Investigation of air pollution concentration in Kathmandu valley during winter season

KONDO Akira, KAGA Akikazu, IMAMURA Kiyoshi, INOUE Yoshio, SUGISAWA Masahiko, SHRESTHA Manohar Lal, SAPKOTA Balkrishan

(1. Graduate School of Engineering, Department of Environmental Engineering, Osaka University, Japan. E-mail: kondo@env.eng.osaka-u.ac.jp; 2. Environmental Pollution Control Center, Osaka Prefecture, Japan; 3. Institute of Engineering, Pulchowk, Tribhuvan University, Nepal)

Abstract: The monthly concentrations of NO₂, NOₓ, SO₂, and O₃ measured by a passive sampler from February 2003 to January 2004 showed that the air pollution during the winter season in Kathmandu valley was higher than the summer season. The O₃ level was found the highest during April, May and June due to strong radiation. The hourly concentrations of NOₓ, NO, O₃, and suspended particulate matter (SPM) were also measured by automatic instruments on December 2003. Temperature at the height of 60 m and 400 m at Raniban Mountain in the northwest of Kathmandu valley was measured on February 2001 in the winter season and the average potential temperature gradient was estimated from observed temperature. Wind speed was also measured at the department of hydrology, airport section, from 18 February to 6 March 2001. It was found that the stable layer and the calm condition in the atmosphere strongly affected the appearance of the maximum concentrations of NOₓ and SPM in the morning, and that the unstable layer and the windy condition in the atmosphere was considerably relevant to the decrease of air pollution concentrations at daytime. The emission amounts of NOₓ, HCs and total suspended particle (TSP) from transport sector in 2003 were estimated from the increasing rate of vehicles on the basis of the emission amounts in 1993 to be 3751 t/a, 30570 t/a and 1317 t/a, respectively. The diurnal concentrations in 2003 calculated by the two-layers box model reproduced the characteristics of air pollution in Kathmandu valley such as the maximum value of O₃ in altitude, the maximum value of NO in the morning, and the decrease of NO and NO₂ at daytime. The comparison with the concentrations in 1993 calculated suggested that the main cause of air pollution was the emission from transport sector.

Keywords: air pollution concentration; Kathmandu valley; box model

Introduction

Kathmandu valley is surrounded by mountains and possesses the marvelous scenery of the Himalayas towards the northern side of the valley. It is located at the center portion of the east-west running Himalayan belt with an elevation of about 1300 m to 1400 m above sea level. It is the largest urbanized area with a population of about 1.6 million inhabitants and covers an area of about 899 km² (CBS, 2002). Due to the geographical structure like a bowl, air pollution in Kathmandu easily becomes severe. Therefore, some recent researches have focused on the air pollution problems. Air pollutants have also been the main cause of decreasing tendency of the visibility distance in the valley. Shrestha (Shrestha, 1994) analyzed the visibility of Kathmandu valley from 1969 to 1993 and showed the deterioration from 1980. URB AIR (URBAIR, 1996) reported that it has the adverse effect on the tourism industry. Sapkota (Sapkota, 2002) also showed the deterioration in the visibility. Regarding the measurement of air pollutants, Sharma (Sharma, 1992) measured total suspended particle (TSP) concentration at 15 main roadside locations and reported that its concentration was in the range of 197~525 µg/m³. Karmacharya and Shrestha (Karmacharya, 1993) also measured 24 h average concentration of TSP, SPM, SO₂, NO₂, CO and Pb at 9 roadside locations and found 182~555 µg/m³, 64~127 µg/m³, 12~36 µg/m³, <11 µg/m³ and 0.18~0.55 µg/m³, respectively. Mathur (Mathur, 1993) reported that the concentrations of TSP, SPM, SO₂, NO₂, CO and Pb from September to December were 102~867 µg/m³, 53~201 µg/m³, 13~225 µg/m³, 14~126 µg/m³, <5 ppm and 2~5 ppm, respectively. ENPHO (ENPHO, 1993) concluded that lead concentration was 0.53 µg/m³ while NO₂, CO were within WHO guidelines. NESS (NESS, 1999) reported that TSP has already increased above the acceptable limits of WHO guidelines. However, the continuous measurements throughout a year or throughout a day have not been conducted. We measured monthly NOₓ, NO₂, SO₂ and O₃ concentrations by a passive sampling for a period of one year. In addition, we measured hourly NOₓ, NO₂, O₃ and SPM concentrations by automatic instruments on December 2003. The characteristics of the observed air pollution were discussed from atmospheric stability. Emission inventories in Kathmandu valley were conducted by Shrestha and Mall (Shrestha, 1996); Adhikari (Adhikari, 1997) and Sharma (Sharma, 2000). The present emission amounts of NOₓ, SOₓ, TSP and CH₄ in 2003 were estimated from the increasing rate of vehicles on the basis of the emission amounts in 1993. NOₓ, NO₂, O₃ and SPM concentrations by using two-layer box model including photochemical reaction were calculated and compared with the measured concentrations. The aim of this study is to investigate the characteristics of air pollution in Kathmandu valley throughout the measurements, the emission inventories and the simulation.

1 Air pollutant concentration and meteorological condition in Kathmandu valley

The air pollution of Kathmandu valley was studied by measuring the air pollutant level and the meteorological condition. The monthly concentrations of NO₂, NOₓ, SO₂ and O₃ were measured by a passive sampler for a period of one year. The hourly concentrations of NOₓ, NO₂, O₃ and SPM were also measured by automatic instruments on December 2003. The hourly temperature and the hourly wind speed were measured in winter season of another year. Although the year of the concentrations measured is different
from the year of the meteorological condition measured, the characteristic of the air pollution in Kathmandu valley can be discussed from data in the different years.

1.1 Annual air pollutant concentration

Passive samplers of NO\textsubscript{2}, NO\textsubscript{x}, SO\textsubscript{2} and O\textsubscript{3} manufactured by Ogawa Incorporated, Japan, were used to know the monthly air pollution trend of Kathmandu valley from February 2003 to January 2004. The gaseous air pollutions were measured at Institute of Engineering, Tribhuvan University (IOE), Pulchok and Department of Hydrology and Meteorology (DHM), Babarmahal. The sampling locations are shown in Fig.1. Both locations are enough away from road and the passive samplers were placed at approximately 10 m above the ground level. These two locations were approximately 5 km separated. The filters of these passive samplers were changed after every 15 d.

![Measurement locations in Kathmandu valley](image)

The methods of the analysis (Ogawa, 1997) are as follows. NO\textsubscript{x} and NO\textsubscript{2} filter was kept in 8 ml of ultra pure water shaking properly for more than 10 min and 2 ml of color reagent (solution of sulfanilamide and NEDA in 10:1 ratio) was mixed in it. After cooling in ice water for 10 min and returning to room temperature, the solution was analyzed by a spectrophotometer. SO\textsubscript{2} was analyzed by keeping SO\textsubscript{2} passive filter in 8 ml of pure water and 0.2 ml of 1.75% H\textsubscript{2}O\textsubscript{2}, and occasional shaking was done. This SO\textsubscript{2} was analyzed by an ion chromatography. Similarly, O\textsubscript{3} passive filter was also kept in 5 ml pure water for 30 min while shaking occasionally and it was analyzed by an ion chromatography (ICS-1000, Dionex, USA).

The monthly average concentrations of NO\textsubscript{x}, NO\textsubscript{2}, SO\textsubscript{2} and O\textsubscript{3} are shown in Fig.2, 3, 4 and 5, respectively. Air pollutant levels of NO\textsubscript{x}, NO\textsubscript{2} and SO\textsubscript{2} were observed higher in winter season (Dec. to Feb.) than the summer season (May to Aug.). The NO\textsubscript{x} level in the valley was found from 21 ppb to 31 ppb during winter season and the lowest level of 4.5 ppb was observed during summer season. The NO\textsubscript{2} level was found from 11 ppb to 19 ppb during winter season and the lowest level of 4 ppb was observed during summer season. The SO\textsubscript{2} level was found from 13 ppb to 23 ppb during winter season and the lowest level of 3 ppb was observed during summer season. The concentration levels measured at IOE and DHM were below the WHO guidelines. The study of the Leaders Nepal (Leaders, 1998) had also reported that the gaseous air pollutants measured were below WHO guidelines. The O\textsubscript{3} level was found the highest during April, May and June. The cause is that solar radiation during these periods is very strong, though NO\textsubscript{2} level is lower than winter season. This result suggests that the effect of solar radiation is more dominant than NO\textsubscript{2} level in order to generate O\textsubscript{3}. As the concentration levels of both IOE and DHM were almost similar, these concentrations are thought to be representative values in Kathmandu valley.

![Monthly average of NO\textsubscript{x} concentration](image)

![Monthly average of NO\textsubscript{2} concentration](image)

![Monthly average of SO\textsubscript{2} concentration](image)

![Monthly average of O\textsubscript{3} concentration](image)
1.2 Diurnal air pollutant concentration

The air pollutants of NO\textsubscript{x}, NO\textsubscript{x}, O\textsubscript{3}, and SPM have been also measured by two automatic instruments (Kimoto, NA-623 and OA-683, Japan) from December 2003 at IOE. As we have concern to the period air pollution concentration becomes high, the diurnal average variations of NO\textsubscript{x}, NO, and O\textsubscript{3} concentration on December are shown in Fig. 6. NO was calculated by subtracting NO\textsubscript{x} concentration from NO\textsubscript{x} concentration. The highest concentration of NO appeared at 8 a.m. and then the highest concentration of NO\textsubscript{x} appeared at 9 a.m. After that the concentrations of NO and NO\textsubscript{x} decreased and became minimum at 12 a.m. to 2 p.m. The concentration of NO\textsubscript{x} increased again and had the second peak at 6 p.m. However, the concentration of NO was still low. The high concentration in the morning results from exhaust gas of automobile, because most nitrogen oxide emitted from exhaust gas is emitted as NO. However, the high concentration in the evening does not result from exhaust gas of automobile, because NO concentration is not high. This phenomenon is one of the characteristics of air pollution in Kathmandu valley. O\textsubscript{3} concentration became minimum at 7 a.m., increased rapidly, had the maximum value of 48 ppb at 12 a.m. and decreased linearly. The time that O\textsubscript{3} concentration attains to the maximum value is 3 h faster than Japan. The early time of the maximum concentration is also one of the characteristics of air pollution in Kathmandu valley.

![Fig. 6 Diurnal variations of NO, NO\textsubscript{x}, and O\textsubscript{3} concentration on December 2003](image)

The diurnal average variation of SPM concentration on December is shown in Fig. 7. The highest concentration of 150 µg/m\textsuperscript{3} appeared at 9 a.m. After that the concentrations decreased and reached the lowest of 35 µg/m\textsuperscript{3} at 2 p.m. The concentration increased again and had the second peak of 105 µg/m\textsuperscript{3} at 9 p.m. as well as NO\textsubscript{x}. This high concentration in the evening is presumed that the emission from household for cooking is the suspicious cause.

![Fig. 7 Diurnal variations of SPM concentration on December 2003](image)

1.3 Diurnal atmospheric stability and wind speed

The temperature on February 2001 was measured at two different altitudes of Ranibhan Mountain, which located at the northwest of Kathmandu valley (Fig. 1). This place was selected, as access is easy. Digital thermometer (MR5300, Chino Inc., Japan) was used for the temperature measurement. Two thermometers were placed at altitude of 1380 m and 1720 m from the sea level, respectively. The measurements were done at the interval of 10 min for 9 d. From these two temperatures, the potential temperature gradient, which is well used as the index of atmospheric stability, was obtained as the following method. If temperature at altitude z is T, potential temperature \theta at dry adiabatic condition is expressed by

\[ \theta = T + 0.0098z \]  

(1)

The potential temperature gradient G is roughly determined by

\[ G = \frac{\partial \theta}{\partial z} = \frac{\theta_1 - \theta_2}{z_1 - z_2} \]  

(2)

The diurnal average variation of potential temperature gradient for 9 d is shown in Fig. 8. The positive value shows the stable condition of the atmosphere while the negative value shows the unstable atmosphere. The atmosphere of Kathmandu valley is strongly stable until 9 a.m., changes to unstable condition, continues until 6 p.m. and again changes to stable condition. The time when the concentrations of NO\textsubscript{x} and TSP become high in the morning coincides with the stable period of atmosphere. The time when the lowest concentration appears on the contrary coincides with the unstable period of atmosphere. The relation between air pollution concentration and atmospheric stability can be obviously recognized, because the daily difference of temperature in winter season is intense.

![Fig. 8 Diurnal variations of potential temperature gradient on February 2001](image)

The wind velocity was measured at the department of hydrology, airport section, from 18 February to 6 March 2001. The diurnal average wind velocity is shown in Fig. 9. Wind velocity was almost calm at night time and became gradually windy after 9 a.m. The maximum wind velocity of 3.5 m/s was observed at 4 p.m. and it became calm again. Potential temperature gradient and wind velocity measured suggested that the inversion layer is strongly formed in the morning and the mixing layer is formed in daytime. These meteorological conditions are also strongly associated with air pollution concentration.

2 Emission inventories in Kathmandu valley

2.1 Emission amounts of TSP, NO\textsubscript{x}, and SO\textsubscript{x}

The main sources of TSP, NO\textsubscript{x}, and SO\textsubscript{x} are transport, household and industries. Vehicles of transport section are
classified into trucks, buses, minibuses, jeeps, tractors, cars, 3-wheels and 2-wheels. The chief industrial were brick and cement but the cement factory stopped the operation at 2000. Brick is classified into Bull Trench type and Chinese type. Shrestha and Malla (Shrestha, 1996) estimated emission amounts of TSP, NOx, and SOx for above categories from energy use in 1993. Regmi (Regmi, 2003) also estimated emission amounts of TSP, NOx, and SOx from energy use in 2001. URB AIR (URBAIR, 1996) estimated re-suspension amount of TSP from mileage data in 1993 using a emission factor of 2 g/km. The summary of these emission amounts is shown in Table 1. The number of vehicles from 1993 to 2000 is increasing at the increase rate of 12% a (BZTMO, 2001). This increase of emission amounts from transport in Table 1 approximately associate with the increase of the number of vehicles. The emission amounts from transport in 2003 when we measured air pollution concentrations were estimated from the increasing rate of vehicles. These results are also shown in Table 1. The re-suspension emission amount in 2002 becomes 3153 t/a using this increasing rate. The emission amounts from household and industrial are assumed to be the same as 2001.

Table 1 Emission amounts of TSP, NOx, and SOx

<table>
<thead>
<tr>
<th></th>
<th>1993(1)</th>
<th>2001(2)</th>
<th>2003</th>
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<tr>
<td>Transport</td>
<td>475</td>
<td>977</td>
<td>1317</td>
</tr>
<tr>
<td>Re-suspension</td>
<td>1530(3)</td>
<td>—</td>
<td>4242</td>
</tr>
<tr>
<td>Household</td>
<td>2382</td>
<td>2988</td>
<td>2988</td>
</tr>
<tr>
<td>Industrial</td>
<td>3574(615)</td>
<td>4835</td>
<td>4835</td>
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</table>

<table>
<thead>
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<th>1993(1)</th>
<th>2001(2)</th>
<th>2003</th>
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<tr>
<td>Transport</td>
<td>1353</td>
<td>3069</td>
<td>3751</td>
</tr>
<tr>
<td>Household</td>
<td>213</td>
<td>260</td>
<td>250</td>
</tr>
<tr>
<td>Industrial</td>
<td>628(127)</td>
<td>539</td>
<td>539</td>
</tr>
</tbody>
</table>

Notes: (1) Shrestha, 1996, a numeral in the parentheses from cement; (2) Regmi 2003; (3) URB AIR, 1996

2.2 Emission amounts of HCs

Shrestha and Malla (Shrestha, 1996) estimated that emission amounts of HCs from transport, household and industrial were 11024, 1281 and 1492 t/a. The emission amount from transport accounted for almost 80% of the total amount. HCs concentrations were measured 8 roadside locations on November 2003. The locations are shown in Fig. 1. The emission amount of each HCs was estimated from the proportional allotment of each HCs concentration and two assumptions. One assumption is that HCs concentration is linearly related to its emission amount from vehicles near roadside. Another assumption is that the present emission amounts of HCs have increased at the increasing rate of vehicles. The emission amounts in 2003 became 30570 t/a. HCs concentrations and HCs emission amounts are shown in Table 2. The emission amounts of PAR, OLE, TOL and XYL, which mean paraffin, olefin, toluene and xylene, respectively and are chemical substances in CBMIV (Carbon Band Mechanism IV; Gerry, 1989) which is one of the photochemical reaction model, were also estimated by the conversion rate in Table 2 and were 33440, 912, 8098 and 4216 t/a, respectively. Paraffin is much emitted from isopentane, methyl-pentane and pentane.

Table 2 Concentration of HCs and emission amount of HCs

<table>
<thead>
<tr>
<th>Name</th>
<th>Measurement, ppb</th>
<th>MW(12), EA(13), Conversion rate</th>
<th>PAR</th>
<th>OLE</th>
<th>TOL</th>
<th>XYL</th>
<th>PAR</th>
<th>OLE</th>
<th>TOL</th>
<th>XYL</th>
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<tr>
<td>Propane</td>
<td>4.79</td>
<td>9.52</td>
<td>5.22</td>
<td>1.99</td>
<td>0.17</td>
<td>0.82</td>
<td>10.24</td>
<td>22.97</td>
<td>6.97</td>
<td>42</td>
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<tr>
<td>n-Propane</td>
<td>2.9</td>
<td>3.81</td>
<td>2.29</td>
<td>0.54</td>
<td>0.21</td>
<td>0.57</td>
<td>3.64</td>
<td>5.43</td>
<td>2.42</td>
<td>44</td>
</tr>
<tr>
<td>Isobutane</td>
<td>2.21</td>
<td>3.14</td>
<td>1.79</td>
<td>0.34</td>
<td>0.07</td>
<td>0.33</td>
<td>2.89</td>
<td>6.59</td>
<td>2.17</td>
<td>58</td>
</tr>
<tr>
<td>n-Butane</td>
<td>2.63</td>
<td>3.39</td>
<td>2.66</td>
<td>0.55</td>
<td>0.1</td>
<td>0.35</td>
<td>4.09</td>
<td>9.07</td>
<td>2.86</td>
<td>58</td>
</tr>
<tr>
<td>Isopentane</td>
<td>6.08</td>
<td>6.53</td>
<td>8.18</td>
<td>1.61</td>
<td>0.13</td>
<td>0.48</td>
<td>13.42</td>
<td>28.1</td>
<td>8.07</td>
<td>72</td>
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<td>Acetone</td>
<td>6.29</td>
<td>3.95</td>
<td>5.44</td>
<td>2.66</td>
<td>2.49</td>
<td>2.1</td>
<td>2.65</td>
<td>2.72</td>
<td>3.54</td>
<td>58</td>
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<tr>
<td>n-Pentane</td>
<td>3.13</td>
<td>3.36</td>
<td>4.09</td>
<td>0.87</td>
<td>0.09</td>
<td>0.28</td>
<td>6.6</td>
<td>14.21</td>
<td>4.06</td>
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<td>2-Methylpentane</td>
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<td>2.37</td>
<td>2.9</td>
<td>0.55</td>
<td>0.06</td>
<td>0.22</td>
<td>4.88</td>
<td>11.55</td>
<td>3.09</td>
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<tr>
<td>3-Methylpentane</td>
<td>1.57</td>
<td>1.68</td>
<td>2.06</td>
<td>0.39</td>
<td>0.05</td>
<td>0.14</td>
<td>3.34</td>
<td>8.01</td>
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<td>n-Hexane</td>
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<td>2.47</td>
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<td>0.06</td>
<td>0.16</td>
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<tr>
<td>Benzene</td>
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<td>5.81</td>
<td>6.39</td>
<td>1.84</td>
<td>0.26</td>
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<td>18.0</td>
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<tr>
<td>Ethylbenzene</td>
<td>1.43</td>
<td>1.84</td>
<td>2.03</td>
<td>0.42</td>
<td>0.03</td>
<td>0.12</td>
<td>3.26</td>
<td>9.72</td>
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<td>106</td>
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<tr>
<td>n-Xylene</td>
<td>2.76</td>
<td>3.97</td>
<td>3.88</td>
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<td>0.22</td>
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<td>20.85</td>
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<tr>
<td>m-Xylene</td>
<td>2.76</td>
<td>3.96</td>
<td>3.88</td>
<td>0.93</td>
<td>0.06</td>
<td>0.22</td>
<td>7.1</td>
<td>20.84</td>
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<td>106</td>
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<tr>
<td>p-Xylene</td>
<td>0.1</td>
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<tr>
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<td>2.88</td>
<td>0.65</td>
<td>0.05</td>
<td>0.17</td>
<td>4.86</td>
<td>14.68</td>
<td>3.51</td>
<td>106</td>
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</tbody>
</table>

Notes: (1) Molecular weight; (2) emission amount
3 Simulation by box model

3.1 Model equations

In order to calculate air pollutant concentrations, we used the two-layer box model (Kim, 2001), which is based on the principle of mass conservation. It is composed of two layers in a box where the lower one is considered as the mixing layer of atmosphere and the upper layer is considered the atmosphere above the mixing layer. Four processes i.e. ventilation, surface deposition, air pollutant emissions and chemical reactions were considered in the lower layer. Two processes i.e. ventilation and chemical reactions were considered in the upper layer. The pollutants transfer process between the lower and upper layer due to the daily change in the height of the lower layer was also considered. The concept of the physical process occurring in the two layers is shown in Fig. 10.

![Fig. 10 Outline of two-layer box model](image)

The mass conservation equations for the lower and upper layer can be written by

$$\frac{dc_l}{dt} = R_1 + \frac{Q_l}{h} - D_l - V_{h_l} + \left(\frac{dc_u}{dt}\right)_{\text{loss}},$$

$$\frac{dc_u}{dt} = R_2 - V_{h_u} + \left(\frac{dc_l}{dt}\right)_{\text{loss}},$$

where the subscripts 1 and 2 represented the lower layer and the upper layer. The subscript i represented chemical species. $R$, $Q$, $D$, $V$, and $\left(\frac{dc}{dt}\right)_{\text{loss}}$ represent chemical reaction, emission, deposition, ventilation and transfer terms, respectively. Each term is given by

$$Q = \frac{E}{h},$$

$$D = \frac{c}{h} \cdot V,$$

$$V = N \cdot c,$$

$$\left(\frac{dc_l}{dt}\right)_{\text{loss}} = \begin{cases} \frac{c_2-c_1}{h} \cdot \frac{dh}{dt} & \frac{dh}{dt} > 0 \\ 0 & \frac{dh}{dt} \leq 0 \end{cases},$$

$$\left(\frac{dc_u}{dt}\right)_{\text{loss}} = \begin{cases} 0 & \frac{dh}{dt} > 0 \\ \frac{c_2-c_1}{h} \cdot \frac{dh}{dt} & \frac{dh}{dt} \leq 0 \end{cases},$$

where $E$ represents the emission flux, $h$ represents the height of the lower layer (the mixing layer), $V_h$ is the deposition velocity, $N$ is the ventilation rate, and $H$ is the vertical height of a box. CBMIV (Gerry, 1989) was used as chemical reaction model.

3.2 Model parameters

The parameter values were given as follows. The length, the width and the vertical height of a box are 1.8 km, 1.8 km and 1300 m, respectively. The height of the mixing layer is made linearly increase from 8 a.m., reaches to the maximum height of 1200 m at 2 p.m., and is made linearly decrease until 8 p.m. The height of the mixing layer from 8 p.m. to 8 a.m. is the constant of 100 m. The ventilation rate is 0.26 $m^3/\text{s}$ from the average wind speed in Fig. 9. The deposition velocities of NO, NO$_2$, O$_3$, RHs, and TSP are 0.1, 0.1, 0.6, 0.2, and 0.8 $cm/s$, respectively. The average emission fluxes of NOx and TSP are $0.0220 \times 10^{-6} m^3/(m^2 \cdot s)$ and 0.133 $\mu g/(m^2 \cdot s)$ from Table 2, respectively. The average emission fluxes of PAR, OLE, TOL and XYL are 0.465 $m^3/(m^2 \cdot s)$, 0.0127 $m^3/(m^2 \cdot s)$, 0.113 $m^3/(m^2 \cdot s)$ and 0.0592 $m^3/(m^2 \cdot s)$, respectively. The hourly emission pattern from transport was decided by traffic volume data. The hourly emission pattern from household was decided by energy use in house. The hourly emission pattern from industry was assumed to be a constant.

![Fig. 11 Diurnal variations of NO, NO$_2$ and O$_3$ concentration calculated](image)

![Fig. 12 Diurnal variations of SPM concentration calculated](image)

3.3 Simulation results

The air pollutant concentrations using the two-layer box model were calculated for three days of December 2003. The results of the day 3 are shown in Fig. 11 and 12, which corresponded to the measurement concentrations in Fig. 6 and Fig. 7. The maximum value of O$_3$ and its time, the maximum value of NO at 8 a.m. and the decrease of NO and NO$_2$ at daytime were reproduced by this model. Generally the daily patterns of air pollutant concentrations by this model could be duplicated compared with the measurement concentrations. Some disagreement can be seen in the high concentration of NO$_2$ during the night time and in the decreasing rate of O$_3$ concentration. These causes are supposed to be in that the height of the mixing layer was unsuitable. However, these
suggested that the emission amounts estimated in the section 2 were fairly good. Also regarding SPM concentration, two peaks at 8 a.m. and 9 p.m. and the daily pattern could be well reproduced by this model, though the concentration was a bit low. The cause of the high concentration at 8 a.m. is from transport, while the cause at 9 p.m. is from household owing to the formation of the stable layer, though its amount is small. This proved also that the emission amount of SPM including re-suspension was fairly good. Using the emission amounts in 1993, air pollution concentrations in 1993 were calculated by the same model. The maximum concentration of SPM increased from 74 µg/m³ in 1993 to 132 µg/m³ in 2003 and the maximum concentration of O₃ increased from 38 ppb in 1993 to 56 ppb in 2003 and the time when the maximum concentration of O₃ appears was 2 h fast. These simulation results suggest that the reduction of emission amounts from transport is most required in order to improve air quality in Kathmandu valley.

4 Conclusions

The monthly concentrations of NOₓ, NOx and SO₃ measured by a passive sampler from February 2003 to January 2004 were 15, 26 and 18 ppb in the winter season, respectively and were 4, 4.5 and 3 ppb in the summer season, respectively. The O₃ level was found the highest during April, May and June due to strong radiation. The hourly concentrations of NOₓ, NOx, O₃ and SPM were also measured by automatic instruments in December, 2003. Temperature at the height of 60 m and 400 m at Ramibhan Mountain in the northwest of Kathmandu valley was measured in February 2001 in the winter season and the average potential temperature gradient was estimated from temperature. Wind speed was also measured at the department of hydrology, airport section, from 18 February to 6 March 2001. It was found that the stable layer and the calm condition in the atmosphere strongly affected the appearance of the maximum concentrations of NOₓ and SPM at 9 a.m. and that the unstable layer and the windy condition in the atmosphere was considerably relevant to the decrease of air pollution concentrations at daytime. The low concentration of NO suggested that the maximum concentrations of NOₓ and TSP in the evening resulted from the emission from household.

The emission amounts of NOₓ, HCs and TSP from transport sector in 2003 were estimated from the increase rate of vehicles and were 3751, 30570 and 1317 t/a, respectively. The emission amounts of PAR, OLE, TOL and XYL, which were chemical species in photochemical model, were estimated from the assumption that HCs concentrations measured near roadside were linear to those emissions. The diurnal concentrations in 2003 calculated by the two-layer box model reproduced the characteristic of air pollution in Kathmandu valley such as the maximum value of O₃ and its time, the maximum value of NO at 8 a.m. and the decrease of NO and NOₓ at daytime. The calculations in 1993 and in 2003 showed the increase of maximum concentration of SPM from 74 µg/m³ to 132 µg/m³ and the increase of the maximum concentration of O₃ from 38 ppb to 56 ppb. It suggested that the main cause of air pollution was the emission from transport sector. If vehicles increase at the same increase rate, the air quality in Kathmandu valley will be worse. The maintenance of vehicles for the reduction of the emission and the improvement of roads for the reduction of re-suspension are urgently required to recover the beautiful view of Himalayan.

Acknowledgement: The authors are grateful to JSPS, Japan, for the financial supports.

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(Received for review February 24, 2005. Accepted May 8, 2005)