the mixing height for dilution of local air in the valley was 300–600 m above the ground level. Thus local air flows generated in the valley during the afternoon hours may contribute to dilution of pollutants in the valley.

3. Results and discussion

3.1. $PM_{2.5}$ levels in the valley

Kathmandu Valley experiences four distinct seasons pre-monsoon, monsoon, post-monsoon and winter. Fig. 3 shows the daily average $PM_{2.5}$ levels in the valley in a whole year 2006–2007. $PM_{2.5}$ data shows two distinct features: (1) almost similar with less fluctuation during the pre-monsoon and monsoon, and (2) a steep rise from the post-monsoon to the winter resulting in peak values at late winter. Seasonal average values and standard deviation of $PM_{2.5}$ in year 2006–2007 were as follows: $69 \pm 37\ \mu g/m^3$ in the pre-monsoon period; $30 \pm 12\ \mu g/m^3$ in the monsoon period; $53 \pm 22\ \mu g/m^3$ in the post-monsoon period; and $90 \pm 24\ \mu g/m^3$ in

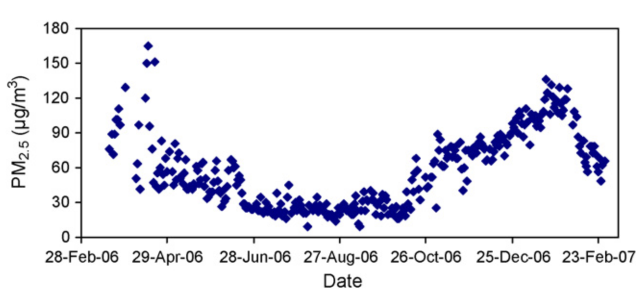

Fig. 3. Daily average $PM_{2.5}$ in a year 2006–2007 at Thamel center of Kathmandu Valley.

winter. The minimum levels were observed during the summer monsoon (June–September) and the maximum ones were identified during the winter (December–February). The high and low trends indicate a strong seasonal influence of the $PM_{2.5}$ values. From the beginning of post-monsoon period (October), the $PM_{2.5}$ concentrations in the valley increases linearly with time and reaches to peak values in late winter (first week of February). Also, the air temperature in the valley slowly drops from the post-monsoon and reaches the lowest in the late winter. The increased energy consumption by decreasing the air temperature in the valley leads to more emissions of air pollutants, such as $PM_{2.5}$, NO_x and SO_x, which could be formation sources of secondary particulate matter. Low air temperature, combined with calm winds during winter, reduces the ambient ventilation which could be a cause of continuous increase in $PM_{2.5}$ concentrations in the valley air during winter. The air temperature increases with starting a summer season, resulting in lower energy uses and thus lower air emissions. 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 $PM_{2.5}$ components are removed by rainout and washout mechanisms along with rainfall activities during monsoon periods and are diluted by the increased ambient ventilation during summer. Currently, Nepal does not have ambient standards or guideline values of $PM_{2.5}$. When compared to the WHO guidelines ($25\ \mu g/m^3$ based on 24 h, $10\ \mu g/m^3$ based on annual average) and the USA standard ($35\ \mu g/m^3$ based on 24 h, $15\ \mu g/m^3$ based on annual average), Kathmandu Valley air shows very high $PM_{2.5}$ pollution throughout the year. Regmi and Kitada [15] reported a large number of patients suffering from particulate matter exposure during winter in the valley. Our survey at three hospitals in year 2007 showed increase of 25–30% of outpatients relating to respiratory diseases or symptoms which might be associated with greatly increased concentrations of fine particles such as $PM_{2.5}$.

3.2. Morning and evening peaks

Fig. 4 shows $PM_{2.5}$ measurement results at Thamel (RA) in December 2006. Features of the diurnal cycle are (i) repetitive cycle each day, (ii) two distinct morning and evening peaks, and (iii) higher morning peak concentration than the evening. The atmospheric conditions do not vary much from day to day in the valley. The valley is not greatly influenced by air masses entering from outside the valley. Thus the diurnal cycles may be associated with local air emissions, such as traffic emissions, physicochemical processes along with local traffic emissions, meteorological conditions and/or air circulation patterns in the valley. The interest of this study was whether the morning and evening peaks are due to the local emissions or some other factors. It is known that traffic is the major source of $PM_{2.5}$ in the valley [16]. The traffic activity during the nighttime is negligible in the valley. The traffic activity starts from the early morning (around 5:00 LST) and continues till night (22:00 LST). If we assume that the pollutant peaks are mainly due to traffic activities and the traffic emissions in morning rush hours are similar to those in evening rush hours, then the morning peak values would be similar to the evening ones. Also, the evening peaks are expected slightly higher than the morning peaks. It is because the evening peaks may show the accumulation effects of air pollutants, such as fine particles, generated from increased anthropogenic activities during the day time periods. Similar concentration patterns (lower in the morning and higher in the evening) in diurnal cycle for various types of pollutants have been observed elsewhere [16–21] and their peak observations were highly correlated to rush hour traffic emissions. However, the observed data showed that the morning peak concentrations in the Kathmandu valley were much higher than the evening ones. One of the main reasons for these facts

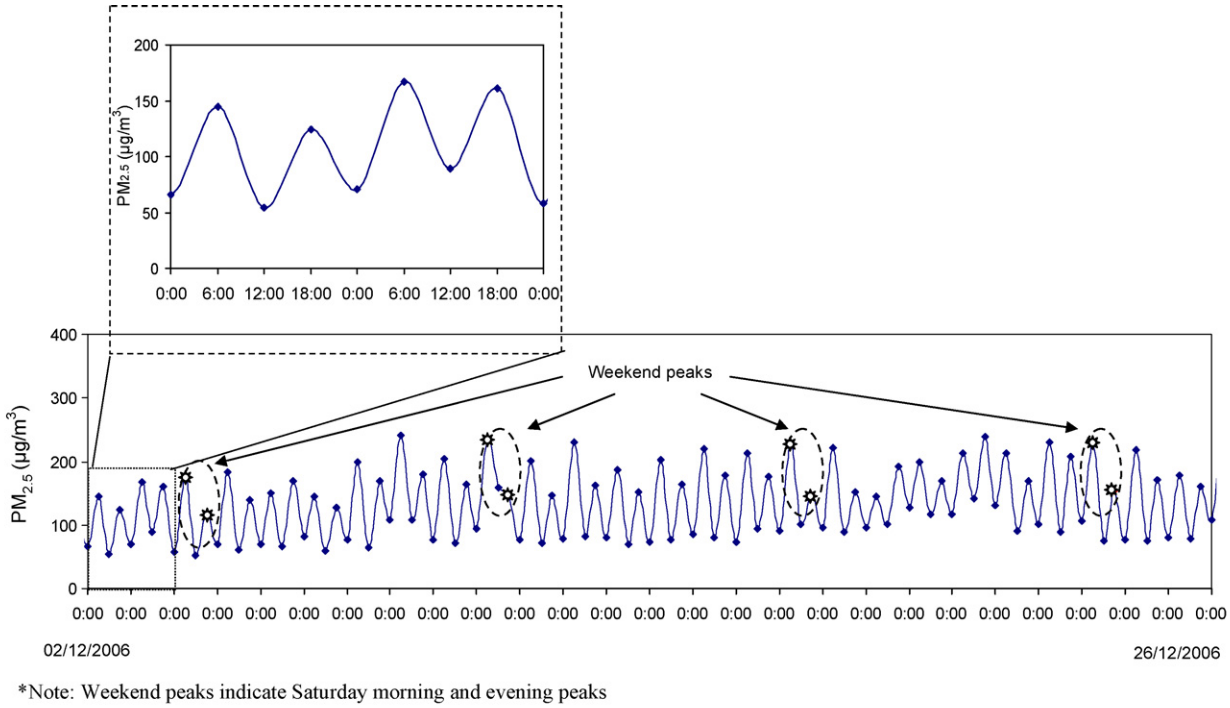

Fig. 4. Diurnal cycle of $PM_{2.5}$ at Thamel (RA) in winter (2006) with morning and evening weekend peaks (☼).

would be the difference in the ambient temperature and wind speed between morning and evening peak periods. From Fig. 2, it can be seen that the ambient temperature (about 5 °C) and wind speed (almost zero) at the time of morning peaks of 6:00 LST are much lower than those at the time of evening peaks of around 18:00 LST (about 15 °C and 3 m/s). The lowered ambient temperature and very weak winds with almost zero wind speed during the morning peak periods could decrease the ambient ventilation, resulting in the increased morning peaks of $PM_{2.5}$ as compared the evening ones.

Recently, Regmi et al. [14] reported the local flow patterns of the near surface winds in Kathmandu Valley at three different times (5:45 LST, 11:45 LST, 17:45 LST) of late wintertime. The entire valley remains calm during the morning hours and a relatively strong downslope wind prevails in the surrounding mountains. During this period the southwesterly wind, which comes from the narrow Bagmati River gorge, penetrates the valley. In the afternoon hours the southwesterly wind disappears and a northwesterly wind strengthens. In the late afternoon the Kathmandu Valley experiences a strong westerly wind, which reduces peak concentrations of $PM_{2.5}$ in the valley from the beginning of the evening periods.

There are several studies which deal with similar patterns of peaks of several types of pollutants, such as $PM_{2.5}$, PM_{10}, ozone, carbon monoxide, NO_x, and SO_x in valley. Many investigators have proposed several mechanisms for air circulation in valleys According to Garcia et al. [22], surface warming in the morning due to sunlight causes the warm air to rise and chip away at the inversion layer. The resulting mixing layer grows and finally breaks through the upper-most inversion layer. Other proposals made by Atkinson [2] and Prevot et al. [17] are the warming of side-walls of the mountains in the morning resulting in an uplift of the air from the valley bottom. The vacant space created by the uplift of basin air along the side-wall of hills is replaced by air coming up the river valley. A similar explanation was given by Whiteman [23] who proposed the replacement of air masses that moved upward by subsidence over the valley center rather than generating a strong replacement by the river valley. For each case the air circulation mechanism depends on the size of the valley and its topography. To explain the effects of the size and topography of the valley, this study considered the downward movement of polluted air over the valley as possibly due to air subsidence resulting from the upslope wind circulation over the hills and mountains in the morning. The authors also considered the subsidence effects caused by katabatic winds resulting from thermal effects in the basin during the afternoon, followed by local wind flows which are mainly responsible for governing the pollutant dynamics in the valley.

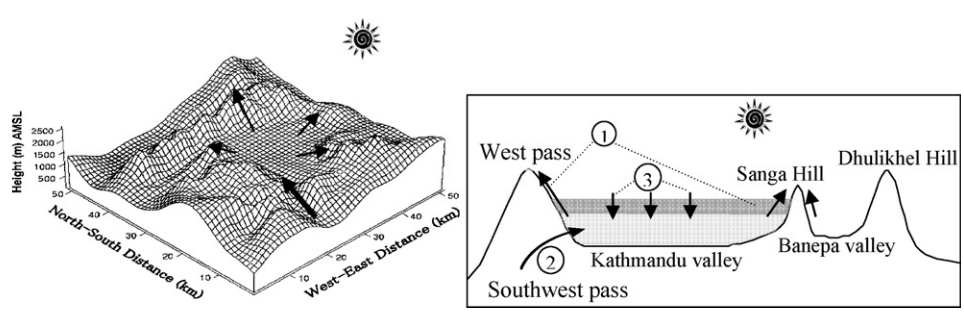

Fig. 5. Early morning wind pattern in Kathmandu Valley (left) and sketch in vertical west-east cross section (right).

3.3. Morning dynamics of $PM_{2.5}$

Fig. 5 shows the early morning wind patterns (left) and the postulated morning dynamics of $PM_{2.5}$ concentration in the valley (right). The black shaded layer in Fig. 5 represents a stagnant area of air pollutants, which can be seen from the surrounding hills of the valley with the naked eye. In the morning, winds blow up from the basin to the surrounding hills due to heat from the early sunshine on the surrounding hills making the air layer warmer. The uplift of air in the hills results in winds blowing from the bottom of the basin up the hill slopes, shown as in Fig. 5. The surrounding hills have an increased temperature up to 5 °C compared to the valley basin in the morning during winter [14]. The temperature difference in the morning creates the pressure difference between the basin and top of the hill resulting uplift of basin wind to the hills creating void space at the basin. This void space would be filled with the wind coming through the river gorge from the southwest, shown as in Fig. 5. Fig. 6 shows formation and disappearance of the morning fog observed from the southwest side hill of the valley at different times in the morning period of winter. The morning fog during early morning hours in winter is common in the valley. The morning fog on the southwest edge slowly disappeared as time passes while it remained at the other parts of the valley. This supports the hypothesis that air mass from the southwest intrudes into the valley during the late morning period. The uplifted air mass over the valley gets cooled. Then the cold air mass over the valley could have downward movement to the basin, shown as in Fig. 5. As the colder air mass moves downward, it can carry downward the pollutants in the stagnant air over the valley. The $PM_{2.5}$ or fine particles remaining in the cold mass (black '☼' mark shown in Fig. 5) are added into local particle emissions generated in the valley during the morning period. Thus, the $PM_{2.5}$ peak in the morning is not only due to the morning rush hour emission, but also due to the addition of $PM_{2.5}$ produced from the previous day and then transported over the valley.

This kind of air circulation or movement is supported by the weekend (Saturday) diurnal concentration of $PM_{2.5}$. Fig. 4 shows the weekend peaks of $PM_{2.5}$ concentrations in the valley. On the weekends, the morning peak concentration was higher, however, the evening peak concentration was much lower as compared to respective weekday peaks (Table 1). As Sunday is a working day in Nepal, weekend peaks refer to morning and evening concentrations on Saturday only. The valley has additional traffic activities, which usually happen to every city all over the world, during Friday afternoon and nighttime periods as compared normal weekdays. The higher weekend (Saturday) morning peak concentration of $PM_{2.5}$ is possibly due to the addition of the $PM_{2.5}$, resulted from increased traffic activities of the previous day, to the normal fresh emissions in the weekend (Saturday) morning. The lower evening peak on the weekend could be correlated to the reduced traffic activity during daytime and nighttime periods on Saturday.

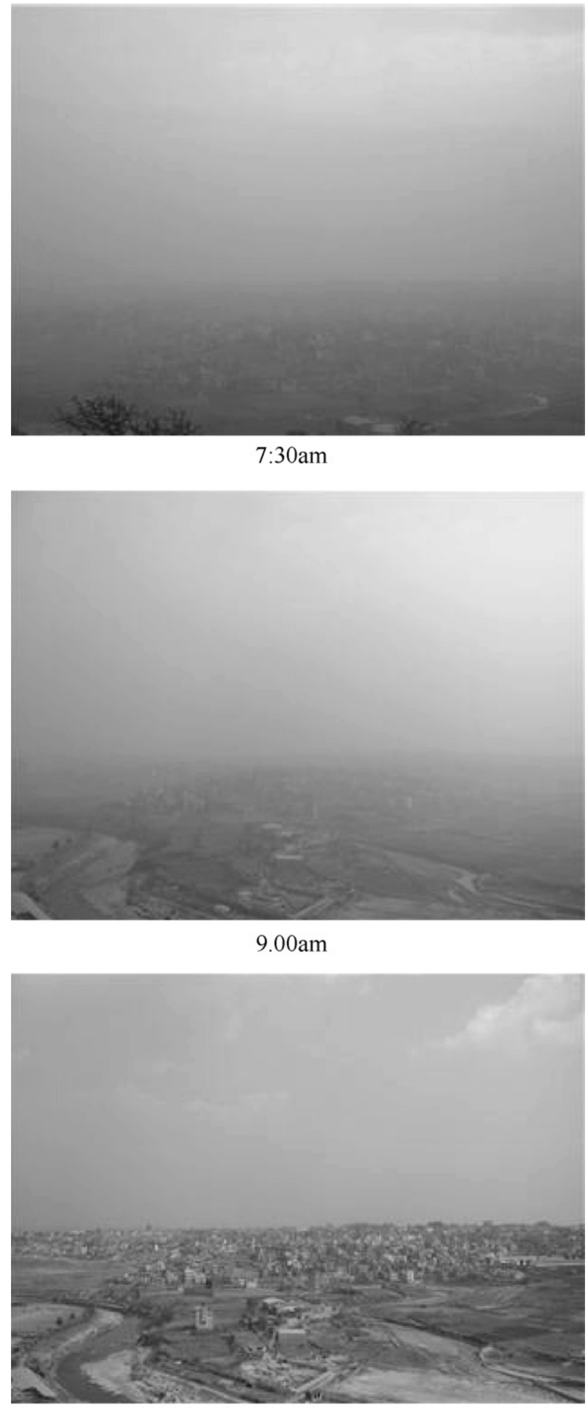

Fig. 6. Winter morning fog observed from the Southwest hill (Sanga Hill) of the Kathmandu Valley in February of 2007.

3.4. Late afternoon dynamics of $PM_{2.5}$

Fig. 7 shows the late afternoon wind pattern (left) and postulated late afternoon dynamics of $PM_{2.5}$ concentration in the valley. As the basin gets warmed along with approaching and passing noon, the southwesterly wind slowly ceases and a westerly wind starts to appear. As the daytime progresses, the inversion layer starts to be broken up and air mixing reaches a maximum around 14:00–16:00 LST. The strong westerly wind helps to dilute and/or remove some of the pollutants that reach the mixing height by carrying them towards Sanga Hill, and thus the pollutants could move to the Banepa Valley over Sanga Hill. The Fraud number calculated by Kitada and Regmi [24] showed that there is a hydraulic jump of air almost at the middle of the valley during the late afternoon, giving rise to pollutant dispersion around the valley. The hydraulic jump helps to move upward the surface air with the pollutants to the mixing height, reaching up to 600 m above the ground as reported by Raman et al. [13]. Furthermore, Pandey [14] reported that the air pollutants could reach up to 600 m above the valley floor or even higher during the afternoon. The proposed hypothesis is also supported by the afternoon westerly wind (Fig. 7) that flows east to west [14]. The strong westerly wind helps to dilute and/or remove some of the pollutants that reach the mixing height by carrying them towards Sanga Hill, and thus, in this manner the pollutants could move to the Banepa Valley over Sanga Hill. The hydraulic jump

Table 1
A comparison of average and standard deviation of $PM_{2.5}$ concentrations on weekdays and weekends of winter (December 2006 to February 2007) in Kathmandu Valley.

Time of day	$PM_{2.5}$ concentration (Avg. ± SD), μg/m^3		Avg. conc. ratio of weekday/weekend
	Weekdays ($n = 66$)	Weekend ($n = 10$)	
Morning (06:00 LST)	201 ± 52	232 ± 50	0.87
Afternoon (12:00 LST)	108 ± 45	158 ± 32	0.68
Evening (18:00 LST)	175 ± 50	146 ± 17	1.20
Night (00:00 LST)	94 ± 24	81 ± 22	1.16

Avg: average; SD: standard deviation; conc: concentration; weekdays: Sunday through Friday; Weekend: Saturday; n: number of days for measurement.

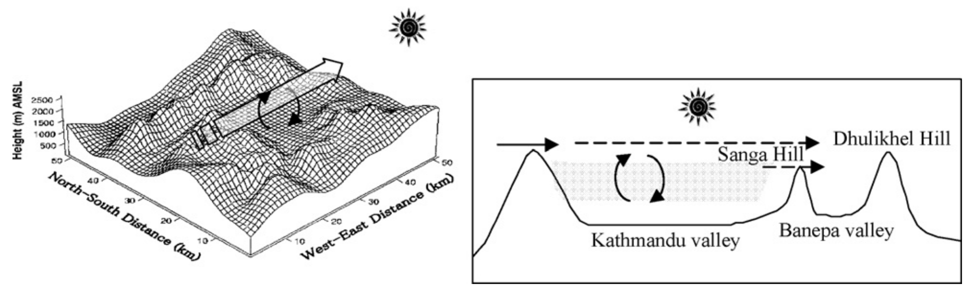

Fig. 7. Late afternoon wind pattern in Kathmandu Valley (left) and sketch in vertical west-east cross section (right).

can help to remove the pollutants in the valley through the exit to the nearby Banepa Valley where the PM concentration increases in the evening by 10–20 μg/m^3. These combined removal mechanisms of the fine particles during the afternoon periods in the Kathmandu Valley resulted in much lower afternoon $PM_{2.5}$ values in weekdays than morning and evening peak values shown in Table 1. Much of the pollutions that do not reach the mixing height remain in the atmosphere. By the evening, the temperature and wind speed drop slowly. These drops cause some of the suspended $PM_{2.5}$ in the upper layer of the troposphere to subside to the surface and combine with freshly emitted $PM_{2.5}$ or fine particles resulting in evening peaks. However, the dilution and removal of some $PM_{2.5}$ generated during the day causes the evening $PM_{2.5}$ peak concentration to be lower than the morning.

3.5. Accumulation effects

Fig. 8 shows the daily average $PM_{2.5}$ from 1 October 2006 to March 2007 (post-monsoon to winter). The first week of October had similar $PM_{2.5}$ values extending for several days, indicating a balanced condition of addition and removal of $PM_{2.5}$ in the valley. Average $PM_{2.5}$ concentrations during the first five working days in the first week of October 2006 showed maximum values of 87 ± 6 μg/m^3 in the morning and minimum values of 18 ± 4 μg/m^3 at night. The difference between the maximum and the minimum values was 69 μg/m^3. Thus the author assumed that the average

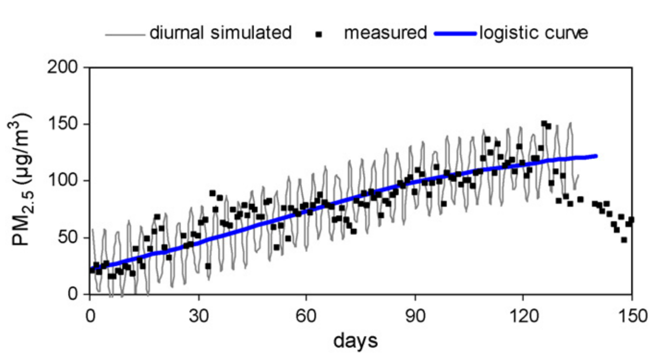

Fig. 8. Concentration variation of $PM_{2.5}$ from 1 October 2006 to 4 March 2007.

daily load of $PM_{2.5}$ concentrations would be 69 μg/m^3 in the valley. From the second week of October, the $PM_{2.5}$ values start to rise sharply and remain high until the beginning of February. The continuous rise of $PM_{2.5}$ concentration has been assumed by the contribution of increased pollutant concentration from day to day, lasting through the winter. This is caused by stagnant wind and temperature inversion in the valley that consists of stronger subsidence and radiation inversions during the wintertime than other seasons. Thus, the pollutants are accumulated in the valley. As spring arrives, the wind speed and air temperature increase and the $PM_{2.5}$ concentrations sharply decrease. This sharp decrease of fine particles can be seen from around 125 days (from the second week of February in Fig. 8) after started to get cold period. In the beginning of February $PM_{2.5}$ reached the highest value of 140–145 μg/m^3 and the average value of $PM_{2.5}$ in the cold period (October–February) was 78 ± 4 μg/m^3. These values of $PM_{2.5}$ are much higher than the ambient air quality standards or guidelines (35 μg/m^3: USA, 25 μg/m^3: Australia, EU and WHO based on the 24-h mean). Coincidently, there was more significant increase in patients with diseases associated with a high concentration of fine particulates or $PM_{2.5}$ in the valley during winter compared other seasons [14]. As mentioned above, our survey during winter at three hospitals in the years 2006–2007 showed increase of 25–30% of outpatients related to respiratory diseases or symptoms.

The cumulative behavior of $PM_{2.5}$ was simulated using a logistic curve $y = [k/(1 + \exp(p - qx)] + a\sin(bx)$ where y is days, x is $PM_{2.5}$ concentration and k, p, q, a, and b are constants. The first part of the equation, $[k/(1 + \exp(p - qx)]$, represents the daily average $PM_{2.5}$ growth and the second part of equation, $a\sin(bx)$, describes the diurnal variation. The constant 'k' represents the mean $PM_{2.5}$ value for the first week in February. For simplicity in modeling from the limited availability of the data, we assumed that i) maximum peak occurs at the 12:00 LST and the minimum occurs at 24:00 LST and (ii) everyday a fixed amount of $PM_{2.5}$ is added in the valley during the cold periods in the simulation. The equation was applied to the remaining data for 2003–2004 and 2004–2005 for validation. The equation in these years fit well. Table 2 provides the constant values used for regression in the two winter periods. The coefficient of determination (R^2) given in the table represents the fitness of the equation to the measured data. The high R^2 value for 3 years of data shows that the model explains the accumulation mechanism well during the cold season. The model shows that $PM_{2.5}$ accumulation

Table 2
Constant values for logistic curves ($y = [k/(1 + \exp(p - qx)] + a\sin(bx)$).

Winter year	Parameters					
	k	p	q	a	b	R^2
1/10/2006 to 7/2/2007	120	0.03	1.54	35	2π	0.80
1/11/2004 to 7/2/2005	180	0.03	1.92	35	2π	0.78
30/11/2003 to 7/2/2004	130	0.03	1.53	35	2π	0.76

in the valley during the winter season is alarming and the way to reduce this poses a great challenge. According to the model that was developed, it is essential to curb almost half of the $PM_{2.5}$ from the beginning of winter to reduce the maximum $PM_{2.5}$ concentration by half during winter or cold period.

4. Conclusions

Based on the diurnal $PM_{2.5}$ measurements conducted in the Kathmandu Valley and the subsequent analysis, the following conclusions can be drawn:

- Similar peak patterns of $PM_{2.5}$ concentrations were observed in winter, indicating the repetitive cycle in the valley.
- Morning and evening peaks were observed every day with higher values in the morning than those in the evening.
- The peak values of wind speed and temperature profile in the mid-afternoon helped to reduce the afternoon concentration of $PM_{2.5}$.
- Downward movement of polluted air over the valley, possibly due to subsidence resulting from anabatic winds during the morning hours, could be the major cause of the pronounced morning peak concentrations.
- Intrusion of wind into the valley and air mixing during the day, followed by westerly wind, sweeps air pollution out to the eastern Banepa Valley resulting in the decrease in the evening peak concentrations as compared morning ones.
- The continuous increase of $PM_{2.5}$ concentration during winter indicated a daily accumulation, which may increase the concentration level of the next morning due to subsidence of the pollutant layer in the valley.
- The growth of $PM_{2.5}$ in winter in Kathmandu Valley can be explained by using the logistic growth model [$y = [k/(1 + \exp(p - qx)] + a\sin(bx)$] where y is days, x is $PM_{2.5}$ concentration and k, p, q, a, and b are constants.

References

[1] P.C. Mannis, B.L. Sawford, A model of katabatic wind, J. Atmos. Sci. 36 (1979) 619–630.
[2] B.W. Atkinson, Mesoscale Atmospheric Circulations, Academic Press, 1981, pp. 495.
[3] C.B. Clements, C.D. Whiterman, J.D. Horel, Observations of a cold air pool in a remote mountain basins, in: 9th Conference on Mountain Meteorology, 7–11 August, Boston AMS, J4.4, 2000, p. 4.
[4] R.M. Banta, P.B. Shepson, J.W. Bottenheim, K.G. Anlauf, H.A. Wiebe, A. Gallant, T. Biesenthal, L.D. Oliver, C.J. Zhu, I.G. Mckendry, D.G. Steyn, Nocturnal cleansing flows in a tributary valley, Atmos. Environ. 31 (4) (1997) 2147–2162.
[5] M. Hedley, D.L. Singleton, Evaluation of an air quality simulation of the lower fraser valley-I meteorology, Atmos. Environ. 31 (1997) 1605–1615.
[6] G. Baumbach, U. Vogt, Experimental determination of the effect of mountain-valley breeze circulation on air pollution in the vicinity of Freiburg, Atmos. Environ. 33 (1999) 4019–4027.
[7] T.A.J. Kuhlbusch, A.C. John, H. Fissan, Diurnal variations of aerosol characteristics at a rural measuring site close to the Ruhr-Area, Germany, Atmos. Environ. 35 (Suppl. 1) (2001) 13–21.
[8] A.D. Jacilevich, A.R. Gracia, E. Caetano, Locally induced surface air confluence by complex terrain and its effect on air pollution in the valley of Mexico, Atmos. Environ. 39 (2005) 5481–5489.
[9] W.J. Shaw, J.C. Doran, R.L. Coulter, Boundary-layer evolution over Phoenix Arizona and the premature mixing of pollutants in the early morning, Atmos. Environ. 39 (2005) 773–786.
[10] A.G. Triantafyllou, P.A. Kassomenos, Aspects of atmospheric flow and dispersion of air pollutants in a mountainous basin, Sci. Total Environ. 297 (1–3) (2002) 85–103.
[11] C.K. Sharma, Urban air quality of Kathmandu valley "Kingdom of Nepal", Atmos. Environ. 31 (1997) 2877–2883.
[12] B. Sapkota, R. Dhaubadel, Atmospheric turbidity over Kathmandu Valley, Atmos. Environ. 36 (2002) 1249–1257.
[13] M.V. Ramana, V. Ramanathan, I.A. Podgorny, B.B. Pradhan, B. Shrestha, The direct observation of large aerosol radiative forcing in the Himalayan region, Geophys. Res. Lett. 31 (2004) L05111, doi:10.1029/2003GL018824.
[14] R.P. Regmi, T. Kitada, G. Kurata, Numerical simulation of late wintertime local flows in Kathmandu Valley, Nepal: implication for air pollution transport, J. Appl. Meteor. 42 (2003) 389–403.
[15] A. Pandey, The diurnal cycle of air pollution in the Kathmandu Valley, Nepal, Ph.D. Thesis, Massachusetts Institute of Technology, US, 2006.
[16] R.P. Regmi, T. Kitada, Human-air pollution exposure map of the Kathmandu Valley, Nepal: assessment based on chemical transport simulation, J. Global Environ. Eng. 9 (2003) 89–109.
[17] A.S.H. Prevot, J. Dommen, M. Baumle, M. Furger, Diurnal variation of volatile organic compounds and local circulation system in an Alpine valley, Atmos. Environ. 34 (2000) 1413–1423.
[18] J. Ruuskanen, Th. Tuch, H. Ten Brink, A. Peters, A. Khlystov, A. Mirme, G.P.A. Kos, B. Brunekreef, H.E. Wichmann, G. Buzorius, Concentrations of ultrafine, fine and $PM_{2.5}$ particles in three European cities, Atmos. Environ. 35 (2001) 3729–3738.
[19] V. Gros, K. Tsigaridis, B. Bonsang, M. Kanakidou, C. Pio, Factors controlling the diurnal variation of CO above a forested area in southeast Europe, Atmos. Environ. 36 (2002) 3127–3135.
[20] L. Laakso, T. Hussein, P. Aarnio, M. Komppula, V. Hiltunen, Y. Viisanen, M. Kulmala, Diurnal and annual characteristics of particle mass and number concentrations in urban, rural and Arctic environments in Finland, Atmos. Environ. 37 (2003) 2629–2641.
[21] W. Ta, T. Wang, H. Xiao, X. Zhu, Z. Xiao, Gaseous and particulate air pollution in the Lanzhou Valley, China, Sci. Total Environ. 320 (2–3) (2004) 163–176.
[22] J.A. Garcia, M.L. Cancillo, J.L. Cano, A case study of the morning evolution of the convective boundary layer depth, J. Appl. Meteor. 41 (2002) 1053–1059.
[23] C.D. Whiteman, Breakup of temperature inversion in deep mountain valleys: part I. Observations, J. Appl. Meteor. 21 (1982) 270–289.
[24] T. Kitada, R.P. Regmi, Dynamics of air pollution transport in late wintertime over Kathmandu Valley, Nepal: as revealed with numerical simulation, J. Appl. Meteor. 42 (2003) 1770–1798.