Diurnal cycle of air pollution in the Kathmandu Valley, Nepal: Observations

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Diurnal cycle of air pollution in the Kathmandu Valley, Nepal: Observations

 Arnico K. Panday\textsuperscript{1,2} and Ronald G. Prinn\textsuperscript{2}

Received 1 January 2008; revised 11 November 2008; accepted 28 January 2009; published 9 May 2009.

[1] During the dry season of 2004–2005 we carried out field measurements of air pollution and meteorology in the Kathmandu Valley, Nepal. We measured the trace gases carbon monoxide (CO) and ozone (O\textsubscript{3}) and particulates (PM\textsubscript{10}), as well as meteorological variables. In our field observations we noted a very regular pattern of morning and evening peaks in CO and PM\textsubscript{10} occurring daily in the valley bottom, interspersed with low values in the afternoons and at night. This pattern occurred even on days with unusual timing of emissions and was influenced by the timing of ventilation from the valley. Meteorological variables showed great day-to-day similarity, with a strong westerly wind blowing through the valley from late morning until dusk. We found that the air mass on nearby mountaintops was disconnected from pollution within the valley during the night, but received significant pollution during the morning, when up-slope flows began. At a pass on the western edge of the valley we found a diurnal switch in wind direction, with an inflow from late morning until late evening, and an outflow during the rest of the time. We found that part of the morning peak in pollution was caused by recirculation of pollutants emitted the night before, which spend the night in elevated layers over the valley.


1. Introduction

[2] Cities that are located in basins surrounded by tall mountains often face severe air pollution problems. The diurnal cycle of air pollution in those cities is often strongly influenced by the mountains. Mountains block horizontal winds that would otherwise blow locally emitted emissions away. Nighttime cooling of the mountain sides creates downslope flows of denser cold air; in wide basins this cold air can pool, suppressing vertical mixing of pollutants. Daytime heating of mountain slopes, on the other hand, creates vertical transport of pollutants up the slopes. Meanwhile horizontal flows through a basin are strongly affected by the location and orientation of mountain passes and gaps, as well as by the shape of the topography outside of the basin.

[3] Mountain-enclosed cities that are growing rapidly, and that are located in developing countries, are particularly vulnerable to air pollution problems. In recent years the international scientific community has extensively studied several such cities, including Mexico City [Bosser, 1997; Fast and Zhong, 1998; de Foy et al., 2006; McKinley et al., 2005; Molina et al., 2007; Molina and Molina, 2002; Raga et al., 2001; Shirley et al., 2006; Whiteman et al., 2006b], and Santiago de Chile [Rappengluck et al., 2000, 2005; Romero et al., 1999; Schmitz, 2005]. Other urban mountain basins in developing countries have seen much less research. We present here results from a study designed to understand the processes responsible for the accumulation and ventilation of air pollution in the Kathmandu Valley, a mountain basin in the Himalayan foothills of Nepal.

[4] We carried out field measurements in the Kathmandu Valley during the 9-month dry season from September 2004 to June 2005. Our principal goal was to understand how surface emissions and valley ventilation together shaped the observed diurnal cycles in air pollutants. We focused on continuous measurements of two primary pollutants (CO, particulates) and one secondary pollutant (O\textsubscript{3}), as well as several meteorological variables.

[5] CO is a particularly useful indicator of urban air pollution. It shares many combustion sources with particulate matter and with other urban primary pollutants. For example it is well correlated with NMHC from combustion sources [Kuebler et al., 1996; Moellman-Coers et al., 2002]. It tends to show greater spatial homogeneity [Holmes et al., 2005] than many shorter-lived pollutants whose concentration is strongly affected by local sources. In fact, compared to most urban air pollutants, carbon monoxide has a long atmospheric lifetime, from 1.1 to 2.4 months in the tropical boundary layer, and from 2.2 to 3 months in the midlatitude lower troposphere [Martin et al., 2002]. The long lifetime has several implications. The gas has often been utilized as a tracer of long distance and intercontinental pollution.
transport [Bertschi and Jaffe, 2005; Guttikunda et al., 2005; Lobert and Harris, 2002; Stohl et al., 2002]. More importantly, it meant that, on the timescale of its emission and ventilation from urban areas (hours to a day), CO could be treated effectively as an inert tracer.

[6] We measured PM$_{10}$ even though it shares many of the same combustions sources with CO, because its shorter lifetime could help us distinguish spikes in the data from local pollution sources. In addition, the portability of the PM$_{10}$ instrument allowed it to be occasionally lent to local university students for their class projects on pollution exposure, in exchange for help with simultaneous bag sampling of CO at multiple locations.

[7] Section 2 of this paper introduces the Kathmandu Valley. Section 3 describes past field research in Kathmandu. Section 4 describes our field experiment, Section 5 presents results from the field observations. Section 6 discusses these results, distilling out key questions needing further investigation. These questions are addressed through theoretical investigations using a numerical model, which are presented in a companion paper (A. J. K. Panday et al., Diurnal cycle of air pollution in the Kathmandu Valley, Nepal: 2. Modeling results, submitted to Journal of Geophysical Research, 2009).

2. Kathmandu Valley

[8] The Kathmandu Valley is located in the midhills of Nepal, halfway between the Ganges Plains and the Tibetan Plateau, at a latitude of 27.7°N. It is shaped like a circular bowl with a flat floor area of 340 km$^2$, averaging 1300 m above sea level (masl). Its total watershed area is 625 km$^2$. Surrounding the valley is a ring of mountains ranging from 2000 to 2800 m above sea level, with five mountain passes dipping down to 1500–1550 masl. There is no river inlet into the valley, and only one narrow winding outlet (the Bagmati River) at the basin floor level. Neighboring valleys to the west, north, northeast, and south have substantially lower elevations. The Kathmandu Valley’s climate is influenced by the South Asian summer monsoon. It receives up to 90% of its annual rainfall during the three summer months. During that time intense convection and heavy rains keep the valley’s air relatively clean. Air pollution is a concern largely during the remaining nine months’ dry season. A more detailed description of the Kathmandu Valley’s geography can be found in a doctoral dissertation [Panday, 2006].

[9] Over the past quarter century the Kathmandu Valley’s population has quadrupled to more than 2.5 million. Between 1990 and 2003 the total vehicle fleet grew from 45,871 to 249,282 with the number of motorcycles growing from 22,359 to 173,646 [Faiz et al., 2006]. Today the number of motorcycles exceeds three hundred thousand, while larger vehicles total more than a hundred thousand. Traffic is the biggest source of CO within the Kathmandu Valley, accounting for ~60% of the total emissions [Kitada and Regmi, 2003; Shrestha and Malla, 1996]. Rush hours are responsible for distinct morning and evening peaks in traffic and in congestion. Most of the valley’s population cooks one large meal in the morning, and one in the evening, mostly using fuel sources that produce CO (LPG, kerosene, and firewood). The third major source of CO, namely industries (especially brick kilns), do not have emissions that vary as distinctly over the course of the day.

3. Past Research in the Kathmandu Valley

[10] Air pollution in the Kathmandu Valley has become a visible problem that catches much attention, with widely publicized statistics showing a doubling in hospital admissions due to respiratory illnesses over a 5-year period, with especially large numbers recorded in the winter months [Clean Energy Nepal, 2005]. Less attention has been paid to the physical processes responsible for the accumulation and ventilation of air pollutants within the valley. Research conducted prior to our study provided only partial glimpses into what appeared to be a complex system of human-environmental interactions.

[11] Records kept at the valley-center airport show a large decrease in visibility between the late 1960s and the mid-1990s [Larssen et al., 1997]. The first published measurements of CO in Kathmandu found concentrations in the city center averaging 2 ppm, and ranging from less than 1 ppm to 2.5 ppm in winter 1982–1983 [Davidson et al., 1986]. These concentrations are not too different from what we found in 2004–2005. In 1982–1983, the vehicle fleet was very small compared to today, but a much larger fraction of households used biofuels.

[12] Several passive sampling campaigns have collected NO$_x$ and SO$_2$ data around the valley over several weeks each [Larssen et al., 1997; Leaders Nepal, 1999; Nepal Environmental and Scientific Services, 1999; Regmi and Kitada, 2003] quantifying the average pollution exposure in different regions of the valley. They generally found polluted conditions in the city and in the brick-kiln region of the valley’s southeast. One study quantified 28 non-methane hydrocarbons in 38 flask samples collected around Kathmandu [Sharma et al., 2000] and found significant weekday to weekend differences in species emitted by automobiles. High-frequency measurements of atmospheric turbidity over 21 days [Sapkota and Dhaubadel, 2002] and of condensation nuclei count over 9 days [Hindman and Upadhyay, 2002] provided some observations of the aerosol diurnal cycle. Both aerosol studies showed that the Kathmandu valley generally experienced morning and evening peaks in pollution. Hindman and Upadhyay [2002] also operated two automated weather stations in the valley for nine days, finding a regular pattern of calm nights and strong afternoon westerly winds. A team from MIT and Chalmers University ran a DOAS instrument in Kathmandu in January 2003, finding morning and evening peaks in NO$_x$ [Yu et al., 2008].

[13] As part of the Atmospheric Brown Clouds project [Ramanathan et al., 2005], two nephelometers were installed near Kathmandu in winter 2003. During their setup phase, a high-resolution micropulse lidar was run from 9 to 17 February 2003 to measure the vertical aerosol extinction profile over Kathmandu [Ramana et al., 2004]. The lidar found a layer of local pollutants near the surface, as well as an elevated layer of regional pollutants centered at 1.3 km above the surface. The same project also measured aerosol optical depth, and broadband global radiative fluxes [Ramanathan and Ramana, 2005]. The authors found aerosol optical depths in Kathmandu in the range of 0.3–0.5, and...
a diurnally averaged surface aerosol forcing of $-25\ \text{Wm}^{-2}$. They speculate that the layer of aerosols observed at 1.3 km above the surface might have been lofted by orographic flows. More recently published data of ozone and NO$_x$ measurements at Pulchowk near Kathmandu between November 2003 and October 2004 found the highest ozone levels in the premonsoon period, and the lowest in winter [Pudasainee et al., 2006]. The authors also found that ozone was higher on weekends and days with general strikes than on regular weekdays. An increase in ozone with a drop in NO$_x$ emissions suggests a VOC limited regime [Sillman et al., 1990].

[14] The only other routine air quality measurements in the valley prior to our field experiment have been gravimetric daily average PM$_{10}$ measurements carried out by the Ministry of Population and Environment at six locations since late 2002 (http://www.most.gov.np/pollution/pollution.php).

4. Experimental Setup

[15] From September 2004 until June 2005 we measured carbon monoxide, PM$_{10}$, and ozone, as well as meteorological parameters with an automated weather station and an acoustic sounder (SODAR) around the Kathmandu Valley. The temperature profile of the boundary layer was recorded by loggers installed at the top and bottom of a mountain, at four different heights on a 72-m TV tower in the valley center, near the top of another 50-m tower, and on a hill overlooking our main laboratory site. Figure 1 and Table 1 show the locations of individual sites. Table 2 provides details about the instrument deployment. Bag sampling provided information about the spatial distribution of CO. In this section we describe briefly the set up at each site.

[16] A main laboratory was set up in Kathmandu, to house the continuous monitoring instruments and to serve as a base of operations. Selection criteria for the main laboratory included that it be downwind of Kathmandu city, and that it have good security, generator back-up power supply, and public transportation access. The site also had to be surrounded by open space and thus be some distance from local pollution sources. Available space at the Hyatt Regency Hotel, which occupies 37 acres of gardens in Bouddha, met all these criteria. The southern end of the hotel building had a free-standing fire escape tower.

<p>| Table 1. Locations of Our Instrument and Sampling Sites in and Around the Kathmandu Valley |</p>
<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bouddha laboratory</td>
<td>Enclosure on Hyatt fire escape, Bouddha</td>
<td>27°43.29’N</td>
<td>85°21.42’E</td>
<td>1350 m</td>
</tr>
<tr>
<td>Hyatt roof</td>
<td>Weather station above top gable</td>
<td>27°43.27’N</td>
<td>85°21.42’E</td>
<td>1363 m</td>
</tr>
<tr>
<td>Nagarkot</td>
<td>Pipe from roof of Hotel Viewpoint</td>
<td>27°43.42’N</td>
<td>85°31.52’E</td>
<td>1972 m</td>
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<tr>
<td>Kharipati</td>
<td>Tree among fields</td>
<td>27°42.45’N</td>
<td>85°28.22’E</td>
<td>1372 m</td>
</tr>
<tr>
<td>TV tower</td>
<td>72-m-tall metal tower</td>
<td>27°41.77’N</td>
<td>85°19.60’E</td>
<td>1300 m (base)</td>
</tr>
<tr>
<td>Dharahara</td>
<td>City-center 52-m tower with park at base</td>
<td>27°42.01’N</td>
<td>85°18.70’E</td>
<td>1294 m (base)</td>
</tr>
<tr>
<td>SODAR</td>
<td>Roof of CTEVT building</td>
<td>27°46.92’N</td>
<td>85°22.47’E</td>
<td>1321 m</td>
</tr>
<tr>
<td>Hattiban</td>
<td>10-m view tower overlooking valley</td>
<td>27°37.73’N</td>
<td>85°16.41’E</td>
<td>1784 m</td>
</tr>
<tr>
<td>Pulahari</td>
<td>Pole on seven-storey tall monastery roof</td>
<td>27°44.74’N</td>
<td>85°22.49’E</td>
<td>1476 m</td>
</tr>
<tr>
<td>Bhimdhunga</td>
<td>Grassy ridge, 50 m from pass</td>
<td>27°43.58’N</td>
<td>85°13.83’E</td>
<td>1496 m</td>
</tr>
</tbody>
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Table 2. Details of the Instrument Deployment at Each Site

<table>
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<tr>
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<th>Instrument</th>
<th>Parameters Measured</th>
<th>Time Period of Deployment</th>
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<tr>
<td>Bouddha laboratory</td>
<td>Teledyne API 300EU</td>
<td>CO</td>
<td>Sep 2004 to Jun 2005</td>
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<td></td>
<td>2B Technology model 202</td>
<td>Ozone</td>
<td>Sept 2004 to Jun 2005</td>
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<tr>
<td></td>
<td>TSI Dusttrak</td>
<td>PM$_{10}$</td>
<td>Sep 2004 to May 2005</td>
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<tr>
<td>Hyatt roof</td>
<td>Rainwise Portlog</td>
<td>Temperature</td>
<td>Sep 2004 and Dec 2004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Humidity</td>
<td>2004 to Jun 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Solar radiation</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Pressure</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Rainfall</td>
<td></td>
</tr>
<tr>
<td>Nagarkot</td>
<td>Onset Hobo H8 Pro</td>
<td>Temperature</td>
<td>Jan 2005 to Jun 2005</td>
</tr>
<tr>
<td></td>
<td>2B Technology model 202</td>
<td>Ozone</td>
<td>Dec 2004, Jan and Apr 2005</td>
</tr>
<tr>
<td>Kharipati</td>
<td>Onset Hobo H8 Pro</td>
<td>Temperature</td>
<td>Jan 2005 to Jun 2005</td>
</tr>
<tr>
<td>TV tower</td>
<td>4 × Onset Hobo H8 Pro</td>
<td>Temp. at 4 levels</td>
<td>Jan 2005 to Jun 2005</td>
</tr>
<tr>
<td>Dharahara</td>
<td>Gemini Tinytag</td>
<td>Temperature</td>
<td>Jan 2005 to Apr 2005</td>
</tr>
<tr>
<td>SODAR</td>
<td>Remtech PA-0</td>
<td>Wind profiles</td>
<td>Sep 2005 and Apr 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mixed layer height</td>
<td>2005 to Jun 2005</td>
</tr>
<tr>
<td>Hattiban</td>
<td>Gemini Tinytag</td>
<td>Temperature</td>
<td>Apr 2005 to May 2005</td>
</tr>
<tr>
<td>Pullahari</td>
<td>Gemini Tinytag</td>
<td>Temperature</td>
<td>Feb 2005 to Jun 2005</td>
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<tr>
<td>Bhimdhunga</td>
<td>Rainwise Portlog</td>
<td>Temperature</td>
<td>3 times in April 2005</td>
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<td></td>
<td></td>
<td>Humidity</td>
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<td></td>
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<td>Solar radiation</td>
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<td>Pressure</td>
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<td></td>
<td>Rainfall</td>
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connected to the main building via bridges. A metal-frame- and-wood-panel enclosure was built on the fifth-floor landing of this tower. It housed our gas filter—correlation CO instrument (API 300EU, Teledyne Advanced Pollution Instrumentation, San Diego, CA), a UV-absorption ozone instrument (Model 202, 2B Technology, Boulder, CO) zero air and calibration gas cylinders (Scott Marrin and BOC Gases), computers, spare parts and tools, field sampling equipment, and, after each bag sampling campaign, filled sampling bags prior to their analysis. The optical PM$_{10}$ instrument (Dusttrak, TSI Inc, Shoreview, Minnesota) sat nearby in its own environmental enclosure. Our air sample inlet funnel was suspended 1.8 m south of the edge of the building, 12.5 m above ground, overlooking the hotel’s grounds. The nearest road and parking lot were 60 m away. The sampling inlet was located at a point which had direct views of the valley-rim mountains to the northeast, east, south, west, and northwest of the Kathmandu Valley, and where it was fully exposed to ambient winds. Additional details about the available instrument choices, instrument measurement techniques, inlet and sample line plumbing, as well as calibration procedures, are given by Panday [2006, section 2.4].

[17] An automated weather station (Portlog, Rainwise Inc., Bangor, Maine) was installed on the main roof of the Hyatt building, approximately 20 m above the ground, on its own tripod mast, at a corner of the north-south running gable of the hotel’s roof. During several days in April, May and June 2005, the weather station was alternatively deployed at Bhimdhunga Pass, on the western entrance to the valley for a few days at a time. There it was set up on a grassy ridge at the water divide of the valley, 50 m south of and 15 m higher than the road.

[18] Choosing a site for our sodar (acoustic sounder, model Pa-0, Remtech S.A., Velizy Cedex, France) required special considerations. A sodar works by emitting discrete acoustic frequencies into the atmosphere, and measuring the timing and frequency shift of the return signal to calculate the mixed layer height and vertical wind profile. The sodar antenna needed to have a clear sky view down to large zenith angles to avoid beam reflection off nearby objects. Ambient noise also had to be low, while the sodar’s loud beeping sounds should not disturb nearby residents. After evaluating 12 sites with a digital sound meter (Model 322, Center Technology, Taipei, Taiwan), we installed the sodar on the fourth-floor roof of the Council for Technical Education and Vocational Training (CTEVT) building in Sano Thimi, due east of the airport, and close to valley’s geographic center.

[19] Generally sodars perform best during the day when a convective boundary layer is topped by an inversion; they have more difficulty detecting the nighttime boundary layer height when an inversion extends down close to the ground [Beyrich, 1997; Venkatesan et al., 1995]. We also needed detailed measurements of the nighttime temperature inversions. Since tether sondes were incompatible with the daytime air traffic in the valley and helium was not readily available, we chose 1-min measurements of temperature on existing towers and on the valley rim mountains. This approach has successfully been compared with tether sondes by Whiteman et al. [2004]; inexpensive temperature loggers on basin sidewalls were found to provide good proxies for temperature soundings in a basin’s free air during times of low wind speeds and stable nighttime conditions. We used seven Hobo H8 Pro temperature loggers (Onset Computers, Bourne, Massachusetts), with external thermistors in an epoxy-potted cylinders installed inside radiation shields. These sensors have been extensively tested [Whiteman et al., 2000a], and have been used to study cold pools in the Columbia basin over horizontal scales of tens of kilometers [Whiteman et al., 2001] as well as in a tower study of drainage flows in gullies [Mahrt et al., 2001]. In addition we used two Gemini Tinytag loggers with temperature shields (Gemini Data Loggers, Chichester, U.K.). After several days of intercomparison at the laboratory in Kathmandu, one of the nine loggers was set aside for mobile measurements on the roof of a GPS-equipped automobile. Four loggers were installed 62, 48, 26, and 5 m above ground on the tallest structure at the center of the valley: the
72-m-tall Nepal Television (NTV) Metro transmission tower inside the Singhadurbar government secretariat compound.

Another logger was first installed 48 m above ground on the Dharahara tower in central Kathmandu, and then moved to Hattiban ridge (1785 masl) in early April 2005. Other temperature loggers were installed at Nagarkot Peak’s Hotel Viewpoint (1975 masl), on a tree at Kharipati (elevation 1375 masl) at the base of Nagarkot, and at Pulahari Monastery (1500 masl), on a hill overlooking the Hyatt hotel. Details of these sites are described by Panday [2006].

We only had one real-time CO instrument in Kathmandu, yet were interested in understanding the spatial heterogeneity of this trace gas, especially its concentrations upwind of the city, and on mountaintops surrounding the valley. Spatial heterogeneity of CO has previously been studied in Santiago de Chile with the help of 30 investigators spread around the city, who simultaneously filled flasks that were then analyzed at a central laboratory to provide contour maps of CO around the city [Chen et al., 1999]. To emulate this approach, we used six model 222–2301 Grab Air bag sampling pumps (SKC Inc., Pennsylvania) to fill a set of up to 190 5-L foil bags with polypropylene fittings (SKC model 245–25). We collected at least hourly samples at a number of locations around the Kathmandu Valley, over the full 24-h diurnal cycle, and then brought the samples to our main laboratory for analysis.

For this task, we collaborated with the Central Department of Environmental Science at Tribhuvan University. A typical bag sampling day saw teams of 2–3 students camping at five or six locations within the Kathmandu Valley and on surrounding passes and peaks, filling bags every 30–60 min at preset times while recording local meteorological conditions. Successful bag sampling campaigns were carried out eight times between February and May 2005. On several bag sampling days a digital camera (Nikon D70, Nikon, Japan) was set up on the Hattiban view tower for time-lapse photography of the valley fog and haze layers to help inform our meteorological analysis. Studies of the dynamics of cold air pools by photographing the heights of fog and air pollution layers viewed from mountaintops have been carried out extensively in the former Yugoslavia in the 1970s [Rakovec et al., 2002].

5. Results

Throughout the nine month study, we observed a very regular diurnal pattern in the air quality and meteorology of the Kathmandu Valley. Figure 2 shows measurements of CO at the Bouddha laboratory during 2 weeks each in October 2004 and January 2005. Several patterns stand out immediately. First, every single day showed a morning and an evening peak. The low values were similar on most days (between 350 and 500 ppb), but the morning and evening peak values showed greater variation. Second, peak values were significantly higher in January than in October. While they seldom reached 1.5 ppm in October, they
regularly approached 3 ppm in January. Third, nighttime and afternoon low values still far exceeded typical northern hemispheric clean air values; at Nepal’s latitude, clean-air tropospheric CO mixing ratios would be closer to 150 ppb (http://agage.eas.gatech.edu/images/Data_figures/gcmd_month/co_AmonS5.pdf). During our entire measurement period, CO rarely dropped below 350 ppb, with low values more frequently hovering around 500 ppb.

Figures 3–8 show data from a 48-h period in February when all instruments except the sodar functioned reliably, and when we also had a 24-h period of bag sampling, shown in Figure 3. Other locations on the valley floor, Dharahara and CTEVT, also showed the twin peak diurnal pattern found at the Bouddha laboratory. The mountaintop locations, Nagarkot and Hattiban, meanwhile, showed steady nighttime CO values around 450 ppb. At night these mountaintop sites were far above the valley floor boundary layer, so their CO measurements reflected regional background levels similar to what was found arriving in Kathmandu during the afternoon when westerly winds were sweeping into the valley. During the daytime, the mountaintop sites experienced higher, fluctuating CO values, with a very pronounced increase in the morning (presumably when the first polluted air parcels from the city started arriving). These patterns were repeated during subsequent bag sampling campaigns at these same sites and at other similar locations.

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Our meteorological observations in the Kathmandu valley help explain the observed diurnal cycle of pollutants. Figure 5 shows wind and solar radiation data from the rooftop weather station at the Bouddha laboratory. Nights were characterized by low wind speeds and varying wind directions. The highest wind speeds were reached during the afternoon, when there were consistent westerlies. Mountain basins often experience a sharp increase in wind speed at the time when the nocturnal inversion has completely dissipated [Banta and Cotton, 1981; Whiteman, 1982]. In the Bolivian Altiplano, strong inflows through the western passes (facing
toward the Pacific lowlands) have been observed a few hours after sunrise, coinciding with the transformation of a stable nocturnal boundary layer over the Altiplano into a convective boundary layer [Egger et al., 2005]. Figure 6 shows relative humidity, temperature, dew point, and barometric pressure at the same rooftop weather station. The relative humidity data (Figures 6), shows saturated conditions during early morning hours, matching our observation of fog that lasted several hours. In Figures 6b and 6c, we see daytime fluctuations in dew point temperature, suggesting arrival of different air masses. There is an afternoon dip in barometric pressure.

![Figure 4.](image-url)  
(a) CO, (b) PM$_{10}$, and (c) ozone measurements at the Bouddha laboratory from 1200 Nepal Standard Time (NST) on 9 February 2004 through 1200 NST on 11 February 2004.

![Figure 5.](image-url)  
(a) Wind direction, (b) wind speed (1-min average in black, maximum gusts in green), and (c) solar radiation measured by the rooftop weather station at the Bouddha laboratory from 1200 NST on 9 February 2004 through 1200 NST on 11 February 2004.
Figure 7 gives a visual overview of the Kathmandu Valley’s morning fog as seen from Hattiban view tower on the morning of 4 February, while collecting bag samples (Figure 4). It illustrates the formation of a thin veil of fog over the city before dawn, and its gradual thickening and lifting.

Figure 8a shows the temperature on Nagarkot Peak (1975m), and at Kharipati (1375m), at the base of Nagarkot. Nagarkot was cooler than Kharipati during the day, but warmer at night. The lapse rate, computed from the temperature difference between the two sites (Figure 8b), shows a temperature inversion at night, while from 1200 to 1500 Nepal Standard Time (NST) the lapse rate approached the dry adiabatic lapse rate, indicating a vertically well mixed atmosphere. Figure 8c shows temperature at the Bouddha rooftop weather station (1363 m) and Pullahari monastery (1476 m), while Figure 8d shows the lapse rate between the two. It is evident that the 1363–1476 m altitude layer also experienced a temperature inversion at night; in fact our TV tower temperature measurements showed stable conditions at night down to the level of 5–25 m above ground, suggesting that vertical mixing was suppressed at the elevations where most of the pollutant emissions took place. During afternoons, the TV tower loggers showed rapid fluctuations including unstable thermals (lapse rate exceeding 40 K/km), while the Kharipati and Nagarkot loggers showed an observed lapse rate approaching the dry adiabatic lapse rate of 9.8 K/km, suggesting a mixed layer of at least 600 m depth. An earlier modeling study had found the Kathmandu Valley’s mixed layer height peaking at 700–900 m above the basin bottom [Regmi et al., 2003]. Additional comparisons between loggers at the same altitude (not shown), found that during the first 2 hours after sunset, Kharipati’s temperature was 3°–5° colder than the temperature at valley center locations (Bouddha and TV tower). This is consistent with the formation of a cold air pool driven by the arrival of katabatic flows from surrounding slopes. Observations of smoke plumes on the valley rim mountains (not displayed) also consistently indicated downslope flows after sunset.

The nighttime vertical stratification within the Kathmandu Valley, and its isolation from air masses above, can be further seen in ozone measurements made alternately at the Bouddha laboratory and on Nagarkot Peak (Figure 9). Ozone levels in Nagarkot did not go to zero at night. This is consistent with ozone observations on remote mountaintops in Arizona [Fast et al., 2000], China [Gao et al., 2005] and Thailand [Pochanart et al., 2001]. At mountaintop locations at night there is insufficient NO to titrate ozone. Often there are additional inputs of ozone from the free troposphere, in contrast to the valleys below, which are isolated at night by stable air [Baltensperger et al., 1997].

Unfortunately between November 2004 and April 2005 the sodar was at the manufacturer’s for repairs. Figure 10 shows sodar data for 11 and 12 May 2007. Other data collected in May (not shown) indicates that, except for warmer temperatures, lack of morning fog, and longer daylight hours, these days in May were very similar to the February days discussed above. While the sodar was capable of estimating the mixed layer height to an altitude exceeding 1000 m, its measurement of wind speed and direction was usually confined to the bottom few hundred meters. Nevertheless, the sodar data shows several patterns that augment what we observed with the weather station on the Hyatt roof in Bouddha. The afternoon westerlies are confined close to the surface. After 2200 NST much weaker...
easterlies push underneath the westerlies, producing a rising region of wind shear. These weak easterlies are seen throughout the night. In the mornings the wind direction changes several times, with some distinctly visible southerlies.

Figure 11 shows 48 h of sodar observations of the mixed layer height above central Kathmandu Valley in May 2005. The sodar-derived mixed layer height was found to be very regular from day to day, peaking between 700 and 1000 m on most days when we had observations, consistent with the temperature logger findings of a mixed layer reaching at least the height of Nagarkot Peak. This is relatively low compared to the height of more than 2 km that is often found over the United States [Berman et al., 1999] and India [Krishnan and Kuhnhikrishnan, 2004], and also significantly lower than what is often found over Mexico City [de Foy et al., 2006]. It is possible that the surprisingly low sodar observations of afternoon mixed layer height in the Kathmandu Valley were due to the limited range of the Pa-0 sodar and its inability to capture the full height of the mixed layer. An alternative explanation will be discussed in a companion paper (Panday et al., submitted manuscript, 2009), where model results show the afternoon westerly winds bringing cooler air into the Kathmandu Valley, creating renewed stratification.

Figures 12a and 12b show wind direction and wind speed at Bhimdhunga Pass on the western valley rim in April 2005. The wind switched back and forth between daytime westerlies (from about 1000 to 2200 NST), and nighttime easterlies. We hypothesize that the nighttime easterlies at the pass began at the time when the valley’s cold air pool filled up to the level of the pass. Our time-lapse photography from Hattiban ridge indicated that the top of the Kathmandu Valley’s winter fog layer matched the height of the passes. The fog has also been observed flowing out across the western passes in the morning and dissipating while descending into the neighboring western...
The descending motion outside the pass indicates that “overflow” of the Kathmandu Valley cold pool across the passes occurs. In several studies elsewhere, cold pools in basins have been found to fill up to the elevation of the height of the lowest mountain barrier [Allwine and Lamb, 1992], from where they can overflow [Neff and King, 1989]. As we shall see later, the Bagmati valley outflow, which is lower than the western passes, has too small a cross section to allow the cold air pool to drain off.

Figure 12c shows CO measurements made simultaneously at the main laboratory in Bouddha, and (with bag sampling) at Bhimdhunga Pass and Nagarkot Peak. Shortly after midnight on 20 April, the main laboratory in the basin

Figure 9. Ozone measurements before and after the instrument was moved from Bouddha (blue) to Nagarkot (black) in (a) December 2004, (b) January 2005, and (c) April 2005.
bottom, Bhimdhunga Pass, and Nagarkot Peak all had similar CO concentrations. However, CO concentrations at Bhimdhunga Pass rose by almost 50% (to 1.8 ppm) from 0000 to 0400 NST while they remained low at the other two sites. Given the lack of local sources, there is only one plausible explanation for this rise in CO observed at the pass, namely, that the easterly winds arriving at the pass were bringing air that had been at the surface within the

Figure 10. Vertical profiles of (a and c) wind direction and (b and d) wind speed on 11 May 2005 (Figures 10a and 10b) and 12 May 2005 (Figures 10c and 10d) as measured by the sodar. Wind speeds are coded in gray scale, with darker shades indicating stronger winds. Wind directions are coded in color, with reddish colors indicating westerly and bluish colors indicating easterly flows. All times in NST.

Figure 11. The mixed layer height measured by the SODAR in Sano Thimi during a typical 48-h time period in May 2005. The sodar’s lower detection limit was 50 m above ground.
Figure 12. (a) Wind direction on Bhimdhunga Pass in April 2005. (b) Minute average wind speed (black) and maximum gusts (green) on Bhimdhunga Pass during the same days. (c) CO measurements at the laboratory in Bouddha, and CO measured with bag sampling on Bhimdhunga Pass and Nagarkot Peak during the same days.

Figure 13. Air photo of fog at Bhimdhunga (BP) and Nagdhunga (NP) passes from the northwest. The fog-covered Kathmandu Valley is in the left half of the middle ground. The Bagmati outflow valley (BV) is in the upper right, and the fog-covered Ganges Plains are in the background.
Kathmandu Valley and polluted by the city during the evening before.

6. Discussion

[34] The results presented in the previous section indicate that the Kathmandu Valley’s air quality and meteorology show a lot of day-to-day similarity. There is a morning and an evening peak in CO and PM$_{10}$ every day, while ozone decreases to zero in the valley bottom at night. Afternoons are marked by strong westerly winds, while at night there appears to be a pooling of cold air in the basin bottom up to the level of the western passes. Here we consider several questions in order to understand this pattern better.

[35] First, why is there such a regular twin peak pattern in CO and PM$_{10}$ in the valley bottom in Kathmandu? Morning and evening peaks in urban CO have been observed in some other cities as well, including in Bangkok [Zhang and Oanh, 2002], Santiago de Chile [Rappenglück et al., 2000, 2005; Schmitz, 2005], Buenos Aires [Bogo et al., 2001], Athens [Gros et al., 2002], and at times in Hong Kong [Wang and Kwok, 2003]. In southern California [Qin et al., 2004] and in Brisbane [Morawska et al., 2002] morning and evening CO peaks were found to be stronger on weekdays than on weekends. Often the observed peaks were found to be a direct result of local rush-hour traffic emissions; in Buenos Aires and Santiago de Chile the peaks correlated very well with traffic volumes.

[36] Figure 14 compares daily CO variations on four consecutive days in January 2005. If the morning and evening peaks were directly correlated with traffic or cooking, they would be found at the same time each day. Instead, on Tuesday and Wednesday, 11 and 12 January, the morning peak dropped off sharply around 0900 NST, while on Thursday and Friday, 13 and 14 January, the morning peak reached a maximum shortly after 0900 NST and did not drop off until 1000 NST. Office and school start and end times did not vary substantially from one day to the next, and neither did the rush-hour traffic patterns. We also see that the evening CO peaks began around 1800 NST, even though the heaviest evening rush-hour traffic took place just after 1700 NST. It is also worth noting that the morning peak often began shortly after 0600 NST (at dawn), even though morning traffic and cooking activities remained light until at least 0800 NST. It is thus clear that the twin peak pattern was not just simply result of morning and evening peaks in emission.

[37] Looking back at Figure 2a, we see additional evidence that the CO peaks were not simply caused by traffic or cooking. Days 20 through 25 October 2004 were the main days of the Dashain festival, when hundreds of thousands of people left the Kathmandu Valley to return to their ancestral villages, while offices remained closed. People stayed home or visited relatives, and cooked the morning meal later than usual. There were therefore no morning or evening rush hours. Yet the morning and evening peaks in CO are still visible on these days. The existence of the peaks was thus not a result of diurnal emissions patterns alone. We see, however, that the peak values were lower on the holidays, indicating that emissions volumes might have had an effect on the peak amplitude observed among different days in October. However, because there was no seasonal difference in traffic between a regular weekday in October and a regular weekday in December, emission volumes do not explain the difference between peak amplitudes in these 2 months.

[38] The diurnal cycle of atmospheric CO concentrations near the ground can be affected by factors other than local CO emissions. For example, CO from biomass combustion in rural Thailand was found to have nighttime highs and daytime lows due to reduced nighttime ventilation caused by inversions [Pochanart et al., 2003]. During a year of street-side measurements in Buenos Aires, Argentina [Bogo et al., 2001], days with no wind had higher nighttime values.
of CO, and higher morning peaks. Downwind of Bangkok, Thailand, the heights of the morning CO peaks are strongly dependent upon wind direction [Zhang and Oanh, 2002]. In spring 2002, CO canister sampling upwind, within, and downwind of Santiago de Chile [Rappenglück et al., 2005] found distinct morning and evening peaks within the city, with minimum values at noon, like we found in Kathmandu. An earlier study in Santiago de Chile indicated that there were no evening CO peaks during the summer, because there was still strong ventilation at the time of rush hour [Rappenglück et al., 2000]. It is likely that the winter evening peaks in Kathmandu were taller because of an earlier suppression of ventilation. The pattern observed in Kathmandu appears to be strongly affected by the timing and mechanism of ventilation.

Returning to Figure 4, we see that the prominent noontime spike in ozone on 10 February was accompanied by concurrent small peaks in CO and PM$_{10}$. Figure 15 zooms in to show that the increase in westerly wind speed at 1218 NST on 10 February apparently initiated a small peak each in ozone and CO that was then followed by larger broader peaks in both gases from 1230 to about 1252 NST. The average wind speed from 1130 to 1217 NST was 2.0 m/s, but from 1218 to 1252 NST it was 4.9 m/s. After 1252 NST it was even faster. On the basis of the wind data and Kathmandu Valley geography, we hypothesize that when the stronger westerly winds began, they carried the polluted air mass that had previously been stationary over the city toward the east and past the instruments in Bouddha. The initial peak marked the arrival of polluted air from the nearby Chabahil Ring Road intersection. This was followed by a trough indicating cleaner air from the residential area immediately west of there, and then by a broad peak marking the arrival of polluted air from the main city farther west. The distance from the Bouddha site to the western edge of the city is 10 km. At 4.9 m/s, it would take 34 min to cross the city: that was almost exactly the duration of the ozone and CO peaks. We thus have evidence that the observed peaks in pollution corresponded to rapid transport past our Bouddha sensors of the air mass that had been almost stagnant over the city during the morning. The drop in pollutant concentrations after 1252 NST happened once the tail end of that polluted air mass had gone past the measurement station. From that time onward, throughout the afternoon, the sensors appeared to be measuring air that had initially been upwind of the city (including outside of the western passes), and that had then traversed the city rapidly, picking up less CO and other ozone precursors over the city, while having less time to form ozone in situ by the time of its arrival at the Bouddha laboratory.

The afternoon dip in CO and PM$_{10}$ concentrations in Kathmandu is clearly a result of westerly winds sweeping through the valley. These winds bring cleaner air through passes such as Bhimdhunga on the west, and sweep the valleys’ pollutants out toward the east. But why do pollutant levels drop at night? Figure 16 shows PM$_{10}$ at the time of the Shivaratri festival on 8 March, when hundreds of bonfires were lit at dusk. Unfortunately we don’t have reliable CO data from those days. In the evening of 8 March, we see much higher PM$_{10}$ values than on adjacent evenings. By 2100 NST most of the fires had been extinguished. We see PM$_{10}$ values decrease during the night; however record-high PM$_{10}$ values we measured again the next morning despite the absence of fire emissions. The only plausible explanation is that aerosols emitted by the fires the previous night had returned to the surface observation site after initially having been transported away. This recirculation of pollutants also helps explain why we see the morning peak in pollutants appearing shortly after dawn, even though the peak in cooking and traffic emissions does not happen until several hours later. But where do the pollutants go during the nighttime?

Let us consider the hypothesis that the city’s polluted air mass might follow nighttime drainage flows down the
Bagmati River Valley, and then return to the city when the wind direction in the Bagmati River Valley reversed in the morning. This hypothesis can easily be rejected: drainage flows leaving the Kathmandu Valley down the Bagmati River must flow through the very narrow Chobhar Gorge, and simple dimensional analysis shows that unrealistic supersonic wind speeds would be needed to drain the entire polluted air mass of the valley through the Chobhar Gorge outlet over the course of one night.

What we did observe, and frequently photograph at dawn, were elevated polluted layers over the Kathmandu Valley. Nighttime elevated layers of pollutants have been measured at the top of skyscrapers in Phoenix [Berkowitz et al., 2006] and Milan [Rubino et al., 1998], and by sampling air with a customized tethersonde in Japan [Sahashi et al., 1996]. Elevated layers of aerosols have also been observed over the Rhine Valley [Frioud et al., 2003]. In Figure 12, we saw that at Bhimdhunga Pass, 200 m above the valley floor, CO levels rose after midnight. That was after the evening peak at the valley bottom had subsided, and two hours after an easterly wind had started transporting Kathmandu Valley air out of the pass. Could this rise in CO at the pass indicate the arrival of a lifted layer of CO from the valley bottom?

Figure 17 shows CO bag sampling results at 3 different elevations during the night of 4–5 April at the Boudhda laboratory on the valley bottom, at Pullahari monastery (150 m higher), and at Hattiban (600 m above the valley bottom). During the night, shortly after the evening CO peak subsided in Boudhda around 2300 NST, CO started to rise in Pullahari, and after 0200 NST it started to rise in Hattiban as well. Since Pullahari and Hattiban have no local sources of CO, the observation indicates the arrival of a polluted air mass. This could have been advected horizontally from elsewhere, or it could be pollutants originating in the Kathmandu Valley that are lifted up. Seeing in Figure 17 that CO levels started rising first at the lower-elevation site in Pullahari, let us assume for the moment that we are indeed seeing a nocturnal lifting of pollutants originating in the Kathmandu Valley bottom. What mechanism could lift these during the night, in the presence of a stable cold air pool?

Could pollutants from the valley bottom be lifted by mechanical turbulence? Turbulence in stable nocturnal boundary layers is generally not caused by surface heating, but by shear in the nocturnal jet. A field study involving a 60-m-high instrumented tower near Wichita, Kansas, found turbulence in the stable nocturnal boundary layer that was created by wind shear and that was increasing with height [Mahrt and Vickers, 2002]. Substantial vertical mixing within stable layers is also possible owing to internal gravity waves [Monti et al., 2002; Stull, 1988]. Turbulent transport, like any diffusive process, only happens if there is a gradient in the tracer being transported. For turbulence to be able to transport nighttime pollutants away from the surface, CO concentrations must decrease with altitude. Although we did not have the capability to carry out vertical soundings of CO, we did collect bag samples at several locations near the top of the Kathmandu Valley’s nighttime cold air pool. A look at Figures 12 and 17 shows that CO concentrations at higher locations (Pullahari, Bhimdhunga, Hattiban) exceeded CO concentrations at the valley bottom (as measured at the Boudhda laboratory) for extended periods. In fact concentrations rose at Pullahari, while they continued to drop in Boudhda. Vertical transport appeared to continue for several hours beyond the time when the gradient was reversed. We can thus exclude turbulent transport as the primary agent of nighttime CO removal from the valley bottom.

A more likely explanation of the observed nighttime lifting in pollutants as suggested by the observed low values in the valley bottom and the rising values at higher
elevations is based upon the mechanism that forms the cold air pool in the valley bottom in the first place. This is illustrated in Figure 18. Radiative cooling of mountains generates downslope (katabatic winds) which lead to a pooling of cold air in the basin bottom, as seen in the temperature data (Figure 8a). While doing our field experiments, we observed plumes of smoke on valley rim slopes heading downhill during the evening, indicating such katabatic winds. Parcels of relatively clean cold air arriving in the city from the valley rim mountains flow underneath the less cold, less dense air parcels that are already there, lifting the latter up along with the pollutants they contain. The air parcels that were heavily polluted in the evening rise higher and higher as colder cleaner airflows underneath that is less polluted by the few emissions sources that remain on all night. In the morning, the elevated pollutants mix down again as the growing mixed layer entrains elevated layers of polluted air. We see in Figure 17 that around 0500 NST in Pullahari, and 0600 NST in Hattiban, concentrations of CO dropped suddenly to similar levels found at the Bouddha laboratory, where the CO was starting to rise to a morning peak. This is consistent with the dilution that takes place

![Figure 17](image-url)

**Figure 17.** Bag sampling CO data from 4–5 April 2005 at Pullahari and Hattiban, along with CO measurements at the Bouddha laboratory during the same time period. The horizontal axis spans from 0448 NST on 4 April through until 1912 NST on 5 April.

![Figure 18](image-url)

**Figure 18.** Idealized time sequence illustration of deduced circulation, showing the (top) nighttime lifting and (bottom) morning downward mixing of pollutants. The cities of Kathmandu, Bhaktapur, and Dhulikhel are marked by the letters K, B, and D, respectively. At the eastern and western ends of the valley, both passes and peaks are shown.
when elevated pollutant layers are mixed downward as they are entrained into a growing mixed layer in the morning. [46] To be viable, this explanation does need to pass one check: If the katabatic winds were transporting cold air from the valley-rim mountains to the basin bottom, they would also be bringing in a fresh supply of ozone. Achieving the observed near-zero ozone levels found at the Buddha laboratory at night would require an efficient ozone removal mechanism along the way. Since NO emissions are most likely small late at night (and hence the reaction of NO with ozone is small), we would need ozone to be removed by dry deposition before the cold air arrived at the Buddha measurement location. Even with the low nighttime wind speeds, converging katabatic winds would arrive at the Hyatt sensors from the valley rim base in, at most, a few hours. The katabatic flows would be following the surface, traveling underneath layers of air from which ozone would already have been largely removed. Thus they would not have any en-route replenishment. Existing literature [Lagzi et al., 2004; Matsuda et al., 2005; Sorimachi et al., 2003; Zhang et al., 2002] suggests that agricultural lands (as found between the valley-rim slope and the Hyatt sensors) have ozone dry-deposition velocities on the order of 0.2 cm/s, or 7.2 m/hour. Given that katabatic flows are only a few meters thick, this implies an ozone deposition lifetime of less than 1 h, thus providing a reasonable mechanism for the removal of ozone from air masses arriving at the Hyatt measurement station at night. We conclude that the cold air streaming down the valley rim mountains at night is the most plausible explanation for the clean (low CO, PM$_{10}$ and ozone) ground-level air observed at the Kathmandu Valley bottom between midnight and dawn, and the rising pollution levels observed higher up. In the morning, once the mixed layer starts to grow, the elevated polluted air is mixed down again. This helps explain the early start of the morning pollution peak.

7. Conclusion

[47] We carried out field observations of air pollution in the Kathmandu Valley during the dry season of 2004–2005. We noted that carbon monoxide, as a tracer of anthropogenic emissions, had a distinct diurnal pattern of morning and evening peaks. During the afternoon, the valley was ventilated by strong westerly winds entering through the western passes. In the evening emissions in the valley accumulated in the city and its environs. Late at night, the city air quality improved again, as polluted surface layers appeared to be lifted up owing to the convergence of cleaner colder air into the city driven by katabatic flows on the valley rim slopes. In the early morning, as the mixed layer started to grow, the elevated pollutants were mixed back down into the city.

[48] Analysis of our observations indicates that the twin peak pattern existed owing to an interplay between the timing of emissions and ventilation. The morning peak decreased when the strong westerly winds removed pollutants that had accumulated in the city over the course of the mornings. Our observations do not tell us the pathways of pollutant ventilation out of the valley. They also do not give us a complete picture of the dynamics of the valley’s daytime mixed layer, and nighttime cold air pool. These topics are investigated using the numerical model MM5 in a companion paper (Panday et al., submitted manuscript, 2009).

[49] Although local emissions within the valley play an important role in creating pollution peaks, our CO measurements on mountaintops and Bhimdhunga Pass, as well as the high minimum CO levels ever recorded at the Bouddha laboratory make it clear that there is significant background air pollution present that comes to the Kathmandu Valley from elsewhere. Part of it may be from biofuel combustion in rural Nepal, while part of it is likely to originate in the Ganges Plains.

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