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HUMAN-AIR POLLUTION EXPOSURE MAP OF THE KATHMANDU VALLEY, NEPAL: ASSESMENT BASED ON CHEMICAL TRANSPORT SIMULATION

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Abstract

Human-air pollution exposure in the Kathmandu valley has been studied based on the numerically simulated pollutant fields and residential distribution of population. Human exposure maps were produced and various health outcomes attributable to PM_{10} have been evaluated. Numerical simulation performed with an Eulerian/transport/chemistry/deposition model resonably reproduced the observed spatial distribution of NO_2 and SO_2; and PM_{10} measured at some location with passive samplers during February-March 2001. Exposure analysis reveals that about 44,15,52, and 8 % of the population are living in areas with concentrations above 40 μg m^{-3} of NO_2, SO_2, PM_{10} and $PM_{2.5}$, respectively. The health endpoints attributable to PM_{10} over the Kathmandu valley were quantitatively evaluated and the results show PM_{10} will put significant societal burden.

KEYWORDS: *air quality modeling, human-exposure, Kathmandu valley, Himalayas, Nepal*

1. Introduction

It is rather unfortunate to see that in developing countries like Nepal, struggling for the basic necessities of life, the environmental issues like air pollution that slowly curbs the natural privileges for human well being and long-term economic prosperities have been rarely given necessary thoughts until the problem takes its disastrous shape interacting with then achieved economic growth, infrastructure, industrial establishments and job volumes. The resulting situation may leave little opportunity to take any effective control measures.

Present Kathmandu valley, the capital of Himalayan kingdom of Nepal, witnesses serious planning, environmental and management problems. Traditional planning and community support systems largely cohesive to the nature, observed in the medieval towns of the valley, have been virtually defunct with the changing social values, urban consumption pattern and commercialization of the land. During the last three decades, the population of the valley has increased by more than 106 %. At present, Kathmandu valley captures 1.4 millions of people as well as 25 % of the national industrial establishments.

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Consequently, increased emissions from the domestic and transport sectors and emission from the hundreds of the coal burning brick kilns have severely disturbed the urban life due to the prevalence of an unacceptable level of dust, particulate and other pollutants. This newly emerged problem over the valley appears to put severe societal burden of ill human attributable to air pollution and has raised uncertainties with respect to the environmental protection and conservation of this mountain valley. Developing as an economic island of the country, increasing personal income of the Kathmandu residents (Adhakari, 1998), and subsequent close positive correlation between the personal income and motorization (e.g., Faiz et al., 1995), deterioration of air quality of the Kathmandu valley is likely to accelerate in coming years. It is thus very critical to ensure that Nepal's development efforts over the Kathmandu valley are environmentally sustainable.

Numerous time-series, epidemiological, and cohort researches have consistently shown statistically significant positive association between the ambient air pollutions and mortality and various indices of morbidities as well. While the associations between the prevalence of different air pollutants and adverse human health outcomes have been established, the particulate matter of less than ten micron sizes (PM_{10}) appear to be one of the most useful single measures to exemplify seriousness of air pollution in a given area (e.g., USEPA, 1996; Schwartz, et al., 1996; Vedal, S., 1997; Katsouyanni et al., 1997; Samet et al, 2000; Kunzli et al., 2000; Schwartz, 2001; Zanobetti et al. 2002; etc.). Given the high correlation among pollutants PM_{10} may serve as a surrogate measure for other pollutants including very fine particles and a host of traffic related toxins.

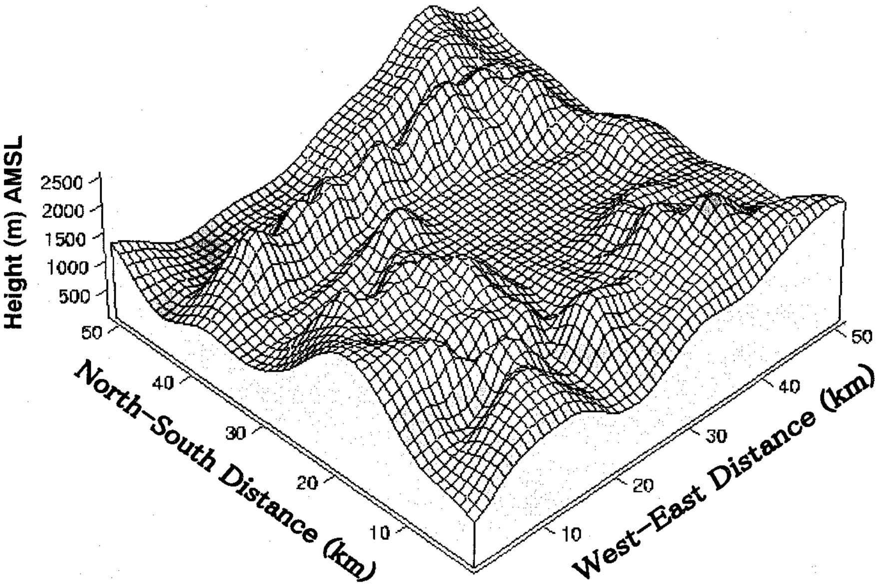

Fig.1: 3-dimensional topographic view of the Kathmandu valley and its surrounding mountains.

Recent numerical and observational findings on prevailing wintertime meteorology (Regmi et al., 2003) and concurrent investigation of air pollutants distribution and their dynamics (Kitada and Regmi, 2003) have revealed that the bowl-shaped Kathmandu valley with high mountains (see Fig. 1), located in the middle of the Himalayas and the vast tropical Gangetic Plain of India, possesses high air pollution potential due to its adverse atmospheric and topographical conditions.

While distribution, dynamics and resulting pollutant fields over the valley were extensively studied (Kitada and Regmi, 2003) for most of the potential pollutants, particulate pollution and public health impacts over the valley were not discussed in the paper. Thus, the objective of this paper is to provide a consolidated analysis of human exposure to pollutant fields and health risk assessment attributable to particulate matter, in particular. Such an analysis performed in the Europe has revealed that particulate matter is the type of pollutant affecting health of the largest number of European residents (Kunzli et al., 2000).

Assessment of regional human risk due to exposure to air pollution requires a comprehensive database of population time-activity and reliable measurement of pollution concentration in both the indoor and outdoor environment. Though there was some related data such as difference between indoor and outdoor NO_2 concentrations (Futawatari et al., 2000), no information was available on particulate matter for Kathmandu valley. Thus the human exposure to air pollutants need to be carried out making use of the residential population distribution and the modeled concentration fields without appreciating the population time-activities and the long-term observational ambient- as well as the indoor-air quality. Based on the Ostro's findings (Ostro, 1994; 1998) on the mortality and morbidity attributable to particulate pollution, an attempt has been made to evaluate the various human health endpoints for Kathmandu residents. Because of the lack of precise health impact data and the typical dose-response functions for the Kathmandu valley, the study appears to be rather abstract in its nature and encompasses uncertainties as well. However, the lack of conclusive information does not necessarily mean that a strategic assessment be ignored.

2. Methodology

2.1 Measurements

During the period of 18 February to 11 March 2001, a dry and severe air pollution season in Kathmandu, an extensive field measurement for spatial distribution of NO_2 and SO_2 were conducted at 22 sites over the Kathmandu valley (see Fig. 2 for observation sites) as well as a scouting like observation for particulate matter (PM_{10}) at four different locations was also conducted using Green Blue Co., Japan passive samplers. While observations for NO_2 and SO_2 cover wide range of area, PM_{10} measurement was performed only at the center of Kathmandu city, central suburb, southern major brickfield, and northern rural area of the valley in an attempt capture the general scenario of the particulate pollution over the valley.

2.2 Emission estimation

A well assesses emission data is always expected for accurate numerical simulation of pollutant fields. Using the emission factor for total suspended particulate matter (TSP) available in Shrestha and Malla (1996) and the procedure described in Kitada and Regmi (2003), emission estimation of TSP was prepared in 1 km × 1 km grid net for 51 km^2 area that covers the whole Kathmandu valley and surrounding mountains including some part of the eastern Banepa valley due to energy utilization in domestic, transport and industrial sectors during the year of 2001. Additionally, road re-suspension was calculated for each grid points using the emission factor of 2 gm/km/car (Shah and Nagpal, 1997) and the grided annual average daily traffic data used in Kitada and Regmi (2003). However, contribution from unregistered small cottage industries, refuse burning and biogenic emissions were not possible to include in this estimation due to the lack of necessary information.

Using the approximate ratio of 0.5 between PM_{10} and TSP for urban environment of Kathmandu (Mathur, 1993) , emission field for PM_{10} was prepared. Assuming that the estimated PM_{10} was contributed half by coarse (particles of sizes in $2.5\ \mu m < d_p < 10 \mu m$) and half by fine (particles of sizes in $d_p < 2.5\ \mu m$) particles, the necessary emission fields for fine and coarse particulates were prepared. The ratio of $PM_{2.5}$ to PM_{10} tends to be low, in developing countries, even in urban area; for example, some samples in Beijing show this ratio varies from 35% to 61% (Hao et al., 2002). Thus we assumed 0.5 for the ratio in preparation of $PM_{2.5}$ emission-as described above. For other pollutants such as SO_2 and NO_x etc. the same emission fields (Kitada and Regmi, 2003) were used in this investigation.

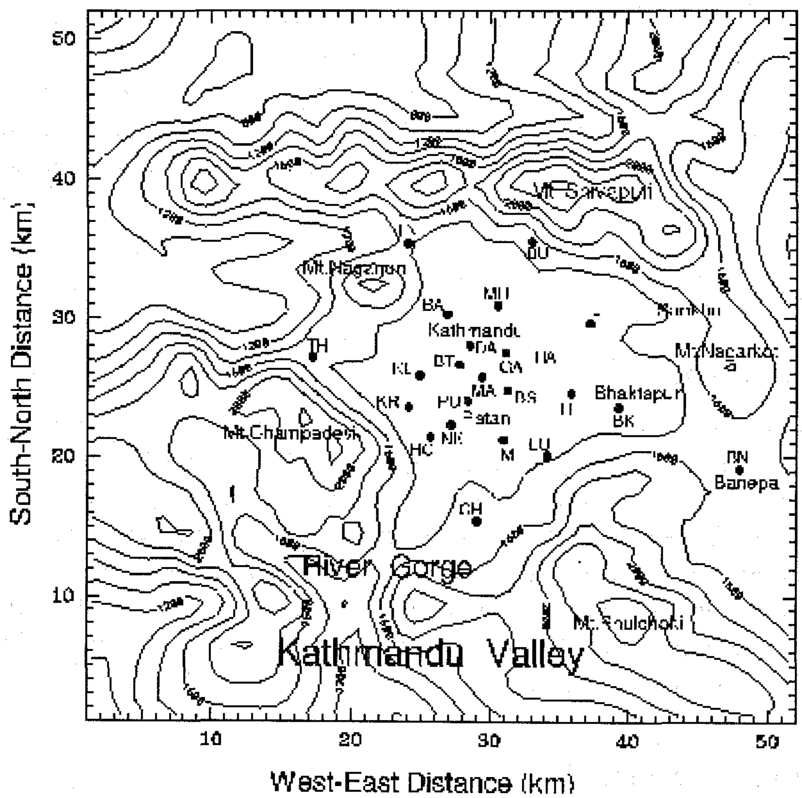

Fig. 2: Calculation domain. The black circles and the letter attached show the air quality measurement sites and the short names of the locations, respectively. Kathmandu, Patan and Bhaktapur are the main cities in the valley. The terrain contour of the valley at the interval of 200 m is also plotted.

2.3 Chemical transport modeling

An extended version of the chemical transport model (Kitada et al., 1984; 1993) that successfully resolved the air pollution transport and transformation processes over the complex terrain of central Japan (Kitada et al., 2000) and over the Kathmandu valley (Kitada and Regmi, 2003) was used to perform present calculation for particulate pollutants. Furthermore, the secondary particulates SO_4^{-2} and NO_3^- have been treated as fine and coarse particles, respectively.

2.3.1 Modeling domain and grid system

The modeling area and grid system were designed to cover the whole Kathmandu valley and its surrounding areas to the extent that pollutant concentrations outside the boundary would be sufficiently small compared to the pollutant strength inside the Kathmandu valley. Variable grid sizes of 3 km and 1 km were applied. The domain grid system consisted of 1 km × 1 km horizontal grid for the 51 km × 51 km area that covers the Kathmandu valley and its surrounding mountains and of three more grids of the size 3 km × 3 km in all sides in order to minimize the boundary effects in the calculation within the Kathmandu valley covered by 51 km × 51 km area (see Figs. 1 and 2). The center of the calculation domain was set at the center of the Kathmandu valley.

The calculation domain was vertically discretized into 15 terrain following layers with increasing layer heights towards the top boundary of the domain. The lowest model layer was set at the surface level and the second layer height was set at about 40 m above the valley floor, and the model top was set at 10 km above the mean sea level.

2.3.2 Meteorological inputs

The necessary mesoscale meteorological input fields for the transport simulation were prepared with the same meteorological flow fields described in Kitada and Regmi (2003) for the period of 0000 UTC (0545 LST) 5 March to 0000 UTC (0545 LST) 7 March 2001. Only these two days were chosen for the simulation since meteorological conditions over the valley typically remain the same with little day-to-day variation and the flow system tends to repeat everyday during the winter (Regmi et al., 2003). The emission scenario over the valley also remains the same throughout the dry season. In this respect, the simulation period, i.e., March 5 to 7 was considered to be representative winter days over the Kathmandu valley.

2.4 Air pollution impact

The human health impacts, i.e., mortality and morbidities, in reference to the calculated particulate pollutant (PM_{10}) concentration fields, were evaluated based on dose-responses (Ostro, 1994; 1998), and this method was adopted by World Bank's Urban Air Quality Management Strategy in Asia, *URBAIR Report* (Shah and Nagpal, 1997). Since dose-response functions for the Kathmandu valley have not been developed, we follow to this method. The health benefits have been calculated for three target concentration levels that may be realistically achieved with appropriate control measures. These target levels or benchmarks for PM_{10} are chosen to be 40 and 20μg m^{-3}, which are the European target standards for 2005 and 2010, respectively (EC, 1999), and an intermediate level 30 μg m^{-3}. Calculation for health benefits that could be achieved with the reduction of prevailing level of pollution at the above target levels have been discussed since a threshold for particulate pollution effects has not been identified within the range of exposures investigated in either short- or long-term studies (Crosignani et al., 2002). There has been general practice of using much lower values of particle concentration targets, for example, Kunzli et al., (2000) used 7.5 μg m^{-3} as a lowest assessed level in the epidemiological studies.

It should be mentioned that we would assume the calculated 24-hours average concentration fields of PM_{10} as the wintertime average as both the meteorology and emission appear to be nearly the same during the winter in Kathmandu. The annual average concentration is estimated by multiplying the calculated 24-hours average by 0.75. The factor of 0.75 was chosen from the ratio of annual average to the wintertime average of observed TSP (DHM, 1995). The department of hydrology and meteorology (DHM), Kathmandu used to carry TSP measurement during the early 1990s and there has been no such measurement in recent years.

The following relations were used for the evaluation of health outcomes over the Kathmandu valley based on Ostro's findings (Ostro, 1994):

Excess death	: $\Sigma_{ij}\, 0.00112 \times ([PM_{ij}] - T_k) \times P_{ij} \times C$
Chronic Bronchitis	: $\Sigma_{ij}\, 6.12 \times 10^{-5} \times ([PM_{ij}] - T_k) \times P_{ij}$
Restricted activity days (RAD)	: $\Sigma_{ij}\, 0.0575 \times ([PM_{ij}] - T_k) \times P_{ij}$
Respiratory hospital diseases (RHD)	: $\Sigma_{ij}\, 1.2 \times 10^{-5} \times ([PM_{ij}] - T_k) \times P_{ij}$
Emergency room visits (ERV)	: $\Sigma_{ij}\, 23.54 \times 10^{-5} \times ([PM_{ij}] - T_k) \times P_{ij}$
Respiratory symptoms days	: $\Sigma_{ij}\, 0.183 \times ([PM_{ij}] - T_k) \times P_{ij}$
Bronchitis on children below 18 years old	: $\Sigma_{ij}\, 0.00169 \times ([PM_{ij}] - T_k) \times P_{ij} \times 0.46$

where i (= 1 to 51) and j (= 1 to 51) denote indices for the grid point, i.e., i for west-east and j for south-north direction. PM_{ij} is the calculated PM_{10} concentration, P_{ij} is the population within the grid point ij, C = 0.0091 is the crude annual mortality rate over the Kathmandu valley (Shrestha, 1993) and T_k is the target value for PM_{10}, i.e., k = 20, 30, 40 μg m^{-3}. We also assume that 46% of the Kathmandu population is under the age of 18 years (MOPE, 2000a).

3. Results and Discussion

3.1 Emission source distribution

Figures 3a shows the estimated sectoral contributions for the total suspended particulate matter (TSP) as per the year 2001. It appears that high prevalence of particulate pollution over the Kathmandu valley was due to the industrial emissions followed by the domestic, and transport sectors. The highest percentage share by the industrial sector mainly resulted from the heavy coal consumption in the brick industries. Nearly 140 movable type Bull's Trench brick kilns were found to be routinely operating over the valley during our field measurement period (February-April, 2001).

The domestic energy sources were dominated by kerosene in the urban area and by biomass sources in the rural areas of the valley although biomass consumption was significant in the urban areas as well. Regarding the transport sector, road re-suspension turns out to be almost double of the exhaust emission.

In Fig. 3b, earlier estimates of TSP have been compared with the present one. Shrestha and Malla (1996) estimated the sectoral emission considering the energy consumption during the year 1993, but re-suspension was not estimated in their study. Likewise, estimation by Shah and Nagpal (1997) was for the year 1995. In Fig. 3b, contribution of Cement factory, about 6000 tons/year, and cottage industries, about 582 tons/year, reported in Shah and Nagpal (1997) was excluded in the figure since the cement factory was shutdown by 2001 and the unregistered small cottage industries were not accessible to include in present estimation. Looking at these estimates, transport and domestic emissions show an increasing trend and the industrial emission appears to be same.

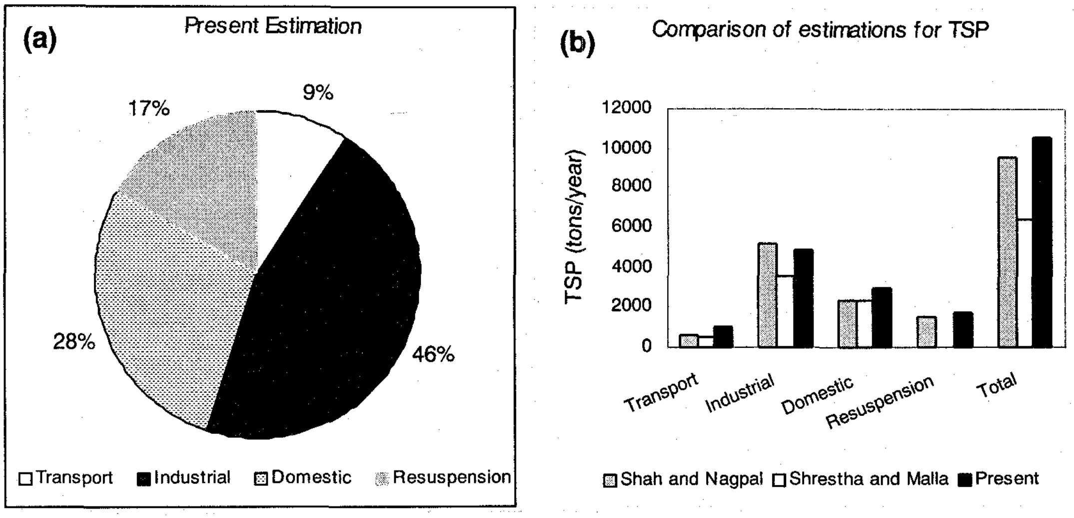

Fig.3: Estimated total suspended particulate matter (TSP) over the Kathmandu valley. (a) Sectoral contribution for TSP estimated by the authors for the target year 2001. (b) Comparison with previous estimation due to Shah and Nagpal (1997) and Shrestha and Malla (1996) for the target years 1995 and 1993, respectively.

The estimated daily emissions of SO_2, NO_x, and TSP in 1 km × 1 km grids during the winter of 2001 are shown in Figs. 4a-c in order to help understanding of relation between the emission source distribution and the calculated as well as the observed concentration distribution of NO_2, SO_2, and particulate matters (PMs). The annual average emissions over the valley were estimated as 3859, 2249, and 10558 metric tons of NO_x, SO_2, and TSP, respectively. In the case of NO_x high emission appears in the western central area of the valley, around "BT", where the city of Kathmandu is located, while the high SO_2 emission can be found in the southern and eastern brickfield areas around "IM", "TI", and "BK" (see Fig. 2 for locations). For TSP, high emission areas appear in the southern and eastern brickfields and over the city of Kathmandu as well. As indicated in Fig. 3a, re-suspension

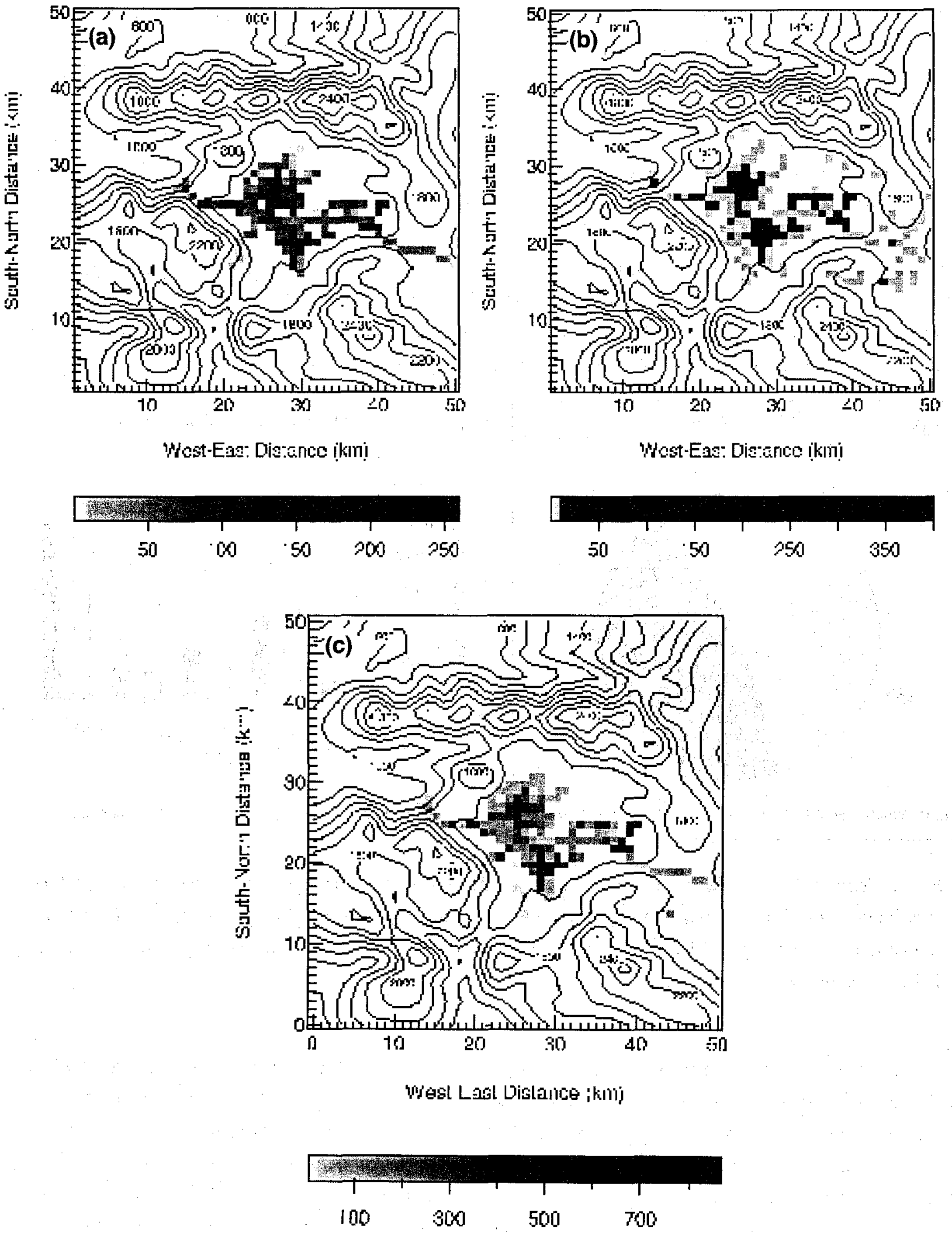

*Fig.*4: Estimated emission strength of (a) NO_x ($kg\text{-}NO_2\ km^{-2}day^{-1}$), (b) SO_2 ($kg\text{-}SO_2\ km^{-2}day^{-1}$), and (c) TSP ($kg\ km^{-2}day^{-1}$) in the Kathmandu valley during the winter.

associated with traffic is an important emission source, and thus, the distribution in Fig. 4c shows enhanced emission along roads.

3.2 Comparison of calculation and observation

To our best knowledge, only a single modeling study of particulate matter over the Kathmandu valley has been reported for the target year 1995 (Shah and Nagpal, 1997); the study used a Gaussian model that utilized meteorological input as joint wind speed/direction/stability matrix prepared with the single point observation data at Tribhuvan International Airport (TIA) (see Fig. 2 for location of TIA). In the study, dispersion condition was assumed spatially uniform over the valley. Moreover the model did not include the secondary particulates resulting from atmospheric chemical reactions. Such a modeling approach would be inefficient for Kathmandu valley that captures complex meteorological and topographic conditions. Comparison of the present calculation with Shah and Nagpal (1997) appears to be inappropriate due to its limitations as well as changed emission scenarios over the years. Instead, we would compare the present calculations with the measurements carried over the Kathmandu valley during the period of simulation in order to check the rationale of the calculated results.

3.2.1 Comparison of PM_{10}

Given the limited three-weeks average observation of PM_{10} during 18 February to 11 March with passive samplers, comparison of model predictions with the observation may not be sufficient. However, a reasonable agreement appears between the calculated 24-hours average concentration and with the observed 3-weeks averages (see Fig. 5a). Moreover, the diurnal variation of PM_{10} (Shrestha et al., 2001) at the location in between the Kathmandu and Patan cities (see "PU" in Fig. 2 for location) during the period of this simulation agrees well with the calculation (see Fig. 5b). Shrestha et al., (2001) had carried a two-week long continuous observation of TSP, which was converted to PM_{10} as 0.5×TSP for the purpose of comparison in Fig. 5b. The high concentration in the early morning in their observation, as shown at time 29 (5 a.m.) and 30 (6 a.m.) in Fig. 5b, could be due to the heavy traffic emission under adverse meteorology of weak wind and stable stratification. Indeed, the site was very close to the major road that links the Kathmandu and Patan cities and their measurement appears consistent with the traffic regulations that limit heavy vehicles playing over the urban areas only in the early morning hours. Relatively low concentration found at around noon is largely due to mixing layer activity developed before the intrusion of valley wind over the Kathmandu basin (see Regmi et al., 2003, and Kitada and Regmi, 2003). In addition, during the nighttime wind over the valley is weak and surface inversion develops; these conditions thus eventually lead to high nighttime concentration (Kitada and Regmi, 2003). Furthermore the 24-hours average of the measurement of Shrestha et al. (2001) for the period of 27 February to 8 March 2001 turns out to be approximately 58 $\mu g\ m^{-3}$ whereas the calculated 24-hours averaged was approximately 60 $\mu g\ m^{-3}$ at the grid point of observation location. All these show that model calculation was successful to capture prevailing concentration and diurnal characteristics over the valley.

Details about the characteristics of the pollutant's dynamics over the valley and physical reasoning have been extensively discussed elsewhere (Kitada and Regmi, 2003). During the night and early morning the air pollution remains more or less constant at high level. Soon after the sunrise, the concentration appears to decrease very rapidly and attends its minimum concentration level close to the noontime. In the afternoon the air pollution starts to builds up over the valley abruptly and by the time of sunset pollution level reaches its high values and remains nearly constant until the next sunrise as could be seen in Fig. 5b. Although concentration levels vary with location, this diurnal characteristic appears to be nearly common throughout the valley (not shown) indicating that the whole valley remains under much higher level of air pollution for most of the time.

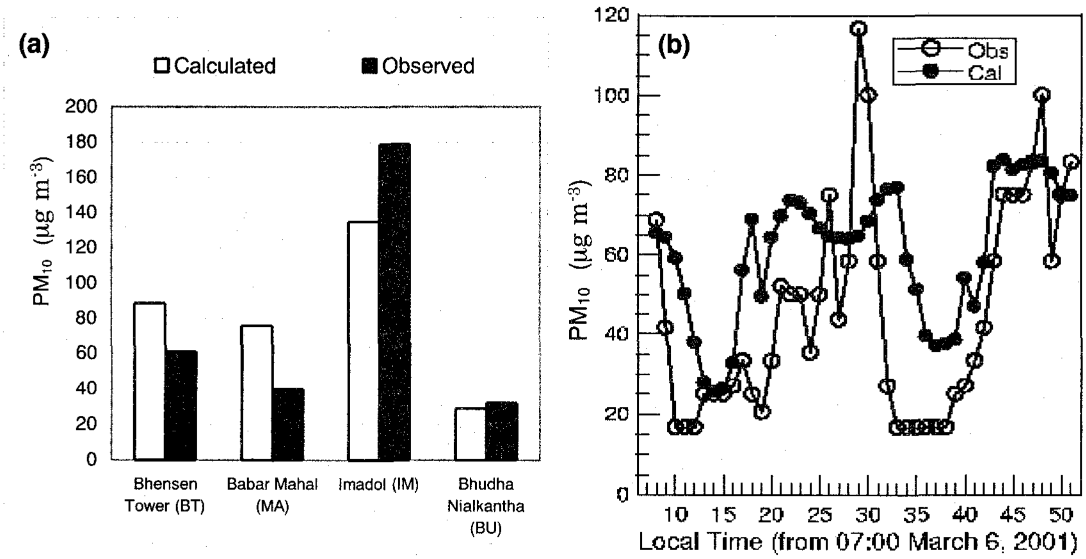

Fig.5: Comparison of calculated and observed PM_{10} over the Kathmandu valley. (a) Calculated 24-hours average, and 3-weeks average measured with passive samplers. (b) Diurnal variation of calculated and observed PM_{10} concentrations. The "observed" PM_{10} is what we estimated from TSP observation by Shrestha et al., (2001); in the estimation typical ratio PM_{10}/TSP ~ 0.5 was used (Mathur (1993).

3.2.2 Comparison of NO_2 and SO_2

In Figs. 6a-b, the calculated 24-hour averages of NO_2 and SO_2 are compared with the measured 3-weeks average concentration over the Kathmandu valley observed during 18 February to 11 March 2001. Both the observation and calculation indicates Kathmandu valley is relatively clean with respect to these pollutants except in few locations.

The calculated SO_2 agrees very well with the observation. At the sites such as TH, TN, CH, and LU near the western and southern edge of the valley (see Fig. 2 for observation sites), the observed and calculated SO_2 are very low. This suggests emission source within the valley largely dominate SO_2 in the valley since these sites are located in the main pathways of local winds flowing into the valley from the outside (Kitada and Regmi, 2003). High SO_2 concentrations at the three sites IM, TI, and BK in the eastern Kathmandu valley resulted due to coal combustion from brickfields. The observed NO_2 shows high concentrations at sites in the central Kathmandu valley; especially, the sites of KL, BT, MA, and DA in the Kathmandu city area show high NO_2. Because of the a variety of emission sources for NO_2 such as domestic fuel burning and automobiles, NO_2 concentration rather show spatial uniformity in contrast to SO_2. Numerical simulation generally captures characteristics of

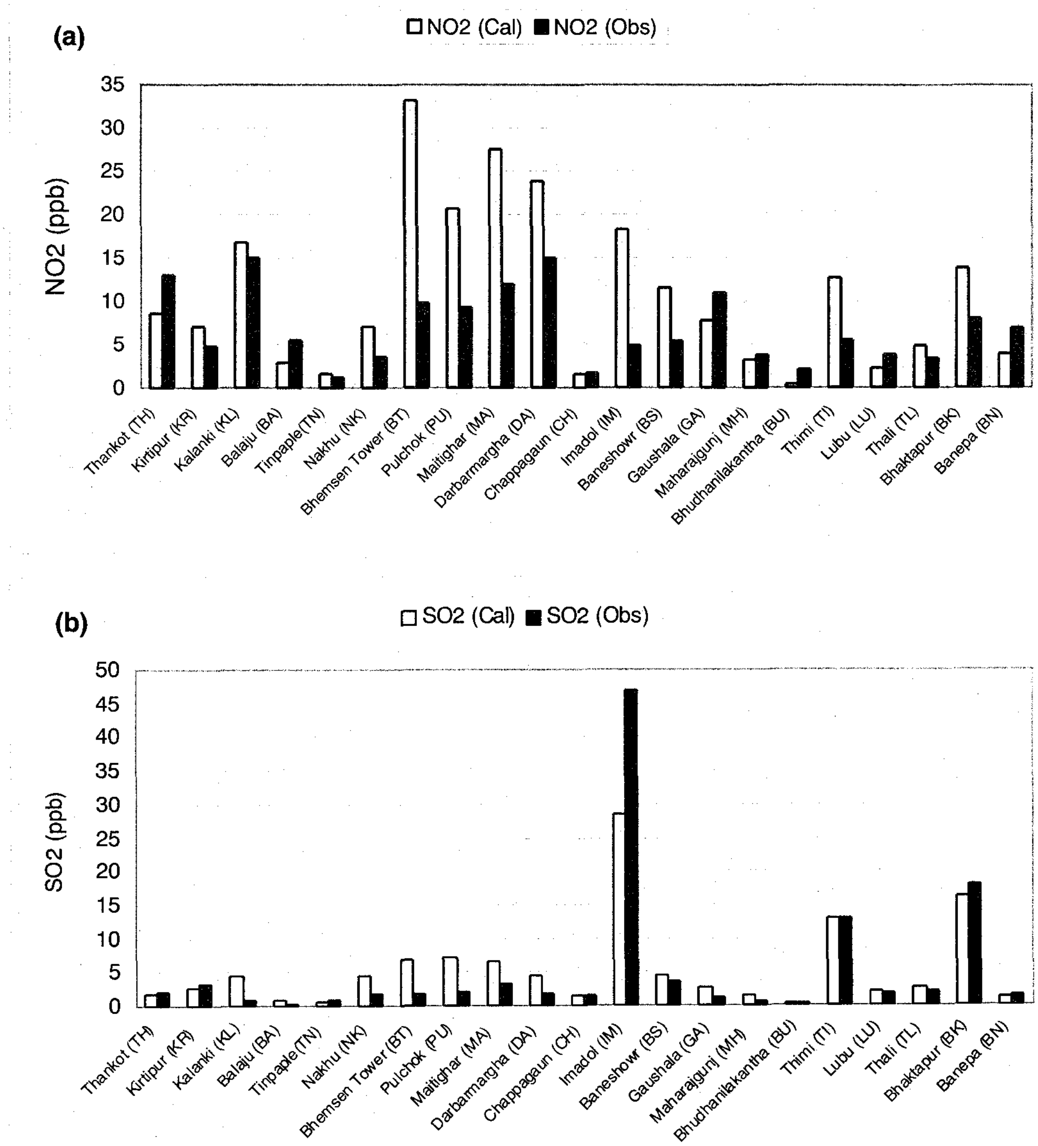

Fig. 6: Comparison of calculated 24-hours average and observed 3-weeks averaged concentration distribution of (a) NO_2 and (b) SO_2.

NO_2 at the sites. At some sites in and around the Kathmandu city area such as BT, PU, and MA, calculated NO_2 and SO_2 show systematically higher value compared with observation (Fig. 6a, b). Though there can be various reasons for this difference such as uncertainty in emission source distribution and errors in transport/chemistry calculation, one probable reason may exist in the measurement method. As previously described, we used passive samplers for our observation. The samplers may show smaller value when they are exposed in dusty and humid condition for long time, because the dust accumulated over the sampler's surface partially prohibits molecular diffusion of gaseous pollutant to the filter paper, that includes chemical agent, by trapping the pollutant. Thus, the sampler's three weeks-long exposure in dusty condition may cause such an underestimation of the gaseous pollutant (personal communication with Green Blue Co., 2002). This may be partially supported by the fact that agreement between the calculation and the "short term (one day)" observation was much better than the "long term" case shown in Fig. 6 (Kitada and Regmi, 2003).

3.3 Pollution air shade and population exposure

In Figs 7a-d, the 24-hours average spatial distributions of calculated NO_2, SO_2, PM_{10} and $PM_{2.5}$ are superimposed over the population distribution in the Kathmandu valley; and the percentage of the population experiencing the various pollution levels of these pollutants are evaluated in Figs. 8a-b.

Kathmandu valley at present captures approximately 1.4 million of people, of which 56 % are considered to live in urban area. The densely populated urban centers comprise the Kathmandu and Patan cities (confined within a 36 km long ring-road) and Bhaktapur city in the eastern edge of the valley as well as the Kirtipur (KR) and Madhayapur Thimi (TI) municipalities (see Fig. 2 for locations). The Banepa municipality in the eastern neighboring valley is located at about 22 km away from the main city of Kathmandu. Scattered villages and housing could be seen through out the valley. However, still agricultural field dominates over the flat valley floor but the substantial area found to be used for brickfields especially in the southern and eastern part of the valley.

Figures 8a-b show the percentage of accumulated population exposed to the concentration of calculated NO_2, SO_2, PM_{10} and $PM_{2.5}$ pollutants above various levels. Distribution of the population exposed to certain range of concentrations (Fig. 8c) reveals that the percentage of population living in areas with concentration of these pollutants above 40 $\mu g\ m^{-3}$ turns out to be about 44, 15, 52, and 8 percents, respectively. More than half of the valley's population exposed above 40 $\mu g\ m^{-3}$ PM_{10} is rather striking since 40 $\mu g\ m^{-3}$ is generally assumed to be the benchmark, i.e., the level of ambient air quality above which is attributed to health impact although several epidemiological studies (e.g., Schwartz and Dockery, 1992; Ostro et al., 1996; Pope et al., 1992) have shown continuous effects down to 10 $\mu g\ m^{-3}$ of PM_{10}. Fig. 8c also shows that more than 33 % of the people are living in areas above 60 $\mu g\ m^{-3}$ PM_{10}, and furthermore around 5% of the people even live in areas above 80 $\mu g\ m^{-3}$ of PM_{10}. It is expected that addition of the emission sources that could not be included into the present estimation may give much higher percentage of population exposures. However, the finding should be viewed with its limitation since population-time-activities and indoor exposure scenarios were not considered.

The spatial human exposure strength, i.e., population multiplied by concentration above certain level, at two reference concentration levels of PM_{10} is illustrated in Fig. 9; Figs. 9a and b for 20 and

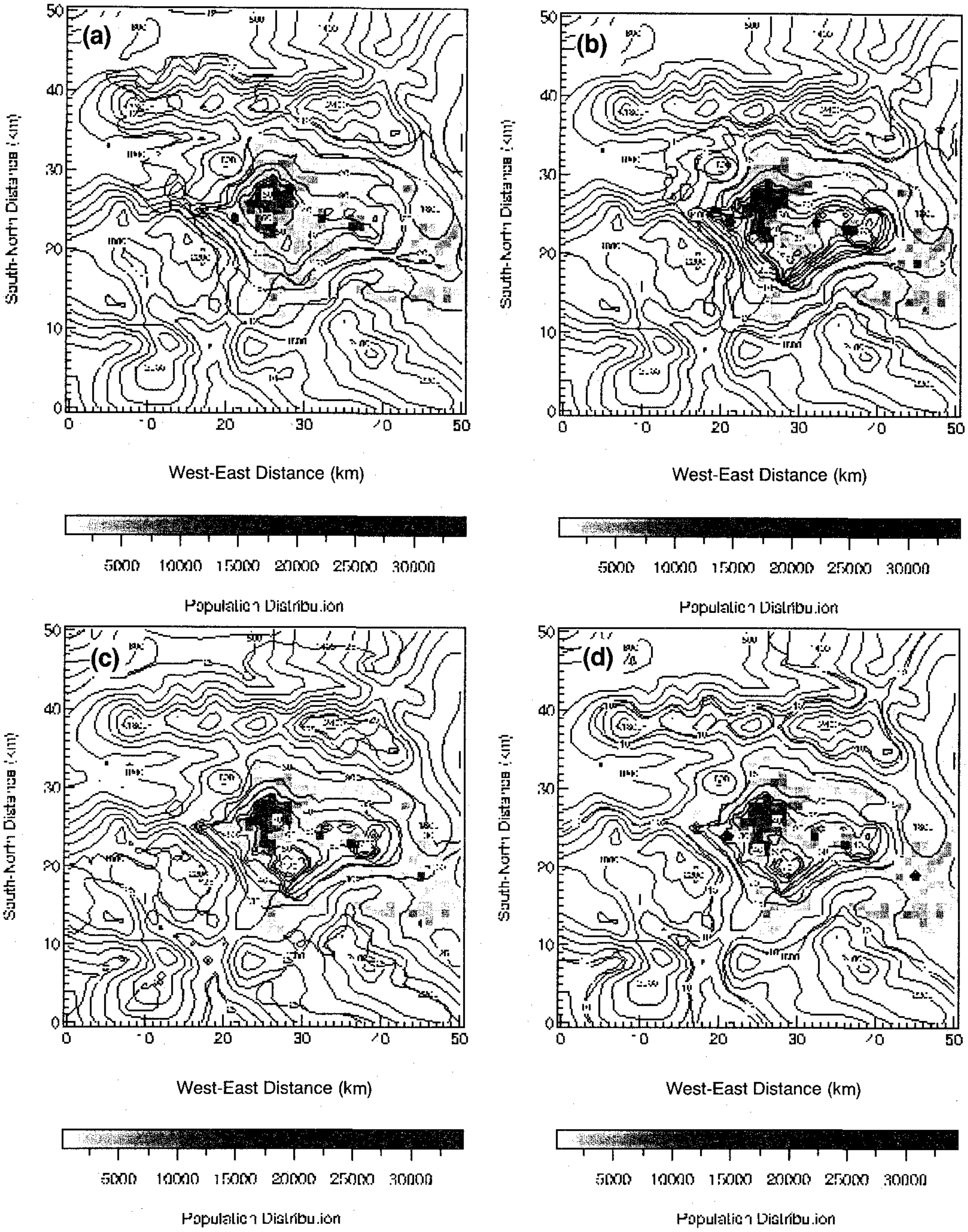

Fig. 7: Spatial distributions of residential population and calculated 24-hours averaged concentration of air pollutants. The population density is shown in 1km^2 grid. In the figures the thick contours show the distribution pattern of (a) NO_2, (b) SO_2, (c) PM_{10}, and (d) $PM_{2.5}$ whereas the thin line contours are used to show the terrain of the Kathmandu valley. Population distribution is represented by raster image and index bars.

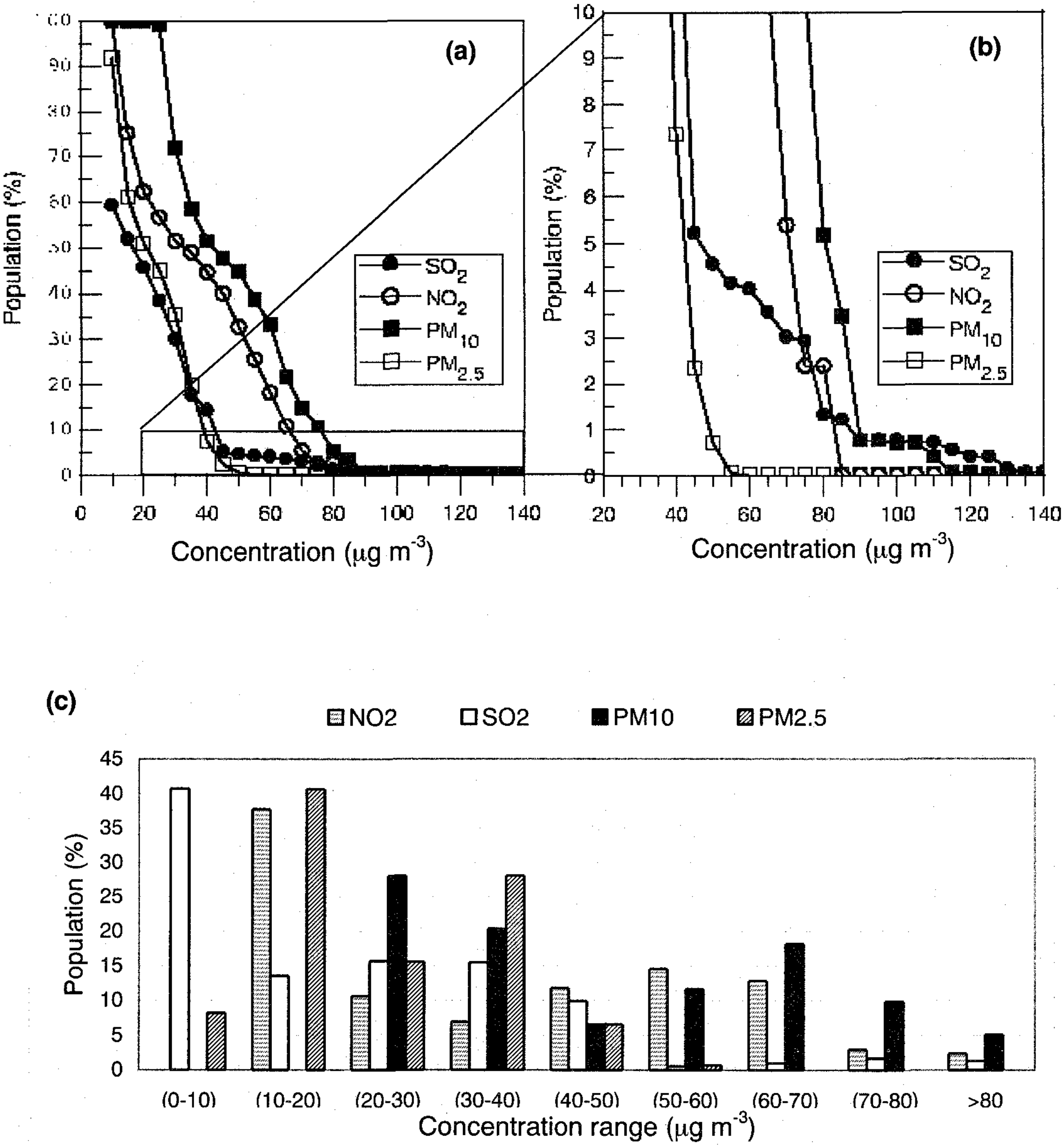

Fig.8: Relationship between the calculated pollutants levels and percentage of population exposed. (a) Covers the wide range of pollutant levels and population exposure percentage, (b) exaggerated population exposed to higher levels, and (c) distribution population exposed to various levels of calculated concentration of NO_2, SO_2, PM_{10} and $PM_{2.5}$. The total population over the study area was estimated to be 1.4 million for the year 2001.

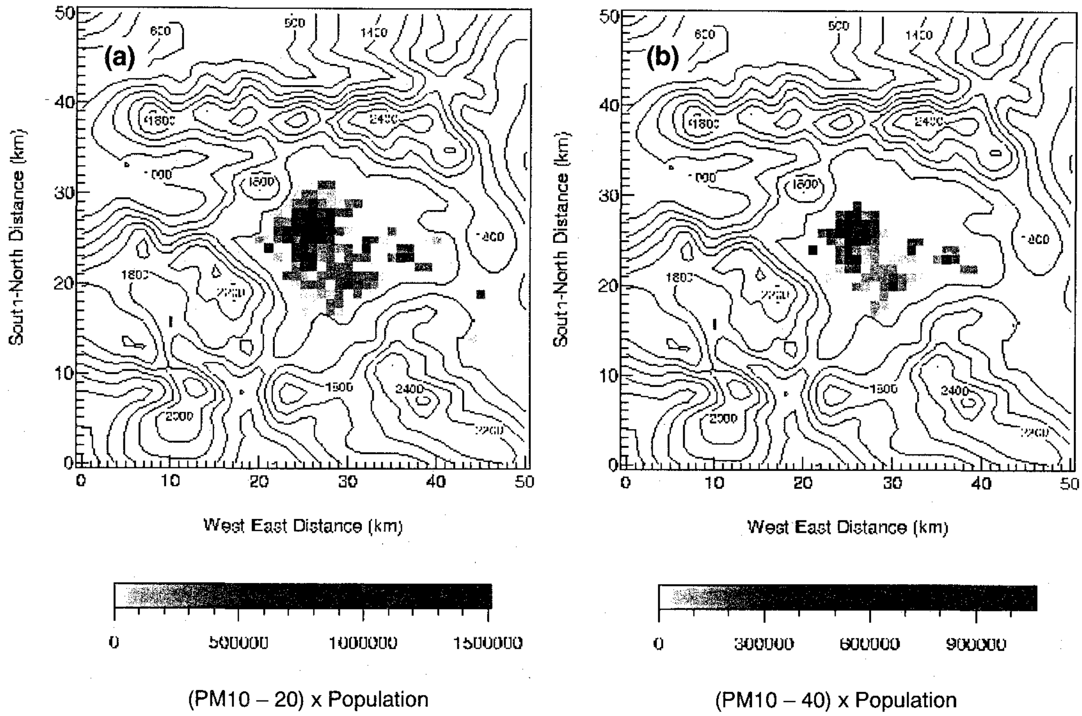

Fig. 9: Human-air pollution exposure-map of the Kathmandu valley (a) above 20μg m^{-3} and (b) above 40μg m^{-3} of PM_{10}. Population density (per $1km^2$) multiplied by excess PM_{10} concentration defined with (PM_{10}-T_k) where T_k is T_{20} (a) and T_{40} (b).

40 μg m^{-3}, respectively. It appears that high exposure strength occurs in the main urban area of Kathmandu, Patan, Thimi, and Bhaktapur cities due to the large population living in these cities whereas in the southern part of the valley the high exposure strength resulted from the higher concentration of particulate matter. The human exposure strength above 20 μg m^{-3} appears significant in almost all parts of the valley whereas the exposure strength above 40 μg m^{-3} appears to be confined in the main western and eastern urban areas as well as in the southern part of the valley. Almost negligible human exposure strength above 40 μg m^{-3} in the northern half of the valley is due to both the low PM_{10} levels and the low population density. It also appears that exposure strength above 20 μg m^{-3} is not confined within the Kathmandu valley but extends to the eastern Banepa and southeastern Panuti municipalities; this may be attributed to the transport of pollutant from the Kathmandu valley with the main stream of the westerly.

3.4 Health outcome of PM_{10} exposure

Using the procedure described in section 2.4, calculated various health outcomes for the Kathmandu residents are represented in Table 1. Although very conservative procedure has been used to estimate the health outcomes that possibly underestimate the true impact, the societal burden of ambient air pollution in the Kathmandu valley attributable to PM_{10} in terms of mortality, morbidity, hospitalization and consequent economic costs appears to be considerably high. It should be renoted that 1.4 million people in the valley is the target in the following discussion.

With the reference level of PM_{10} at 40 $\mu g\ m^{-3}$ about 60 excess deaths are attributed to the prevailing ambient level of PM_{10} in the valley and this number increases to 120 and 226 deaths per year by taking into account of 30 and 20 μgm^{-3} as lower reference levels, respectively. This means that if the PM_{10} level was at these reference levels, the corresponding deaths would be avoided immediately or could have occurred later. Attributable respiratory hospital diseases are in the same order of magnitude with some 71, 141 and 266 cases for the above reference levels. Thousands of cases of childhood bronchitis and restricted activity days as well as millions of days of episodes of respiratory symptoms appear to be the consequences of the high prevalence of PM_{10} over the valley.

Table 1: Human Health endpoints attributable to PM10 pollution over the Kathmandu valley.

Health Outcomes [a]	Reference levels of PM_{10} ($\mu g\ m^{-3}$)				
	20	30	40	41[b]	41[c]
Excess Death	226	120	60	84	55
Chronic Bronchitis	1359	722	364	506	330
Restricted Activity Days	127758	678800	342159	475298	310094
Emergency Room Visit	5230	2778	1400	1945	1269
Bronchitis in Children below 18 years	17272	9177	4625	4847	4192
Respiratory Symptoms Days	4066038	2160355	1088959	1512689	986907
Respiratory hospital diseases	266	141	71	99	65

[a] Evaluated for 1.4 million of people per year; [b] Shah and Nagpal (1997); [c] Present calculation.

The estimated number of health outcomes appears to be relatively lower than the estimation of Shah and Nagpal (1997). The less number of cases in the present estimation was due to the exclusion of emissions from a cement factory in the southwest edge of the valley as it was closed by 2001. The cement factory accounted for 36% of the total TSP emission (Shah and Nagpal, 1997). Our calculation with the cement factory emission (not discussed in the text) increased the mortality cases from 55 (see Table 1) to 115 where the reference of 41 $\mu g\ m^{-3}$ was applied for comparison since Shah and Nagpal (1997) used this number.

3.5 Air quality and health improvement perspective

Considering the exposure map (see Fig. 9a,b) high strength of exposure appears in the cities of Kathmandu and Patan. Considerable reduction in adverse health outcome could be achieved with appropriate emission control measures in transport and domestic sectors as these areas are less affected by the industrial emission, particularly from brick factories which are mostly located in the southern and eastern areas of the valley, and the prevailing southwesterly and northwesterly prevent westward transport of the brickfields emissions (Kitada and Regmi, 2003). On the other hand, for the eastern Madhayapur Thimi and Bhaktapur city areas, an effective control over brick kilns emissions should be necessary since these cities lie in the downward areas of major southwesterly and also southern brick kilns.

Current domestic fuel consumption appears to be highly dominated by kerosene in the urban areas and biomass in the ruler areas. Use of inefficient cooking stoves further enhances the domestic emission and human exposure. Improved cooking stoves as well as replacement of biomass and kerosene use with liquefied petroleum gas (LPG) for cooking and heating purpose would substantially help to reduce the total domestic emission.

Leaded gasoline that contains 0.42 to 0.82 g-Pb per liter and diesel containing as high as 1.0 percent sulfur by weight and often adulterated are normally available in Kathmandu (Adhikari, 1998). Over 33 % of the vehicle failed to comply with the standard set for 3 % CO for petrol operated vehicles and 65 % HSU (Hartridge Smoke Unit) for diesel vehicles (MOPE, 2000b). This indicates that there is immediate need to change the fuel quality for motor vehicles as well as to improve the condition of vehicles. Majority of the vehicles plying over the valley appears to be ill maintained and a decade older.

Regarding the industrial emission, more than half of the industrial units over the valley do not have even rudimentary control measures (Adhikari, 1998) including the brick industries. Nearly all the brick making facilities (about 140) have been using Bull's Trench type of kilns of less than 10 m high. Brick kilns emissions need to better managed in both the physical structure and fuel quality.

Moreover, as the detail of meteorological flows, dynamics of air pollutants and formation of pollutant fields over the Kathmandu valley has been now established (Kitada and Regmi, 2003), urban planners of Nepal may utilize these findings to minimize the air pollution impacts in the valley.

4. Conclusions

Human-air pollution exposure has been studied utilizing the numerically simulated pollutant fields and residential distribution of population over the Kathmandu valley. The numerical simulation was carried with Eulerian/chemistry/deposition model (Kitada et al, 1993 and 2000). Field observation for NO_2 and SO_2 were performed at number of sites and PM_{10} was measured at some key locations of the valley with passive samplers during February-March, 2001. Human-air pollution-exposure maps for Kathmandu valley have been produced and various health outcomes due to the prevalence of PM_{10} are evaluated. Important findings were as follows:

1. Calculation reasonably reproduced the observed spatial distribution of NO_2 and SO_2; and PM_{10} measured at some locations. Calculated diurnal characteristics of PM_{10} well captured the observed diurnal variation of TSP carried by Shrestha et al. (2001) during the period of calculation.
2. Emission inventory of NO_x, SO_2 and suspended particulate matter over the valley due to energy utilization turns out to be 3859, 2249, and 10558 metric tons, respectively, during the year 2001.

These estimated values shows that NOx, SO_2, and TSP appears to be much higher compared to previous estimations. Shrestha and Malla's estimation for the year 1993 (Shrestha and Malla, 1996) were 2199, 1988 and 6455 tons/year for NO_x, SO_2 and TSP, respectively. Likewise, Shah and Nagpal's estimation of TSP for the year 1995 was 9608 tons/year excluding the contribution of cement factory which was closed at present.

3. Calculation as well as observation reveals that the Kathmandu valley still remains relatively clean with respect to NO_2 and SO_2 except in a few locations. High concentration of NO_2 appears in the city of Kathmandu whereas SO_2 was highest in the southern brickfields. PM_{10} shows its highest concentration in the southern brickfields followed by the city of Kathmandu and eastern areas where the city of Bhaktapur is located. Calculation suggests that maximum level of PM_{10} about 135 $\mu g\ m^{-3}$ in the southern brickfields, 80 $\mu g\ m^{-3}$ around the city of Kathmandu, and 70 $\mu g\ m^{-3}$ in the eastern city area of Bhaktapur.

4. Exposure analysis reveals that around 38, 54, 0, and 49 % of population live in the areas with NO_2, SO_2, PM_{10}, and $PM_{2.5}$ less than 20 $\mu g\ m^{-3}$, respectively. Similarly, population living in areas with concentration in between 20 to 40 $\mu g\ m^{-3}$ appears to be about 18, 31, 48 and 43 %, whereas the percentage of population living in areas with concentration of these pollutants above 40 $\mu g\ m^{-3}$ turns out to be about 44, 15, 52, and 8 % in the same order. 33 percent of the people the valley are living in areas above 60 $\mu g\ m^{-3}$ PM_{10} while the percentage of people living in areas above 80 $\mu g\ m^{-3}$ PM_{10} turns out to be around 5 %.

5. Spatial exposure strength, i.e., population times concentration for PM_{10}, occurs in the main urban area of Kathmandu, Patan, Thimi, and Bhaktapur cities due to the large population living in these cities whereas in the southern part of the valley the high exposure strength resulted from the higher concentration of particulate matter as the population density is very low in the area. While the human exposure strength above 20 $\mu g\ m^{-3}$ appears significant in almost all parts of the valley, the exposure strength above 40 $\mu g\ m^{-3}$ appears to be confined in the main western and eastern urban areas as well as in the southern part of the valley. It also appears that exposure strength above 20 $\mu g\ m^{-3}$ is not confined within the Kathmandu valley but extends to the eastern Banepa and southeastern Panuti municipalities, indicating transport of pollutant from the Kathmandu valley in these areas.

6. Although, very conservative methodology was adopted to examine the health endpoints attributable to PM_{10} pollution over the Kathmandu valley, societal burden appears to be significant. With the reference level of PM_{10} at 40 $\mu g\ m^{-3}$ about 60 excess deaths could be attributed to the prevailing ambient level of PM_{10} in the valley and this number increases to 120 and 226 deaths per year by taking into account of 30 and 20 $\mu g\ m^{-3}$ as lower reference levels, respectively. Attributable hospital admissions appear with some 71, 141 and 266 cases for the above reference levels. Thousands of cases of childhood bronchitis and restricted activity days and millions of days of episodes of respiratory symptoms appear to be the consequences of the high prevalence of PM_{10} over the valley.

7. Finally, both the observation and calculation show relatively low levels of NO_2, SO_2 PM_{10} as well as health impacts attributable to PM_{10} pollution over the Kathmandu valley compared with the earlier studies carried over the Kathmandu valley during early 1990s. Perhaps, prevalence of high level of coarse dust particles in the main thoroughfares prompted earlier investigators to come up with extremely high level of air pollution in Kathmandu valley. It appears that air pollution problem

over the Kathmandu valley is the consequences of severe weakness of management in curbing the air pollution.

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