38. Numerical Simulation of Late Wintertime Local Flows in Kathmandu Valley, Nepal -Implication for Air Pollution Transport-

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ABSTRACT: Air pollution transport in Kathmandu valley has been investigated in reference to the observed concentration distribution of NO2 and SO2 and numerical simulation of local flow fields. The spatial distributions of NO2 and SO2 were measured in two ways: one is a 3-weeks average during 18 February to 11 March and the 1-day average on 12 April 2001 at identical sites with passive samplers. Using the PSU-NCAR Mesoscale Model MM5, initializing with ECMWF meteorological fields, meteorological conditions over Kathmandu valley has been simulated.

The simulation reasonably reproduced the characteristic late wintertime meteorological conditions of the valley as inferred from the surface observations at the Airport as well as Sodar observation. The simulation results suggest that intrusion of the cooler air masses into the valley in the afternoon resulted in shallow stable layer, in the lower part of which thermal internal boundary layer developed over Kathmandu valley. Pictures of smoke taken during the observation period confirmed that the shallow stable layer suppressed the vertical dispersion and trapped the air pollutants below 200 meters. The observed spatial distribution of NO2 and SO2 well coincided with the spatial patterns of the shallow southwesterly and northwesterly afternoon winds, intruding and merging into the westerly wind in the Basin. This suggested their major role in valley's air pollution transport thereby causing relatively high concentration in the downwind eastern area of the valley. These southwesterly and northwesterly winds are thought to be the valley winds from the southern plain area and western valley effectively channeled by underlying river gorge and low-mountain passes respectively.

KEYWORDS: Air pollution, meteorology, local flows, Kathmandu, Himalayas.

1. Introduction

Kathmandu valley, a broad circular valley in central Nepal, is located in proximity to the vast tropical Gangetic Plain in the south and Grate Himalayan chain in the north. The valley is completely surrounded by rather steeply rising mountains and hills except having a narrow river gorge in the southwest edge and a few low-mountain pass connecting neighboring valleys as depicted in Fig.1. As the other lower valleys surround the Kathmandu valley, it could execute a dual nature, i.e., it behaves as plateau during the day while as basin in the night and offers rather different characteristics of air mass circulation than the general mountain/valley wind system.

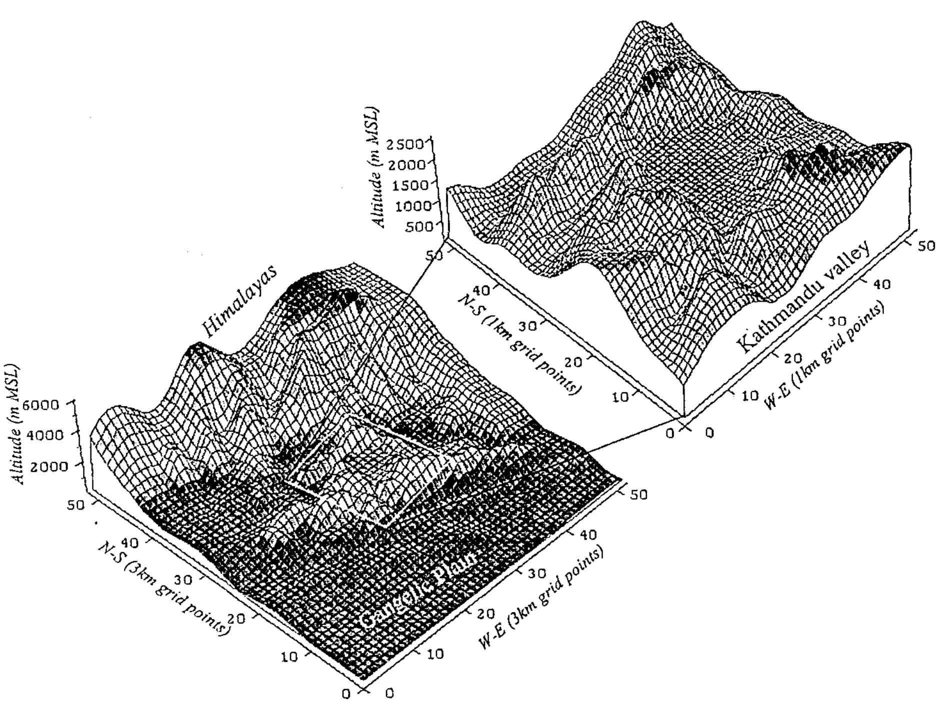

Fig.1: 3-D topographic view of Kathmandu valley and its surroundings.

Environment of Kathmandu valley is said to be undergoing rapid transformations in the last three decades and deterioration of air quality has visibly upsurge in recent years. A few preliminary attempts were made to evaluate the roadside air quality at city centers (Karmacharya and Shrestha 1993; Mathur 1993) and have shown high levels of particulate and other pollutants. However, the detail spatial distribution of air pollutants and prevailing meteorological intricacies and their implication for air pollution were not studies, so far. Thus, our primary interest in this investigation is to assess the prevailing meteorological conditions and spatial distribution of air pollutants; and to elucidate the mechanism of air pollution transport and formation of pollutant fields over Kathmandu valley.

2. Method of study

a. Spatial distribution of NO2 and SO2 pollutants

Field measurements for spatial distribution of NO2 and SO2 were conducted at 22 sites in Kathmandu valley including the eastern downwind valley Banepa in two phases at the same sites, namely, the long-term during 18 February to 11 March and the short-term on 12 April 2001 by using Green Blue Co., Japan passive samplers (see Fig.2 for locations).

b. Sodar observation

In order to understand the structure of lower boundary layer over Kathmandu valley, sodar observations were taken at the center of the Kathmandu valley (SXC) during 6 to 12 April 2001 by using a monostatic sodar, Scintec FAS64, (see Fig.2 for location).

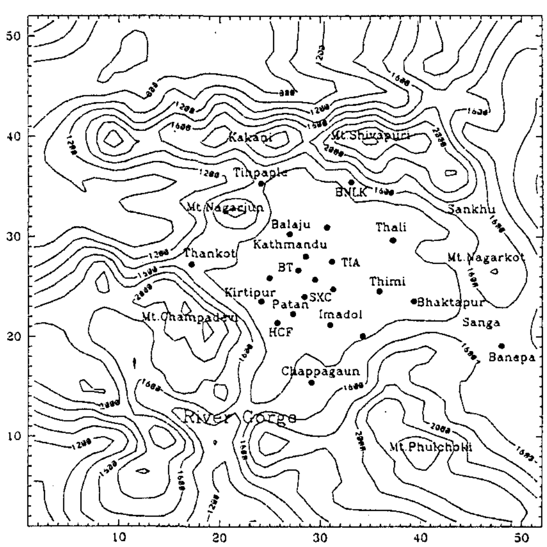

Fig.2: Terrain contours of Kathmandu valley and locations. Bullets represents sampling sites.

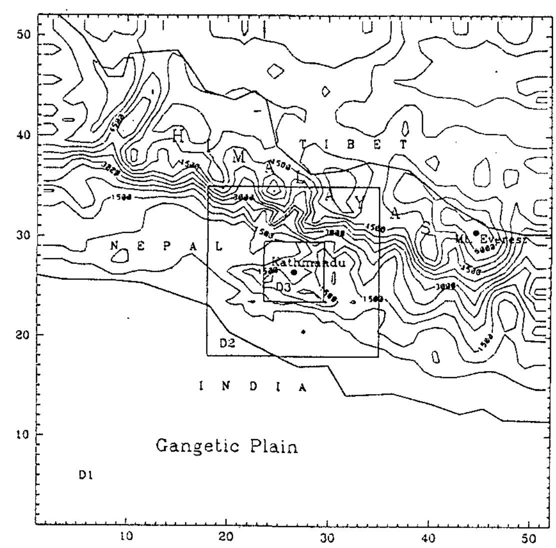

Fig.3: Domains used in the simulation. The grid increments are 9km, 3km, and 1km for domains D1, D2, and D3 respectively.

c. Numerical simulation of Meteorological conditions over Kathmandu

Four days long simulation of the meteorological conditions over Kathmandu valley was performed with the PSU-NCAR Mesoscale Meteorological Model MM5 for the period of 00 UTC 4 March to 00 UTC 8 March 2001 in order to understand the mechanism of development of local flows and to generalize the characteristic interactions and regularities of different flows that plays the important role in local air pollution transport. The domain system in this calculation consists of triply nested two-way interacting meshes each comprising 51x51x23 grids points with 9km, 3km, and 1km horizontal resolutions for coarse, fine and finest domains respectively (see Fig.3). The lowest vertical layer was set at about 40 meters above the ground level and the model top layer at 100 hPa. ECMWF global meteorological fields and USGS land-use and terrain elevation data were used in the calculation.

3. Results and discussions

a1. Characteristics of near surface wind fields over Kathmandu

An objective comparison and verification of the model prediction could not be made due to the lack of any comprehensive meteorological studies in the past. Nevertheless, simulation reasonably reproduced the late wintertime meteorological conditions over Kathmandu valley as inferred form the surface observations at the Airport (TIA) as well as sodar observation. During the four days long simulation, almost regular and systematic local flows with some minor differences pertaining to the prevailing weather conditions were predicted. As the skies of Kathmandu mostly remains clear during the dry season, we would discuss the local flow fields in the light of the most clearest day of the simulation, 6 March 2001.

Simulation showed that after the long period of calm night and morning with deep cold air lake under strong surface inversion, two valley-winds, namely, the southwesterly and northwesterly winds came into Kathmandu valley in the afternoon and merged into the westerly wind and flowed out of the valley down to the eastern Banepa valley. These southwesterly and northwesterly afternoon winds continuing till the evening are though to be the valley winds from the southern plain area and western valley effectively channeled by underlying river gorge and low-mountain passes respectively. The interesting features of these afternoon winds is that the near surface wind in the valley during the late afternoon hours is dominated by the southwesterly wind except in the western area of the valley whereas at about 250 meters above the valley floor the northwesterly wind flows over the whole valley (see Fig.4).

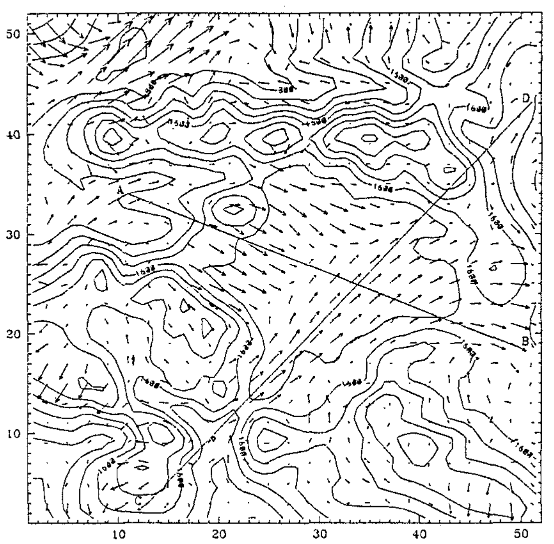

Fig.4: Predicted near surface wind field over Kathmandu valley at 1745 LST and terrain contours.

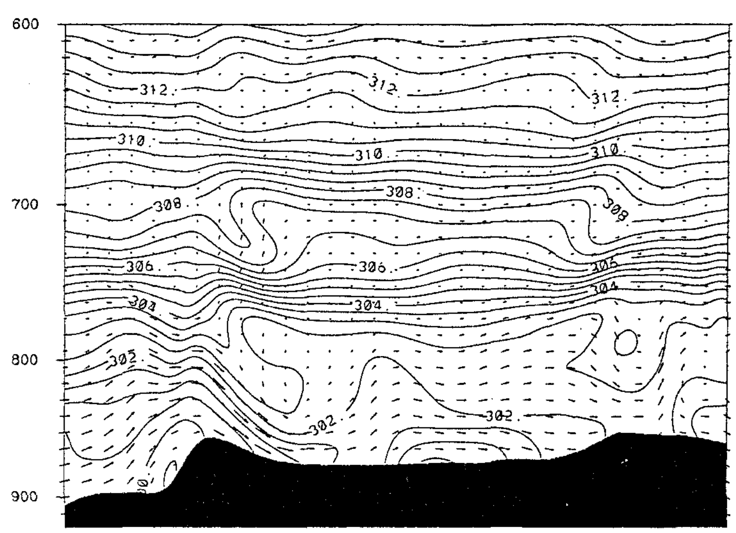

Fig.5: Cross sectional plot of potential temperature and wind vectors along the line A-B (see Fig.4) at 1745 LST.

Regular occurrence of these winds with little day-to-day variation and their strict confinement in the particular areas suggests that a constrained horizontal distribution of the air pollutants closely following the flow fields should have been resulted in Kathmandu valley. This was indeed the case to be discussed latter.

a2. Vertical structure of the valley wind over Kathmandu valley

Nature of the major afternoon winds intruding into the Kathmandu valley and their interaction need to be further examined in order to assess the mechanism of air pollution transport in the valley. The elevated mixed layer over Kathmandu just before the intrusion of the afternoon winds undergoes rapid transformations close to the surface while the upper structure of the mixed layer with pronounced inversion approximately at 700 meters largely retained its characteristics till the late afternoon (see Fig.5). This strong stable layer also exhibits the nature of a weak "critical" layer, which prohibits direct intrusion of the boundary layer air into the free troposphere.

Figures 5 and 6 show the computed cross sections of the potential temperature contours and wind vectors parallel to the cross sectional plains along the line A-B and C-D (see Fig.4) passing through the main stream of the northwesterly and southwesterly flow fields at 1745 LST. The distribution of the potential temperature contours and associated wind vectors demonstrates that both the southwesterly and northwesterly winds intruding from the river gorge and western low-mountain passes are the cooler density flows that moves into the weakly unstable mixed layer over Kathmandu valley. These afternoon winds intruding into the valley are suggested to be very shallow at the depth of 200 meters. This shallow nature of the wind was confirmed in our sodar observation.

As the shallow and cooler air masses intrude into the heated mixed layer over Kathmandu valley, they remained capped with the warm air aloft. The nose of the advancing cooler air then forms a front and convergence of the horizontal wind at the front initiates vertical motion. The smoke flow patterns (see Fig. 7) visualize an upward motion caused by the convergence of the horizontal wind at the front.

The northwesterly wind intruding into the valley from the western mountain passes exhibits a kind of hydraulic jump (see Fig 5) and appears relatively warmer compared to the southwesterly wind that makes smooth horizontal advancement into the valley (see Fig. 6). The relatively warmer northwesterly wind converging with the cooler southwesterly wind lifts up and flows over the layer of the cooler southwesterly wind. The lower potential temperature contour domes at the center of the Fig. 5 correspond to the cooler southwesterly wind towards the northeast at the crossing. The stable layer, also acting as a critical layer, at about 700 meters found to be redirecting the upward flow of northwesterly wind down to the surface in the eastern area of the valley. Thus, the shallow southwesterly wind capped by the relatively warmer northwesterly wind and presence of the strong stable layer over the whole valley in the daytime provides the basic background for the transport of the valley's air pollution.

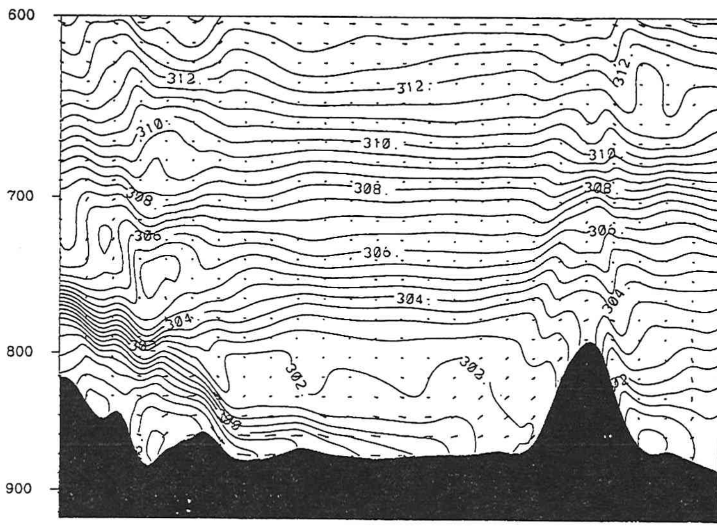

Fig.6: Cross sectional plot of potential temperature and wind vectors along the line C-D (see Fig.4) at 1745 LST.

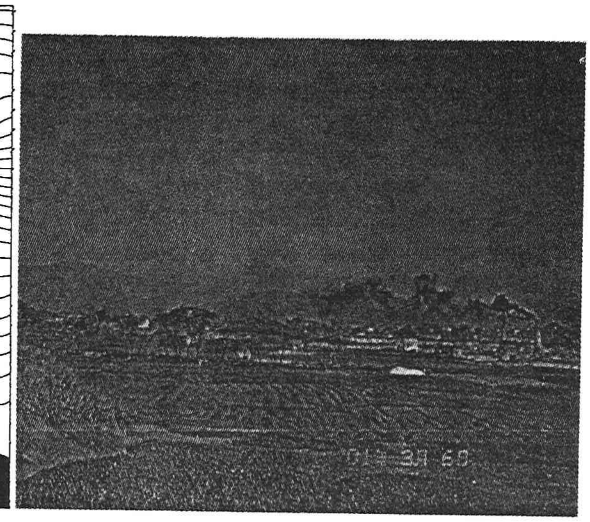

Fig. 7: Photograph of the smoke visualizing the upward motion caused by the convergence of the cool horizontal wind at its front in the afternoon, 6 March 2001.

The shallow cooler air capped with warm air potentially suppresses the vertical dispersion of the pollutants released into it, and results in high concentration near the surface level. A picture (see Fig. 8) taken in the eastern area of the valley in the late afternoon shows multiple dense smoke layering. A thick layer of pollutants appears below about 200 meters height at the center and another above 250 meters in the upper left corner of the photograph. The amicable relationship between the calculated structure of the flow field and the almost regular occurrence of such layering of pollutants close to the sunset in the eastern area of the valley indicates that the simulation captured the real atmospheric condition over Kathmandu valley on the day.

The prevailing topographic and climatic condition of the Kathmandu valley and its surroundings suggest that the mechanism of development of flow system could be the thermally induced pressure gradient driven circulations effectively channeled by underlying mountains and low-mountain passes. Such a mechanism of development of local flows over basin topographies has been proposed for a number of valleys (Atkinson 1981; Doran and Zhong 2000; Kimura and Kuwagata 1996 etc.).

During the night and morning, as the western and eastern valleys are arising from the southern plain and reaches up to the foot of the Himalayas and are also lower than Kathmandu valley (see Fig.1), the general down slope winds from the Himalayas down to the southern plain obviously find more easy ways through these valleys rather than Kathmandu. So the Kathmandu valley remains untouched by such larger scale nighttime down slope winds.

Fig.8: A photograph showing the dense smoke layers in the eastern mountain ranges of Kathmandu valley close to the sun set time, 6 March 2001.

b. Relationships between spatial distribution of air pollutants and calculated flow fields

As the vertical dispersion in Kathmandu valley is highly suppressed due to the formation of shallow internal boundary layers in the daytime and it remains calm or windless during the night and morning under strong surface inversion, the only effective transport process in the valley is the slow horizontal drifting of air pollutants caused by the shallow southwesterly and northwesterly winds intruding and merging into a westerly wind channeling out down to the eastern Banepa valley in the afternoon. In view of these meteorological characteristics, the pollutants released in the southern area should largely be confined downwind areas to the southwesterly wind and that released in the northern and western areas should be confined to the northwesterly wind and relatively high concentration should have been occurred in the eastern area of the valley.

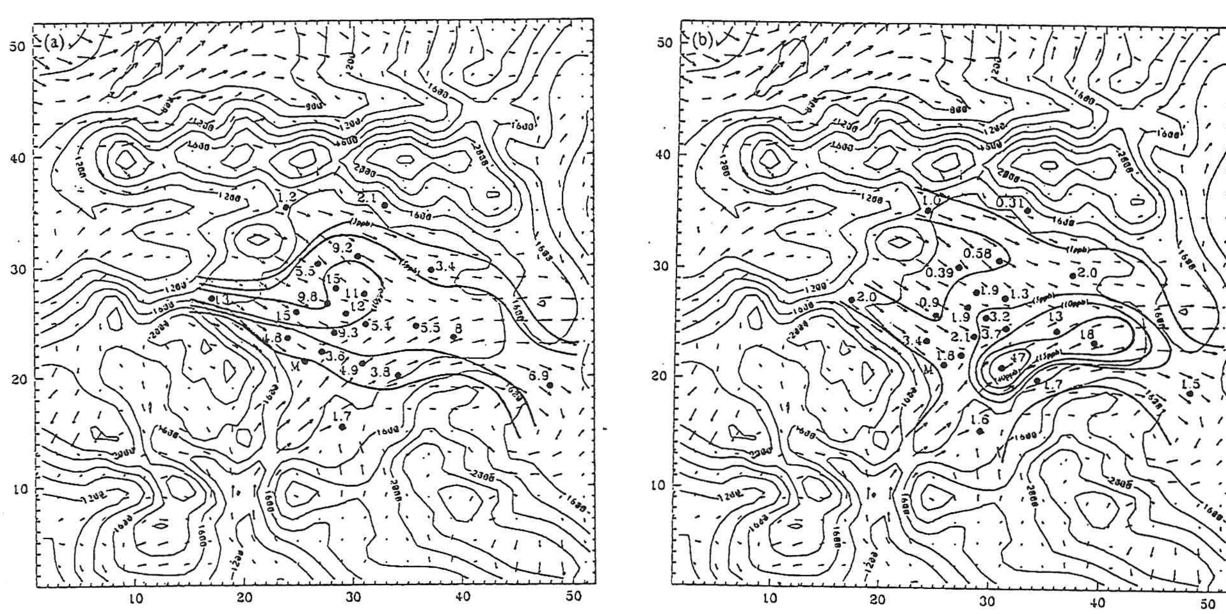

Fig.9: Measured 3-weeks average concentration distributions with simulated near surface wind fields over Kathmandu valley at 1645 LST (a) NO2 and (b) SO2. The letter (M) denotes the missing data for the site.

In order to explore such relationships, the measured concentrations of NO2 and SO2 and manually derived contours were projected on the calculated near surface wind fields for both the long and short-term measurements. Figures 8a,b show such plot for the 3-weeks averaged concentration distribution of NO2 and SO2 superimposed on the calculated near surface wind field at 1645 LST. It can be clearly seen from the figures that the concentration distribution closely follows the predicted near surface wind fields. The spatial distribution patterns of SO2 (Fig. 9a) clearly show that the pollutants emitted in the southern areas of the valley where several dozens of brick kilns are located, largely confines within the southwesterly wind sparing the main urban areas, Kathmandu and Patan. Looking at the spatial distribution of NO2 (Fig. 9b), high concentration appears in the main city area of Kathmandu and areas downwind to northwesterly wind. Moreover, we measured relatively higher concentration of both the NO2 and SO2 in the eastern cities Thimi and Bhaktapur and in the eastern valley Banepa as well.

The spatial distribution patterns of NO2 and SO2, distinctly reflecting their characteristic emission sources distribution, conform that the SO2 rich southwesterly wind stream fed by the southern brickfields and NO2 rich northwesterly wind stream capturing urban emissions merge into a westerly wind that flows down to the eastern Banepa valley carrying these pollutants. These characteristics provide the basic NO2 and SO2 field formation over Kathmandu valley.

4. Conclusions

Characteristics of the late wintertime local flows over Kathmandu valley were investigated using both PSU-NCAR Mesoscale Meteorological Model MM5 and sodar observation. With the calculated meteorological fields, observed data on air pollution such as NO2 and SO2 concentrations and photographs of smoke patterns were analyzed. Thus, air pollution characteristics over Kathmandu valley were explained in detail. Obtained results are as follows:

(1) Based on the surface wind observation at TIA, wind in Kathmandu in late winter can be characterized as calm or very weak wind during the night and morning and relatively strong wind in the afternoon up to evening. These features are reproduced reasonably well in calculated flow. Simulation shows that two valley winds, namely, the southwesterly and northwesterly, come into Kathmandu valley in the afternoon and merge into a westerly wind in the basin and flows down to the Banepa valley. These two winds are thought to be the two thermally induced valley winds originated from the southern plain and western valley effectively channeled into the Kathmandu valley by underlying river gorge and low-mountain passes. Afternoon wind over Kathmandu valley is suggested to be shallow about 200 m at the depth.

(2) The relatively warmer northwesterly wind while converging with the cooler southwesterly wind lifts up and flows over the southwesterly wind. The shallow southwesterly wind capped by the warm northwesterly wind and strong stable layer aloft the northwesterly wind creates shallow thermal internal boundary layers. We believe that these thermal internal boundary layers are responsible for the confinement of air pollutants below 200 meters as well as multiple layering of pollutants over Kathmandu in the afternoon.

(3) Calm night and morning with a deep cold air lake under strong surface inversion and formation of the shallow thermal internal boundary layers during the daytime strongly suppress vertical dispersion over Kathmandu valley all the time. Thus, the only effective transport process in Kathmandu valley appears to be the slow horizontal drifting of air pollutants towards the eastern area of the valley caused by the shallow afternoon winds. Considering these facts, it can be said that Kathmandu valley could easily reach to its saturation if substantial amount of air pollutants are continuously loaded into its atmosphere and may bring disastrous situation.

(4) The observed spatial distribution patterns of NO2 and SO2 found to be closely following the simulated flow fields. The SO2 rich southwesterly wind stream fed by the southern brickfields and NO2 rich northwesterly wind stream capturing urban emissions merge both the pollutants in the eastern part of the valley severely affecting the eastern cities and their surrounding areas.

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