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 the Kathmandu valley/basin has been investigated by numerical simulation of local flows and the observation of NO₂ and SO₂. The observation was performed at 22 sites with passive samplers from February to April 2001, and the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5) was utilized for the flow simulation. The calculation reproduced reasonably well the surface wind and temperature at the Tribhuvan International Airport (TIA) as well as the vertical wind profile taken at the center of the valley by sodar observation. The calculation showed that two characteristic local flows tend to intrude into the valley basin in the afternoon through the mountain gaps surrounding Kathmandu, that is, the southwesterly from the Indian Plain and the northwesterly from the valley west to Kathmandu. These cool wind layers meet at the center of the Kathmandu basin and form a double-layering structure there. The lower layer is shallow with a depth of about 250 m, being composed of the cooler southwesterly air mass from the Indian Plain. It was concluded that this local flow structure suppresses vertical mixing and leads to high air pollution by decreasing the daytime ventilation of air mass over the valley. The observations performed during the period confirmed it.

1. Introduction

Kathmandu valley, a broad circular valley in central Nepal, is located in proximity to the vast tropical Gangetic Plain (India) in the south and the Great Himalayan chain in the north. The valley is completely surrounded by rather steeply rising mountains and hills ranging from 500 to 1500 m above the valley floor, but has a narrow river gorge in the southwest edge and a few low mountain passes connecting neighboring valleys as depicted in Fig. 1. The relatively level valley floor situated at an average elevation of 1350 m above the mean sea level (MSL) is interspersed with shallow streams and low-flow riverbeds.

Because the other lower valleys surround the bowl-shaped Kathmandu valley, it could execute a dual nature, that is, it behaves as a plateau during the daytime by bringing the regional air masses up into the valley and as a basin during the nighttime by forming a deep cold air pool. Winter climate of the Kathmandu valley can be characterized as dry with an average maximum and minimum temperature of 17.0°C and 2.0°C, respectively. In winter, the valley skies remain mostly clear with calm or windless nights followed by dense early morning fog lingering up to 0900 or 1000 local standard time (LST). Wind regularly starts to blow in the afternoon and continues till the evening.

The environment of the Kathmandu valley has rapidly changed in the last three decades and deterioration of air quality has become clear in recent years. A few preliminary measurements of air quality at roadside in city centers have shown high levels of particulate and other pollutants (e.g., Shah and Nagpal 1996). Sharma et al. (2000) attempted to characterize nonmethane hydrocarbons in the downtown of Kathmandu city and at an eastern mountaintop. However, a detailed spatial distribution of air pollutants and the prevailing meteorological intricacies were not studied, so far. It is well known that meteorological conditions in a region often play a dominant role in building up severe air pollution even where local emission is low. Thus our primary interest in this study is to evaluate the prevailing meteorological conditions over the Kathmandu valley and to clarify their relation with air pollution transport, concentration fields of air pollutants, etc.

Because the Himalayas rise steeply from the plains, via a series of folds, up to the height of several thousand meters, a large number of small-scale subdivisions and subclimates exist in the region (Domroes 1979). The local circulations associated with these complex topographic and climatic features interact in a complicated manner. These interactions need to be sufficiently resolved in order to understand the development of local flows and transport of pollutants in the Kathmandu val-
ley. Thus, in this study the prevailing meteorological condition in the Kathmandu valley has been numerically investigated using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5). Preliminary sodar observations were also performed.

Both long- and short-term field measurements of NO$_2$ and SO$_2$ were also carried out. Calculated local flows are examined against the obtained NO$_2$ and SO$_2$ fields and relationships between the local flows and the pollutant fields is discussed in detail.

2. Method of study
   a. Spatial distribution of NO$_2$ and SO$_2$ pollutants

Field measurements for spatial distributions of NO$_2$ and SO$_2$ were conducted at 22 sites in the Kathmandu valley and its eastern downwind valley of Banepa, during dry and severe air pollution season (see Fig. 2a for the observation sites). Vertical distribution of these pollutants were also measured up to 52 m above the ground using the historic Bhensen Tower (BT) located at the center of the Kathmandu city.

Field measurements were carried for a long term (3-week average) during 18 February to 11 March and a short term (1-day average) on 12 April 2001 at the same sites using passive samplers manufactured by Green Blue Co., Japan. Sampling sites were selected to cover regional background, urban, suburbs, brickyards, and downwind areas.

b. Sodar observation

In order to understand the structure of the lower boundary layer, sodar observation was carried out during 6 to 12 April 2001 by using a monostatic sodar (Scintec FAS64, Germany). The sodar was operated continuously with a 15-min averaging time with different probing heights and resolution up to 1000 m from the top of the 15-m-high St. Xavier’s College (SXC) building located at the center of the Kathmandu valley (see Fig. 2a for location).

c. Numerical simulation

Numerical simulation of the meteorological conditions over the Kathmandu valley was performed with
The PSU–NCAR MM5 initializing with European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological data with a resolution of $2.5^\circ \times 2.5^\circ$. A 4-day-long simulation was carried out for the period of 4 March (0000 UTC)–8 March (0000 UTC) 2001. The objective of the simulation was to understand the mechanism of local flows, to generalize their characteristic interactions, and to show the regularities of the local flows that play an important role in air pollution transport. In this calculation we used 25 land use categories and 30-s terrain elevation data by the U.S. Geological Survey (USGS).

The domain system used in this calculation consists of a triply nested two-way interacting mesh. Each domain includes $51 \times 51 \times 23$ grid points, and horizontal grid size is 9, 3, and 1 km for the coarse, fine, and finest domains, respectively. Figure 2b illustrates the domain system used for the MM5 simulation. The D2 and D3 in Fig. 2b indicate the model domain 2 (fine) and the model domain 3 (finest), the topography of which are shown in Fig. 1. The three domains were all centered at $27.7^\circ$N and $85.3^\circ$E in the Kathmandu valley, and indicated by the black circle at the center of Fig. 2b. The lowest vertical layer was set at about 40 m above the ground with increasing layer depth and the top boundary of the model region was set at 100 hPa.

In implementation of MM5, the following parameterization/schemes were used: the Medium-Range Forecast (MRF) scheme (Hong and Pan 1996) for boundary layer, Grell’s method (Grell 1993) for subgrid-scale cumulus parameterization, the “simple ice” scheme (Dudhia 1989) for cloud microphysics, and the “cloud radiation” scheme (Dudhia 1989) for radiation. The cloud-radiation scheme can account for the interactions of long- and shortwave radiation with clear atmosphere, cloud, precipitation, and ground. The subgrid-scale cumulus convection parameterization (Grell 1993) was applied only for the domain 1 since the horizontal grid size were 3 and 1 km for domains 2 and 3, respectively, and these are sufficiently small for explicit resolution of cumulus convection itself. The surface energy budget was treated according to Zhang and Anthes (1982).

d. Emission source distribution and smoke flow pattern

During the period of field measurement, behavior of the smoke released from dozens of coal-burning brick kilns was closely monitored, and pictures of interesting events were frequently taken.

We have also produced the emission-strength map of $\text{SO}_2$ and $\text{NO}_x$ for the Kathmandu valley in 1 km $\times$ 1 km grids. The emission inventory is based on estimated fuel consumption in the domestic, transport, and industrial sectors during the year 2001. These estimates incorporate firsthand information on quantity and types of fuel used in major industrial sources in the Kathmandu valley and their locations except for the unregistered small cottage industries possibly using kerosene. For domestic and transport sectors, we have adopted and updated the information available in various literature, such as domestic energy per capita, the annual average daily traffic distribution on the road network, and emission factors per kilometer-vehicle-travel (e.g., Shrestha and Malla 1996).
3. Simulation results

So far, to our knowledge, no comprehensive numerical as well as experimental studies on the wintertime meteorological conditions in the Kathmandu valley have been reported. Thus, the simulation presented in this paper may be the first attempt to know characteristics of local flow systems in the area. In the following analysis, 6 March 2001 will be utilized as a typical winter day, since it was a very clear day and clear sky is usual in winter in the Kathmandu valley. For example, at the Tribhuvan International Airport observatory (TIA), located at the center of the valley, there were only three rainy days during January–March 2001.

a. Comparison of the calculated wind with observations

TIA is the only meteorological observatory in the Kathmandu valley. Though data at TIA may not be adequate for the desired comparison, the predicted diurnal variations of near-surface wind (see Fig. 3a) and temperature (Fig. 3b) showed relatively good agreement with observation at TIA (see Fig. 2a for location). Diurnal variation of the observed wind (Fig. 3a) is characterized with 1) a long period of “calm” from 1800 LST to 1000 LST on the next day and 2) onset of the wind at around 1200 LST, which continues to around 1800 LST while changing its direction from westerly to northwesterly. The calculated wind in Fig. 3a qualitatively captures these features. (Note the observed winds less than 2 kt, that is, about 1 m s\(^{-1}\), are conventionally recorded as calm. In Fig. 3a, 0 m s\(^{-1}\) is assigned to this calm.) The first feature corresponds to the stably stratified cold air lake in the Kathmandu basin during the nighttime, and the second represents arrival or intrusion of local flows, that is, the valley winds and the plain-to-plateau winds from the neighboring valley and plain. They will be discussed later.

In Figs. 3a,b, 3-week-averaged wind and temperature from 18 February–11 March 2001 at TIA are also plotted. For the 3 weeks, the long-term measurements of NO\(_2\) and SO\(_2\) were performed. The averaged values show their diurnal patterns close to those on 6 March. Thus 6 March again can be thought as a typical winter day.

Furthermore, the vertical structure of the calculated flow qualitatively agrees with the sodar-observed wind although the sodar observation was carried out on a different occasion (see Fig. 4). High wind velocity in the lower layers below about 200 m shows the local flow that arrived in the Kathmandu valley.

b. Surface wind characteristics in the valley

This section discusses the spatial and diurnal characteristics of the surface winds in the Kathmandu valley based on the calculation in the finest domain (see the inset in Fig. 1 and Fig. 2a). During the 4-day-long simulation, almost regular and systematic local flows—with some minor differences pertaining to the prevailing weather conditions—were predicted.
Figure 4. Vertical profiles of the calculated winds at various times on 6 Mar 2001 and the sodar measurement (FAS64) at 1300 LST 12 Apr 2001. Sodar observation at SXC in Fig. 2a.

At 1245 LST, the valley/upslope winds from the Indian Plain and from the western valley deeply intrude into the Kathmandu valley. These two winds, that is, the southwesterly from the river gorge and the northwesterly from the Tinpapel and Thankot low mountain passes, merge into a westerly wind in the basin. On the other hand, the wind from the eastern valley is weak and cannot penetrate into the Kathmandu valley. The reason may be that the elevation of the valley floor is higher than the Kathmandu valley (see Fig. 6) and thus the eastern valley rather behaves as a plateau for Kathmandu. The flow fields in the Kathmandu valley is dominated by the southwesterly and the northwesterly merging into the westerly wind.

At 1345 LST, the enhanced southwesterly and northwesterly winds reach to the eastern low mountain passes and flow out of the valley. During the period of 1445 to 1745 LST, the outflow through the Sanga (eastern) low mountain pass (see Fig. 2a) significantly increases. This enhanced outflow from the Kathmandu valley meets easterly/southeasterly from the Sunkoshi River valley (S) (see Fig. 12) and may develop a clockwise rotor in the southern area of the Banepa valley (see Fig. 5c).

At 1445 LST, the valley/plain-to-plateau winds in the upper layer (300 m) remain, the wind penetration into the Kathmandu valley from the eastern valley is weak and cannot penetrate into the Kathmandu valley. The flow fields in the Kathmandu valley is dominated by the southwesterly and the northwesterly merging into the westerly wind. Beyond 1845 LST, the winds in the Kathmandu valley start to vanish and the northwesterly and the southwesterly begin to decrease their areas and to split up. The western and northwestern areas of the valley are then primarily dominated by the northwesterly penetrating from the Tinpapel and Thankot low mountain passes, whereas the southern, eastern, and northeastern areas of the valley remain influenced by the southwesterly penetrating from the river gorge. At 2045 LST, both the southwesterly and the northwesterly winds appear feeble. However, the southwesterly generates a weak counterclockwise circulation covering the whole valley floor between 2045 and 2145 LST (not shown). After 2245 LST, the whole valley floor becomes calm and gradually returns to the early morning conditions described earlier.

Figure 5a illustrates the calculated near-surface wind over the Kathmandu valley in the early morning. During this period, the entire basin remains calm or windless and relatively strong downslope winds prevail in the surrounding mountain slopes. Drainage flows along the river gorge to the south and downslope wind from the Thankot and Tinpapel low mountain passes (see Fig. 2a for location) to the western valley are also visible. Within the Kathmandu basin, cool air accumulates during the nighttime and its depth may reach up to 400 m in the early morning. Because of the cold air layer, the downslope winds over the mountain slopes facing the valley floor do not penetrate below this height as shown in Fig. 5a.

The surface wind pattern over the Kathmandu valley appears essentially the same with some minor changes up to 0845 LST, but appreciable changes occur in the surrounding mountainous areas such as weakening of the downslope winds and development of upslope winds in the ridge tops after sunrise. At 0945 LST, the drainage flows in the river gorge and downslope wind toward the western valley disappear and the valley wind tends to begin toward the Kathmandu valley. At 1045 LST, the valley winds along the river gorge and the western valley approach the edge of the Kathmandu valley and at 1145 LST they start to penetrate into the Kathmandu valley (Fig. 5b). The valley floor remains calm throughout the morning and even at 1145 LST the wind is still weak at the central part of the valley.

The simulated wind fields also show that at 1745 LST the upslope/valley winds in the southern and western mountain slopes facing opposite to the Kathmandu valley appreciably decrease at the surface level by this time, and at 1845 LST they, on the whole, stop. However, since the valley/plain-to-plateau winds in the upper layer (300 m) remain, the wind penetration into the Kathmandu valley from the western mountain passes and river gorge continues and relatively strong wind prevails in the valley. It is rather interesting to note that the near-surface wind in the valley during late afternoon hours (after 1600 LST) is dominated by the southwesterly except in the western area of the valley (see Fig. 5c), whereas at about 250 m above the valley floor the northwesterly flow appears over the whole valley. Figure 5d illustrates this relation between the northwesterly and the southwesterly; that is, the warmer northwesterly rides across the southwesterly.

Beyond 1845 LST, the winds in the Kathmandu valley floor start to vanish and the northwesterly and the southwesterly begin to decrease their areas and to split up. The western and northwestern areas of the valley are then primarily dominated by the northwesterly penetrating from the Tinpapel and Thankot low mountain passes, whereas the southern, eastern, and northeastern areas of the valley remain influenced by the southwesterly penetrating from the river gorge. At 2045 LST, both the southwesterly and the northwesterly winds appear feeble. However, the southwesterly generates a weak counterclockwise circulation covering the whole valley floor between 2045 and 2145 LST (not shown). After 2245 LST, the whole valley floor becomes calm and gradually returns to the early morning conditions described earlier.
On the basis of these calculated diurnal and spatial patterns of near-surface wind, we could conclude that the major surface winds in the afternoon in the Kathmandu valley are the southwesterly and the northwesterly, which merge into the westerly wind in the basin and finally channel to the Banepa valley. If these were the typical characteristics of the near-surface wind field over the Kathmandu valley, one would expect a vertically constrained distribution of the pollutants closely following these flow fields. This will be discussed later in detail.

c. Vertical structure of the flow fields over Kathmandu

In this section, the nature of the local flows described in the previous section will be further examined in order
to assess their roles in the air pollution transport in the valley.

Vertical cross sections of the calculated winds and potential temperature (e.g., Fig. 6; A–B cross section in Fig. 5c) suggest that intrusion of the cooler air masses into the Kathmandu valley is accompanied by a mountain wave. This mountain wave may be interesting since in the western Kathmandu valley windborne disaster caused by gusty storm is occasionally witnessed in the late afternoon. It often completely uproots the matured trees, removes ordinary building roofs, and severely disturbs the human activities in the spring.

The calculation suggests the mixed layer develops up to 700–900 m over the Kathmandu valley just before the intrusion of the local winds in the afternoon. After it, the mixed layer undergoes rapid transformation in the lower layer close to the surface, whereas its upper structure largely retains its characteristics till the late afternoon (e.g., see Figs. 6 and 7). Figures 6 and 7 show the computed vertical cross sections of the potential temperature and wind along the lines A–B and C–D (see Fig. 5c) at 1745 LST passing through the main streams of the northwesterly and the southwesterly over the Kathmandu valley, respectively. It can be seen in Figs. 6 and 7 that the stably stratified layer extends to about 1000 m above the Kathmandu valley floor and it may limit the depth of the boundary layer. It should be noted that this stable layer covers an area larger than the Kathmandu valley. This strong stable layer exhibits the nature of a weak “critical” layer (Clark and Peltier 1977).

Figures 6 and 7 demonstrate that both the southwesterly from the river gorge (Fig. 7) and the northwesterly from the western low mountain passes (Fig. 6) are the cool density flows that move into the weakly unstable mixed layer over the Kathmandu valley. These winds are shallow with an approximate depth of 250 m, although the northwesterly increases its depth because of hydraulic jump (Fig. 6) as described later. Sodar observation supports this assertion (see Fig. 4).

As the shallow and cool air mass moves into the mixed layer, it remains capped by the warm air aloft. The nose of the advancing cooler air mass then forms a front and generates vertical motion, which is limited by the warm air aloft. This meteorological event was regularly manifested in the smoke flow pattern released by the brick kilns. The smoke flow pattern shown in Fig. 8 visualizes the upward motion caused by the divergence of the horizontal wind at the front. The picture was taken in the eastern area of the valley in the afternoon on 6 March 2001. It shows the smoke released by two coal-burning brick kilns flows horizontally from west to east and then moves upward at its east end.

It can also be inferred from Fig. 6 that the northwesterly from the western mountain passes exhibits characteristics of hydraulic jump. The flow appears relatively warmer compared to the southwesterly, and converging with the cooler southwesterly, it lifts up and moves over southwesterly (see Fig. 6). The area of the lower potential temperature near the surface at the center in Fig. 6 corresponds to the layer of cooler southwesterly, which is moving toward the northeast at the crossing (see Fig. 7). Thus, the near-surface wind in the valley is dominated by the southwesterly except in the western area (see Fig. 5c), while at about 250 m above the ground the northwesterly flows over the whole valley at this time.

To clarify the nature of the hydraulic jump found in Fig. 6, the following internal Froude number, $F_i$, was evaluated at two locations of the western crest and the center of the Kathmandu basin (indicated with Cr and Bo in Fig. 6):

$$F_i = \frac{V}{\left( \frac{\Delta \theta}{\theta gh} \right)^{1/2}}.$$
where $V$ denotes wind velocity, $h$ depth of cooler air layer, $\theta$ the averaged potential temperature of the layer, $\Delta \theta$ is the increase of the potential temperature across the top of the lower cooler flow, and $g$ is the acceleration due to gravity.

At the location Cr, $\Delta \theta$ is about 2 K, $\theta$ is around 300 K, $h$ is 500 m, and $V$ is 6 m s$^{-1}$; thus the Froude number can be evaluated as 1.15 and the flow is supercritical. On the other hand, at Bo (Fig. 6), a similar evaluation shows the Froude number is 0.6 and the flow is subcritical. Thus judging from this change of the flow from supercritical to subcritical, a hydraulic jump may be occurring near the location Bo.

Figure 6 shows the stable layer at the height of about 800 m, which suppresses penetration of the boundary layer air into the free troposphere over the Kathmandu valley. Thus the shallow southwesterly wind capped by the relatively warmer northwesterly and the presence of the strong stable layer over the whole valley in the daytime sets the basic meteorological background for the air pollution transport in the valley.

The vertical dispersion of the pollutants released into the southwesterly layer may be suppressed because of the stable stratification and hence the pollutants build up in the southwesterly layer. Figure 9 shows a picture taken in the eastern area of the valley in the late afternoon on 6 March 2001 and indicates multiple dense smoke layering. In Fig. 9, a thick pollutant layer appears
above about 200 m high and another one above 250 m in the upper-left corner of the picture. The formation of this hazy layering of pollutants coincides well with the calculated flow field.

d. Vertical profiles of temperature and dewpoint

Figure 10a shows the calculated vertical profiles of the temperature and dewpoint at 0545 LST in the Imadol area (see Fig. 2a for location). It could be inferred that a shallow fog layer and strong surface inversion occur in the valley during the early morning. Looking at the series of such hourly profiles on 6 March 2001, a fog layer started to build up after 0445 LST and prevailed until 0745 LST. On the same day, TIA’s weather record showed that “indistinguishable mist or shallow fog (BR)” appeared in the Kathmandu valley during 0600–1000 LST and then it turned into haze at 1030 LST. Thus the weather record qualitatively supports the calculated results.

The strong surface inversion in early morning started to erode after 0745 and disappeared at 0945 LST. Afterward, a mixed layer continued to develop and the height reached its maximum of around 1 km AGL at noon, just before the intrusion of plain-to-plateau flow into the valley. In the afternoon, because of the local flow a shallow cool layer is formed near surface level. Figure 10b shows temperature and dewpoint profiles in this situation at 1745 LST. Inversion close to the surface found in the temperatures indicates the influence of the cooler southwesterly layer. After sunset, the inversion strengthens because of radiational cooling over the Kathmandu valley.

e. Eddy diffusivity over Kathmandu valley

The calculated vertical profiles of eddy diffusivity (Fig. 11) estimates that the eddy diffusivity is small during the night and in the early morning because of the surface inversion resulting from the radiational cooling and the accumulation of cold air. It gradually increases with the morning solar heating, attaining the maximum diffusivity (about 80 m² s⁻¹) close to noon and just before the intrusion of the local winds into the valley. After the intrusion of the southwesterly and northwesterly local winds, the eddy diffusivity rapidly
decreases and beyond the late afternoon it remains weak (about 6 m$^2$ s$^{-1}$).

In consideration of these eddy diffusivity profiles, it can be said that the pollutants released into the atmosphere of the Kathmandu valley are bound close to the surface even in the afternoon. Thus, it appears that the only effective air pollution transport process in Kathmandu valley is the horizontal drifting of pollutants toward the eastern area of the valley caused by the shallow southwesterly and northwesterly winds in the afternoon till the evening.

This situation seems to be similar to that of areas affected by a sea breeze. For example, in Kitada and Kitagawa (1990), the role of the micrometeorological features such as passage of a local front associated with a sea breeze in air pollution transport and transformation has been extensively studied. In the paper it is pointed out that a cold air front and its following flow provide a shallow thermal internal boundary layer, which effectively suppresses the vertical mixing, and the passage of the front could generate complex layering structure in the pollutant fields. In other words, the pollutants released before the arrival of a sea-breeze front move up over the sea-breeze layer and lag behind the breeze, while those released into a sea breeze after the passage of the front tend to migrate with the front.

Similarly, over the Kathmandu valley, the formation of the internal thermal boundary layer in the lower part of a shallow cooler air mass and multiple layering of cold and warm air were predicted (see section 3c). The regular occurrence of the multiple smoke layers in the late afternoon in the eastern edges of the Kathmandu valley could be the consequences of such an effect (see Fig. 9).

f. Larger-scale surface wind characteristics

The intrinsic wind system in the Kathmandu valley appears to be highly influenced by the more larger-scale flow fields that develop between the Himalayas and the Gangetic Plain. Figure 12 shows the calculated near-surface wind in the afternoon for model domain 2. The flow deflection, stagnation, splitting, and acceleration are exemplifying immense topographic modification of the circulation from the plain to the Himalayas pertaining to the complex local terrain of the region.

The flow field shows that at surface level various local flows such as upslope, valley, and plain-to-plateau winds are developing under the effect of characteristic topography. It seems that over plateau areas in mountainous region those local flows are rather strong. The reason could be enhancement of the flows by effective addition of several driving forces causing plain-to-plateau wind and valley wind.

Part of the relatively strong wind along the broad Sunkoshi River valley, which arises from the Indian Plain (see Fig. 12), changes its direction to west and southwest toward a plateau of the Banepa valley. This flow develops a clockwise horizontal circulation in the Banepa valley (see Fig. 5c). Thus, it appears that the larger-scale daytime flow fields associated with the Himalayas and the Gangetic Plain effectively control the airmass circulation over the Kathmandu valley.

For the flow fields in the largest domain (not shown), in general, daytime surface winds are relatively strong and blow toward the mountainous region of Nepal and finally toward the Himalayas through several routes. In some areas, the calculation predicted very high wind speed especially in river gorges and associated valleys similar to Zängl et al. (2001). Calculation also showed remarkable asymmetry between the daytime up-valley wind and the nighttime down-valley wind in the region. The daytime wind is very pronounced and strong whereas the nighttime wind is comparatively weak.

g. Mechanism of development of local flows over Kathmandu valley

Depending upon the topography of the mountain valley and its surrounding environments, different mechanisms govern the local flows in the basins. The prevailing topographic and climatic conditions of the Kathmandu valley/basin and its surroundings indicate that the dominant flow system is thermally induced pressure gradient circulations effectively channeled by underlying mountains and low mountain passes. Such a mechanism of local flows over basin topographies has been
proposed for a number of valleys (Atkinson 1981; Doran and Zhong 2000; Kimura and Kuwagata 1993 etc.).

The Kathmandu valley being located in the middle of the Himalayas surrounded by other lower valleys (see Fig. 1), its flow system offers rather different characteristics than the general mountain valley wind system. The mixed-layer height in Kathmandu is about 700 m and is lower than that over the southern plain, which is about 1–1.2 km (see Fig. 13). Figure 13 strongly suggests that the afternoon southwesterly in the Kathmandu valley is driven by a combination of both upslope and plain-to-plateau winds. The potential temperature differences in the horizontal direction in Fig. 13, for example, about 2.5 K at 1300 m MSL and about 5 K at 200 m MSL, can be considered as an index of the driving force of the plain-to-plateau and upslope winds. For the above estimation of 5 K at 200 m, the hypothetical potential temperature at 200 m MSL at Kathmandu was assumed to be the same as that at 1300 m MSL; that is, the adiabatic lapse rate was assumed for the estimation.

4. Relationships between observed distribution of air pollutants and the calculated flow fields in the Kathmandu valley

a. Spatial distribution of air pollutants

In previous sections we pointed out that the vertical dispersion in the Kathmandu valley could be highly suppressed due to the formation of shallow internal boundary layers in the daytime and due to very weak wind and strong surface inversion during the nighttime and in the morning. The only effective transport process in the valley during the daytime is horizontal advection by the shallow southwesterly and the northwesterly that merge into a westerly in the basin and then channel out to the eastern Banepa valley.

In view of these meteorological characteristics, a vertically constrained and flow-specific distribution of pollutants should be expected. That is, the pollutants released in the southern part of the valley will largely be confined in the northeastern area, downwind of the southwesterly; while those emitted in the northern and western parts will be transported eastward by the northwesterly, and thus a relatively high concentration will be formed in the eastern part of the valley.

In order to study such relationships, contours of the measured concentrations of NO\textsubscript{2} and SO\textsubscript{2} were plotted on the calculated wind fields at near-surface level. Figures 14a,b show such plots for the 3-week-average concentration of NO\textsubscript{2} and SO\textsubscript{2}, respectively. And, similar plots for the 1-day average are shown in Figs. 14c,d.

It can be clearly seen from Figs. 14a–d that the concentration distribution closely follows the predicted near-surface wind fields in all cases. It is rather interesting to note that the distribution pattern largely remains the same for both long- and short-term observations, though these measurements were carried out a month apart. This means that the meteorological condition over Kathmandu is quite stable in winter and early spring and tends to repeat local flows. However, the overall concentration of both the pollutants in the 1-day-average is significantly higher than the 3-week averages. The possible reason will be described in the next section.

Estimated daily emissions of SO\textsubscript{2} and NO\textsubscript{x} in 1 km × 1 km grids during the winter of 2001 are shown in
Figs. 14a,b in order to help understand the relationship between the emission-source distribution and observed concentrations of SO$_2$ and NO$_x$. The annual emissions over the whole Kathmandu valley were calculated as 3859 and 2249 metric tons of NO$_x$ and SO$_2$, respectively. In the case of NO$_x$, high emission appears in the western central area of the valley (around BT in Fig. 2a) where the city of Kathmandu is located. In the case of SO$_2$, high emission can be found in the southern and eastern areas (around Imadol and Bhaktapur in Fig. 2a) and is due to the high consumption of coal in the brickyards. During the period of field measurement, we observed more than six dozen brick kilns routinely operating in the southern area of the valley and nearly an equal number in the eastern area. Scattered brickyards could be seen in the western and southwestern areas, but the northern area of the valley captures no potential emission sources.

The observed spatial distribution patterns of SO$_2$ (Figs. 14b,d) clearly show that the pollutants emitted in the southern area of the valley are largely confined within the area of the southwesterly wind. Thus the emissions from the southern brickyards appear not to have significant effect on the main urban areas of Kathmandu and Patan (see Fig. 2a for location). For the spatial
distribution of \( \text{NO}_2 \) (Figs. 14a,c), high concentrations appear in the city of Kathmandu and in the area downwind to the northwesterly. Moreover, relatively high concentrations of both \( \text{NO}_2 \) and \( \text{SO}_2 \) were observed in the eastern cities of Thimi and Bhaktapur and also in the eastern Banepa valley (Figs. 14a,b).

The observed spatial distributions of \( \text{NO}_2 \) and \( \text{SO}_2 \), distinctly reflecting their characteristic emission-source distributions (see Figs. 15a,b), agree with the possible transport characteristics that the \( \text{SO}_2 \)-rich southwesterly fed by the southern brickyards and \( \text{NO}_2 \)-rich northwesterly capturing urban emissions merge into a westerly. That the westerly carries these pollutants to the eastern Banepa valley is also predicted. These characteristics provide the basic \( \text{NO}_2 \) and \( \text{SO}_2 \) fields over the Kathmandu valley.

The vertical concentration profiles of \( \text{NO}_2 \) and \( \text{SO}_2 \) measured at the city center of Kathmandu city (see Fig. 16) show sharp gradients between 10 and 20 m. Although it could not be overly stressed because of the limited data, the vertical profiles of \( \text{NO}_2 \) and \( \text{SO}_2 \) indicate high frequency of stable stratification during the day or the presence of a stably stratified situation on average over the Kathmandu valley.

b. Possibilities of long-range transport

As can be seen in Figs. 15c,d and Fig. 16, \( \text{NO}_2 \) and \( \text{SO}_2 \) concentrations in short-term measurements are significantly higher than those in long-term measurements. This may suggest the import of pollutants during the
short-term measurement from the surrounding areas into the Kathmandu valley.

The short-term (1-day average) measurement was carried out on 12 April 2001, while the long-term (3-week average) measurement was performed during 18 February–11 March 2001. According to the World Biomass Fire Activity (World Fire Web 2002), there was a quite strong biomass fire on 10 and 11 April 2001 in the Himalayan region, while there were no such activities in February and March. Considering these facts, we speculate that our short-term measurement on 12 April 2001 picked up raise background NO$_2$ and SO$_2$ concentrations by biomass fire activities in the Himalayan region. These pollutants probably flowed into the Kathmandu valley with the valley winds discussed in the previous section. The measured high concentrations of NO$_2$ and SO$_2$ (Figs. 15c,d) at the pathways from outside of the Kathmandu valley, that is, at the northern mountain pass and the southern river gorge may support this long-range transport.

5. Conclusions

Characteristics of the late wintertime local flows over Kathmandu valley were investigated using both the PSU–NCAR MM5 and sodar observation. With the calculated meteorological fields, observed concentrations of NO$_2$ and SO$_2$, and photographs of smoke patterns were analyzed. Air pollution characteristics over Kathmandu valley were explained in detail. Obtained results are as follows:

1) Based on the surface wind observation at TIA, diurnal variation of the wind in Kathmandu in late winter can be characterized as calm during the night and in the morning, and as relatively strong local flows in the afternoon up to the evening. These features are reproduced reasonably well in the calculation. Simulation shows that two valley winds, that is, the southwesterly and northwesterly, come into the Kathmandu valley in the afternoon and merge into a westerly wind in the basin, and it flows to the Banepa valley. These two winds are thought to be the combined valley and plain-to-plateau winds originating from the southern plain and the western valley, and effectively channelled into the Kathmandu valley by an underlying river gorge and low-mountain passes. The southwesterly blowing over the Kathmandu valley is suggested to be shallow, at about 250 m in depth.

2) The northwesterly intruding from the western mountain passes shows the signature of a hydraulic jump. It is relatively warmer than the southwesterly coming from the river gorge. Since the warmer northwesterly tends to move over the southwesterly, the southwesterly is capped by the warm northwesterly and thus a shallow thermal internal boundary layer is formed in the lower part of the southwesterly. This thermal internal boundary layer may be responsible for the trapped air pollutants below 250 m in the eastern area of the Kathmandu basin. It can be concluded that advancement of the two local flows into the mixed layer developed over the Kathmandu valley caused multiple layering of pollutants.

3) During the nighttime, strong surface inversion and a deep cold-air lake would be formed under weak wind; in the afternoon the previously mentioned local flows would generate rather stable stratification. Thus the vertical diffusion of air pollutants would be suppressed. The only effective transport process in Kathmandu valley appears to be the horizontal advection toward the eastern area of the valley caused by the shallow local winds. Considering these facts, it can be said that Kathmandu valley could easily reach its saturation if substantial amounts of air pollutants are continuously loaded into its atmosphere and may bring a disastrous situation.

4) The observed spatial distributions of NO$_2$ and SO$_2$, distinctly reflecting their characteristic emission-source distributions, were found to be closely following the calculated flow fields in both long- and short-term measurements. The SO$_2$-rich southwesterly fed by the southern brickyards and the NO$_2$-rich northwesterly capturing urban emissions merge and transport the pollutants into the eastern part of the valley severely affecting the eastern cities, their surrounding areas, and also the eastern downwind valley, Banepa.

5) Considering the larger-scale flow, long-range transport of potential pollutants into the Kathmandu valley from the southern plain (Nepal and northern Indian areas) could not be ruled out. Extremely high concentrations at background sites on 12 April 2001 suggest the migration of outside pollutants into the Kathmandu valley. Since biomass fire usually becomes quite active in the Himalayan territory in April and this is the windiest month in Kathmandu, we speculate that our April measurement may have captured the background concentrations raised by the biomass fire and advected by the enhanced valley winds.

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