CLIMATE AND AIR QUALITY: A CASE STUDY OF PM_{10} POLLUTION IN KATHMANDU, NEPAL

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1. INTRODUCTION

High concentrations of lower atmospheric pollution (e.g. ozone, lead, and particulate matter) pose a threat to the health of the inhabitants of the Kathmandu Valley, Nepal. (16, 17) Prolonged exposure may lead to respiratory infection and lung inflammation, with the most drastic result being irreversible changes in lung structure and chronic respiratory illness. Those most prone to pollution-related afflictions are children, due to prolonged exposure, and the elderly, due to enhancement of pre-existing respiratory diseases. (12) Because of such threats, high levels of lower atmospheric pollution across the Kathmandu urban area have been of interest to Nepalese scientists and local government agencies over the past decade. (16, 17) In order to combat the problem of air pollution, the Ministry of Population and Environment (MoPE) is interested in a better understanding of the climatological conditions that foster high levels of air pollution in Kathmandu. The ultimate goal of this understanding is an improved forecast model for air pollution, particulate matter specifically. Such a model can provide for better protective measures for all at-risk populations.

Like other growing urban centers, the Kathmandu metropolitan area is particularly susceptible to episodes of high concentrations of particulate matter (PM_{10}). But such high concentrations are likely not solely due to the rapidly growing population. Both the climate and the physical geography of the area must also be considered along with the human aspect in the context of this particular environmental problem. From a human geography perspective, it is clear that the large population of automobile users and industries within the Kathmandu metropolitan area are significant sources of PM_{10}. (4) However, the occurrence of high concentrations of PM_{10} across Kathmandu is likely critically dependent upon both the climate and the physical geography of the region. However, to date, no quantitative studies have been performed to examine the air quality situation in Kathmandu (16).

This article aims to examine the complex interactions between intraseasonal variations in climate and PM_{10} levels so that relevant processes can be understood more fully, thereby enabling better air quality policy decisions. Therefore, the importance of this case study is two-fold: 1) this study defines the linkages between seasonal climatological conditions at the micro- and macro- scales and PM_{10} levels in Kathmandu Valley; and 2) the results of this study provide important insight into future pollution advisory forecasts in metropolitan Kathmandu. Additionally, this study will aid government officials in their efforts to improve pollution transport forecasts as further urban growth in Kathmandu may potentially lead to higher pollution levels that are detrimental to the inhabitants of this area. Given these factors, a better understanding of the natural climatic mechanisms that contribute to PM_{10} transport is essential.

2. BACKGROUND INFORMATION

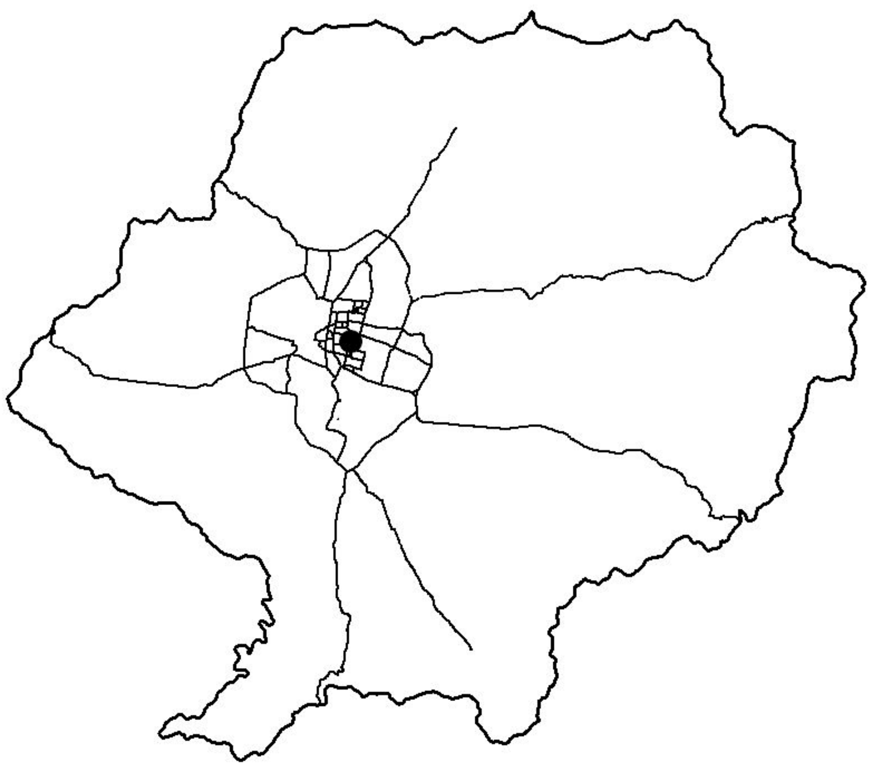
The Kathmandu Valley, which is bowl-like in topography, is about 25 kilometers (km) from east to west and roughly 20 km from north to south. Kathmandu lies at a height of around 1300 meters, while the surrounding mountains range from 1500 meters to 2800 meters in height (Figure 1). The complex topography of Kathmandu often dictates the flow of the lower atmosphere (5, 16), and as the Kathmandu area is situated in a valley surrounded by significantly higher terrain, air pollution dispersion is often limited. While the wet Indian monsoon dominates Nepal in mid- to late-summer, the location of the region under an area of predominant high pressure in winter (19) and early summer results in a consistent lack of a strong background circulation on the synoptic scale. This also precludes significant mixing of the atmosphere and transport of aerosols away from the urban area. (16, 17) The problem of pollution dispersion in an urban area of complex topography is becoming better understood, primarily due to concerns over air quality in Phoenix, Arizona and Los Angeles, California. (3, 10, 11, 14, 18) However, the mechanics of pollution dispersion have been poorly studied in cities of developing nations.

It is thought that the movement of lower atmospheric aerosols within the urbanized valley often follows a distinct pattern. It is plausible that Kathmandu is often subject to a daytime mountain-valley mesoscale thermal circulation, similar to the patterns observed in Phoenix, Arizona. (6, 7, 10, 11, 13, 14, 20) The Kathmandu Valley serves as a theoretically ideal platform for the development of such a circulation, with large amounts of solar radiation warming the mountain-valley environment and no strong background atmospheric circulation to interfere, especially in winter. Capable of transporting lower atmospheric aerosols, the mesoscale circulation should promote an atmospheric flow up the warmed northeastern valley slopes during midday and afternoon hours (14). As the temperatures of the air overlying the warmed slopes increase, the air should become more buoyant, rise, and be replaced with air moving upslope from the valley floor (1, 14), producing what is termed an “anabatic” wind. The result should be an efficient transport of high amounts of lower atmospheric pollution from areas of high ground traffic near the urban center toward northeastern suburbs and the higher elevation areas farther east and north. During nighttime hours, the mountain-valley thermal circulation should reverse to a downslope flow, or “katabatic” wind. Rapidly cooling air overlying the mountain slopes should become more dense and consequently should settle or "drain" back into the valley below. (14, 21) Cool air drainage should play a role in the diurnal transport of lower atmospheric pollution. (14)

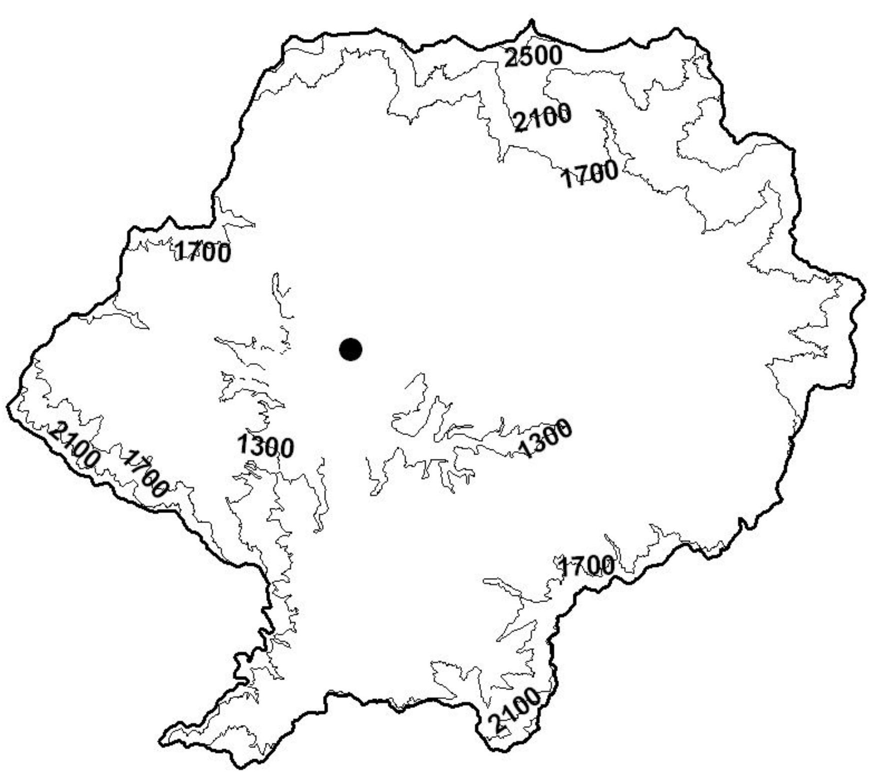
This paper aims to provide evidence of the seasonal patterns of PM_{10} concentrations in Kathmandu. This case study examines the seasonal climatological conditions that are most conducive to high concentrations of PM_{10}. In order to understand the movement of pollutants through the diurnal period better, collected climatic data were examined. The condition of the atmosphere on both the micro- and synoptic scales should influence the evolution of the mountain-valley thermal circulation, making the study of pollution transport across the Kathmandu metropolitan area uniquely appealing to a geographer. A better understanding of the climate and physical geography of the area, coupled with human impacts on air pollution, could lead to an improved PM_{10} forecast model for Kathmandu in the future.

FIGURE 1

MAP OF KATHMANDU VALLEY ROADWAYS (a)
AND SURROUNDING TOPOGRAPHY (b)
(BLACK DOT INDICATING PUTALISADAK)
(FIGURE 1a OVERLAYS FIGURE 1b)



(a)



(b)

3. DATA AND METHODOLOGY

The climatological data used in this study include daily maximum and minimum temperature (T_{max} and T_{min}, respectively; °C), wind speed (m s^{-1}) and direction (degrees) and precipitation (mm). Climatological data were obtained from Nepal's Department of Hydrology and Meteorology for 1999 and 2000. For the months of May and June 2001, a weather monitoring station was established *in situ* by the authors with the cooperation of LEADERS (Society for Legal and Environmental Analysis and Development Research) Nepal.

In order to collect seasonal PM_{10} data, a monitoring station was established at the LEADERS Nepal office located at Putalisadak, one of the busiest commercial areas in Kathmandu. It is believed that the microclimate of the site is reasonably representative of the local area within which high pollution levels are common. The monitoring station was staffed 24 hours a day during all observation periods, collecting continuous one-hour PM_{10} data using a Beta Attenuation Particle Mass monitor. Monitoring was conducted for 76 days in April, October, November and December 1999; October and November 2000; and May and June 2001. As such, data are available for different seasons of the year (Table 1).

TABLE 1
MONITORING PERIOD

Season	Total Monitoring Days	Monitoring Month (Number of Days)
Pre-Monsoon	27	April 1999 (12)
		May 2001 (13)
High Monsoon	16	June 2001 (16)
Post-Monsoon	25	October 1999 (6)
		November 1999 (6)
		October 2000 (7)
		November 2000 (6)
Winter	10	December 1999 (10)

Once the PM_{10} data were collected, the study days were stratified into four categories based on the four seasons that comply with the standards of Nepal's Department of Hydrology and Meteorology (DHM). The first season, the high monsoon, includes days occurring between the months of June and September. The second season, the post-monsoon, is comprised of days occurring in October and November. The next season is winter, and it includes days occurring during the months of December, January, and February. The fourth season, the pre-monsoon, includes daily data from the months of March – May. Nepal has no ambient air quality standard for PM_{10}. Therefore, the United States Environmental Protection Agency's (EPA) standard on ambient air quality for PM_{10} was used as a basis for our analyses.

In order to quantify the within-category similarity of the PM_{10} conditions that characterize the days that comprise each seasonal category, paired-sample t-tests were calculated. Likewise, paired-sample t-test statistics were calculated to show the statistical differences for all microclimatological data across each seasonal category.

4. RESULTS AND ANALYSIS

Using the EPA standard on ambient air quality of 150 $\mu g/m^3$ for PM_{10}, it can be observed that this standard value was exceeded on 41 percent of the monitoring days (Table 2). It was observed that in the dry month of April 1999 (pre-monsoon), this value was exceeded almost 100 percent of the time. In winter (December 1999), with calm winds and stagnant conditions, this standard was exceeded 90 percent of the time. However, during the high monsoon period, this standard value was not exceeded in June of 2001. Thus, it is evident that the rainy days during the high monsoon had better air quality. These findings suggest that the air quality during each season is influenced by a unique set of climatological parameters.

TABLE 2
SUMMARY OF SEASONAL PM_{10}

Season	**Monitoring Month (Number of Days)**	**Percentage of Days with PM_{10} ^{3} 150 mg/m^3**
Pre-Monsoon	April 1999 (12)	100
	May 2001 (13)	0
High Monsoon	June 2001 (16)	0
Post-Monsoon	October 1999 (6)	17
	November 1999 (6)	83
	October 2000 (7)	85
	November 2000 (6)	0
Winter	December 1999 (10)	90
TOTAL		41 (32 days)

While air quality during the pre-monsoon and post-monsoon was generally poor, the observation days in both November 2000 and May 2001 had atypically clean air. This was likely due to the fact that the six monitoring days of November 2000 were relatively windy, while there was a series of pre-monsoon rainstorms that flushed pollutants from the atmosphere in the last few days of May 2001.

Average seasonal concentrations of PM_{10} were obtained from the initial hourly data for different monitoring days in that season. Figure 2 illustrates the average seasonal variation of PM_{10} concentrations. Highest PM_{10} concentrations occurred in winter (198 μg/m^3) and in the pre-monsoon (134 μg/m^3). The high monsoon season had the least amount of PM_{10} concentration (39 μg/m^3), while PM_{10} concentrations for the post-monsoon were higher (146 μg/m^3).

Figure 2 illustrates that concentrations of PM_{10} were found to show a degree of seasonal variation. When statistical comparisons were performed (Table 3) for individual seasons using paired samples tests, the difference between the mean concentration of PM_{10} for pre-monsoon season and post monsoon was not significant ($p = 0.417$). In addition, the difference between the mean concentrations of PM_{10} for the pre-monsoon and winter was not significant ($p = 0.903$). This is likely due to the fact that the last one to two weeks of pre-monsoon in May are relatively rainier than the beginning of the month. Marking the onset of the Indian monsoon, this rain cleanses pollutants from the lower atmosphere. As such, the range of PM_{10} concentrations during the pre-monsoon is comparatively large.

FIGURE 2
AVERAGE SEASONAL PM_{10} CONCENTRATIONS (μg/m^3)

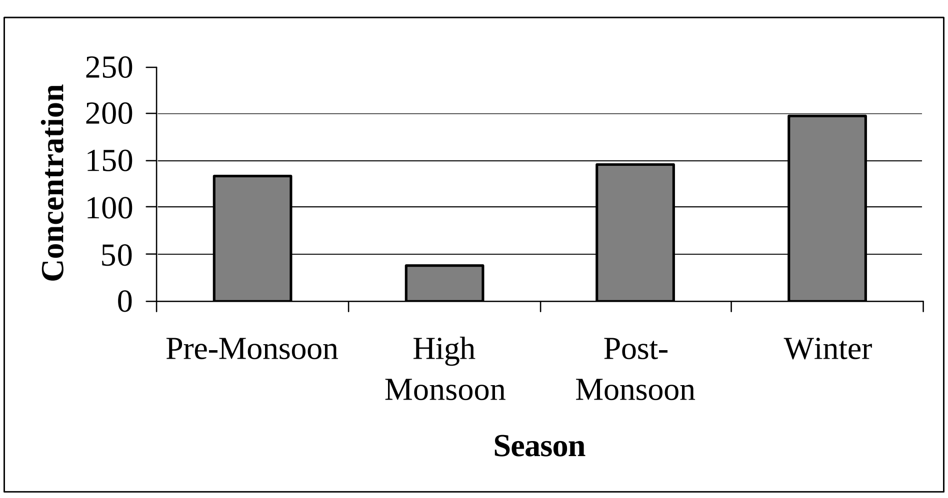


TABLE 3
PAIRED SAMPLES T-TEST
(95 PERCENT LEVEL OF CONFIDENCE)

Paired Samples	**t**	**Significance**
Pre-Monsoon- High Monsoon	8.16	0.000
Pre-Monsoon – Post-Monsoon	-0.83	0.417
Pre-Monsoon – Winter	-0.13	0.903
High Monsoon- Post Monsoon	-10.47	0.000
High Monsoon- Winter	-11.90	0.000
Post-Monsoon – Winter	-4.12	0.003

Information provided in Table 3 shows that the summer monsoon had mean concentrations of PM_{10} that were significantly different from the three other seasons. The rains that occurred during the core monsoon months tended to cleanse the atmosphere. The other three seasons were less wet, while the winter tended to be the driest season. In winter, Kathmandu is generally dominated by subsiding stable air associated with the dominant Siberian high over Asia. (19) The presence of the Siberian high promotes high levels of air pollution. PM_{10} levels were also significantly different between the post-monsoon and winter. As the post-monsoon begins, the atmosphere is still relatively clear due to the recent high monsoon, but the stability of the atmosphere increases as winter approaches.

There was a clear and systematic seasonal variation in PM_{10} concentrations and associated climatological conditions in Kathmandu. April typically had the highest concentrations, followed by December, while the lowest concentrations of PM_{10} were observed in the rainy month of June. Similar seasonal trends have been observed during earlier monitoring performed by the Department of Hydrology and Meteorology in 1994, 1995, 1996 & 1997. (8, 9)

Table 4 shows the average climatological conditions of average wind speed, precipitation, daily maximum and minimum temperatures for each season. It was found that the high monsoon season was associated with high wind speed (in average 8.51 m s^{-1}), high precipitation (average 10.35 mm) and little difference in mean maximum and minimum temperatures. The small difference between the maximum and minimum temperature was indicative of abundant cloud cover during the rainy Indian monsoon. The other seasons had little or no rainfall during the monitoring periods, wind speeds were lower and temperature ranges were higher. This suggests that large amounts of rainfall, high wind speeds, and unstable conditions during the high monsoon helped to cleanse the lower atmosphere of pollutants.

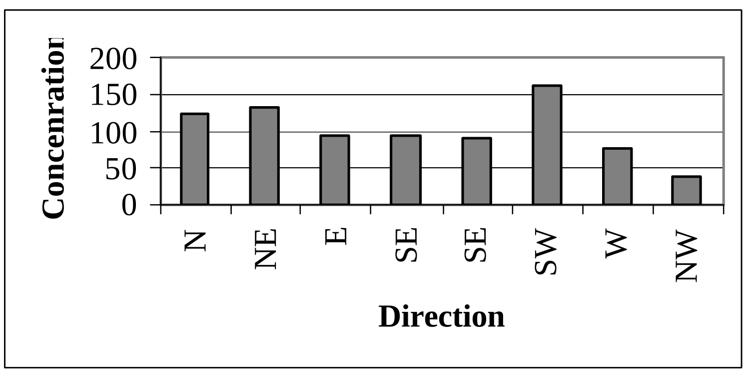
TABLE 4
AVERAGE CLIMATOLOGICAL CONDITIONS FOR EACH SEASON

Season	**Wind Speed (m s^{-1})**	**Precipitation (mm)**	**T_{max} (°C)**	**T_{min} (°C)**
High-monsoon	8.51	10.35	28.4	20.1
Post-monsoon	0.85	0.00	26.0	11.4
Winter	0.91	0.00	21.2	5.6
Pre-monsoon	1.87	1.28	29.6	15.9

While our results suggest that each season had its own unique set of meteorological parameters that influence concentrations of PM_{10} in the ambient air, understanding the role of the physical geography of the area is also essential. It is plausible that the topography of Kathmandu Valley influences the local wind regime and transport of air pollution.

In order to gain a better understanding of the conditions that promote the transport and development of high concentrations of PM_{10}, we also examined the relationship between wind direction and speed and PM_{10} levels at Putalisadak. As shown in Figure 3, the highest amount of PM_{10} (average = 163 μg/m^3) was associated with winds from the southwest. The PM_{10} was highest when the wind speed from this direction was 1-2 m s^{-1}. This suggests that the monitoring station was receiving pollution from sources located to its southwest. Most of the air pollution sources were located to the southeast, south and southwest of the monitoring station. For example, a large cement factory is located to the southwest of Putalisadak, and according to URBAIR (22), it emits 17 percent of Kathmandu's total PM_{10}. Another major source of air pollution was the brick kilns. These brick kilns, which are mostly located in the southern belt of the Valley, emit 28 percent of Kathmandu's total PM_{10}. (22) The high amount of PM_{10} concentration from the south was observed only when the wind speed was high (3-6 m s^{-1}). A plausible reason for this difference could be that the chimney heights of these brick factories are quite low; therefore pollution emitted from these low chimneys generally settles quickly in low-wind conditions, avoiding long-range dispersion.

FIGURE 3
PM_{10} CONCENTRATIONS (μg/m^3) ASSOCIATED WITH WIND DIRECTION



The high concentrations of PM_{10} associated with winds from north and northeast may be due to a "sloshing" effect. A "sloshing" effect is a phenomenon that occurs due to mountain-valley breezes generated by a diurnal thermodynamic circulation. Pollutants carried anabatically by winds flowing from the south, southwest and west during the day could be brought back again by katabatic winds flowing from the north, northeast and east during the night. Similar "sloshing" effects have been observed to transport air pollutants in Phoenix, Arizona and Freiburg, Germany. (2, 10, 14) Therefore, it is plausible that the physical geography of Kathmandu partially dictates the daily concentration and transport of PM_{10}.

5. CONCLUSIONS

As compared to other Asian countries, such as India and Japan, and other developed countries within North America and Europe, virtually no quantitative studies have been undertaken to examine the actual situation of air quality in Nepal. This case study was a first attempt to examine seasonal concentration and transport of anthropogenic PM_{10} in Kathmandu, coupled with an examination of the climate and the physical geography of the region.

Spatiotemporal variations in PM_{10} concentrations in the Kathmandu area result from dynamic human-environmental interactions. Intraseasonal variations in climate play a large role in directly and indirectly controlling ambient particulate matter levels. Variables such as temperature, wind speed and direction, and precipitation affect the concentrations of PM_{10}. Likewise, PM_{10} concentrations are also influenced by changes at the synoptic scale. This is most apparent during both the high monsoon and winter seasons. PM_{10} concentrations are typically highest when Nepal is dominated by the stable conditions associated with the presence of the Siberian high, while concentrations are generally lowest when Nepal is dominated by the Indian monsoon during the windy and rainy summer months.

It has been demonstrated that PM_{10} concentrations are typically greatest under certain distinctive seasonal and climatic conditions. However, this paper also suggests that the physical setting of Kathmandu also influences air pollution concentrations and transport. Kathmandu's mountain-valley setting not only inhibits the diffusion of lower atmospheric air pollution, but it also produces a thermal circulation that has been found to influence air pollution transport, especially in winter. Thus, there is evidence that air pollution is carried out of Kathmandu during the day, while a mountain breeze causes pollution to return to the valley at night. Since the variation in PM_{10} concentration is influenced by different predictable variables, a forecast model for PM_{10} is possible for Kathmandu. A next step is to create such a model and encourage its use in the maintenance and development of the Kathmandu metropolitan area.

6. REFERENCES

1. Arrit, R., and R.A. Pielke. 1986. Interaction of Nocturnal Slope Flows with Ambient Winds. Boundary Layer Meteorology 37:183-95.

2. Baumbach G., & U. Vogt. 1999. Experimental Determination of the Effect of Mountain-Valley Breeze Circulation on Air Pollution in the Vicinity of Freiburg. Atmospheric Environment 33:4019-4027.

3. Berman N.S., D.L. Boyer, A.J. Brazel, S.W. Brazel, R.R. Chen, H.J.S. Fernando, and M.J. Fitch. 1995. Synoptic Classification and Physical Model Experiments to Guide Field Studies in Complex Terrain. Journal of Applied Meteorology 34:719-730.

4. Bhattarai, M.D. 1993. Paper on Industrial Contribution to Air Quality. Urban Air Quality Workshop (URBAIR). Kathmandu, Nepal: Ministry of Industry.

5. Blumen, W., ed. 1990. Atmospheric Processes Over Complex Terrain (Vol. 23, Meteorological Monographs). Boston: American Meteorological Society.

6. Davis, R. E., and D.A. Gay. 1993. An Assessment of Air Quality Variations in the Southwestern United States Using an Upper Air Synoptic Climatology. International Journal of Climatology 13:755-781.

7. Davis, R. E., and D.A. Gay. 1993. A Synoptic Climatological Analysis of Air Quality in the Grand Canyon National Park. Atmospheric Environment 27A:713-727.

8. D.H.M. 1998. Record File of TSP in Kathmandu (Unpublished). Kathmandu, Nepal: Department of Hydrology and Meteorology.

9. D.H.M. 2000. Record File of Climatology for 1999-2000 of Kathmandu (Unpublished). Kathmandu, Nepal: Department of Hydrology and Meteorology.

10. Ellis, A.W., M.L. Hildebrandt, and H.J.S. Fernando. 1999. Evidence of Lower Atmospheric Ozone "Sloshing" in an Urbanized Valley. Physical Geography 20:520-536.

11. Ellis, A.W., M.L. Hildebrandt, W.M. Thomas, and H.J.S. Fernando. 2000. Analysis of the Climatic Mechanisms Contributing to the Summertime Transport of Lower Atmospheric Ozone within Metropolitan Phoenix, Arizona, USA. Climate Research 15:13-31.

12. Gold, D.R., A.I. Damokosh, C.A. Pope, D.W. Dockery, W.F. McDonnell, P. Serrano, A. Retama, and M. Castillejos. 1999. Particulate and Ozone Pollutant Effects on Respiratory Function of Children in Southwest Mexico City. Epidemiology 10:8-16.

13. Green, C.R., and W.D. Sellers. 1964. Arizona Climate. Tucson, Arizona: The University of Arizona.

14. Hildebrandt, M.L. 2000. A Climatological Analysis of Lower Atmospheric Ozone Transport Across Phoenix, Arizona. Papers and Proceedings of the Applied Geography Conferences, Vol. 23, ed. F.A. Schoolmaster, 145-153. Tampa: Applied Geography Conferences, Inc.

15. LEADERS Nepal. 1998. A Citizens Report on Air Pollution in Kathmandu: Children’s Health at Risk. eds. A.K. Pokhrel and B.K. Sharma, Kathmandu, Nepal: Society for Legal and Environmental Analysis and Development Research.

16. LEADERS Nepal 1999. Citizens Report ’99: Air Pollution in the Face of Urbanization. eds. A.K. Pokhrel, S. Pokhrel and K.R. Aryal, Kathmandu, Nepal: Society for Legal and Environmental Analysis and Development Research.

17. LEADERS Nepal 2000. Record File of PM_{10}, NO_x, SO_x, CO in Kathmandu (Unpublished). Kathmandu, Nepal: Society for Legal and Environmental Analysis and Development Research.

18. Lu, R., and R.P. Turco. 1995. Air Pollutant Transport in a Coastal Environment- II: Three-Dimensional Simulation over Los Angeles Basin. Atmospheric Environment 29:1499-1518.

19. Oliver, J. E., and J. J. Hidore. 2002. Climatology: An Atmospheric Science, 2nd Edition. Upper Saddle River, New Jersey: Prentice Hall, Inc.

20. Sellers, W.D., and R.H. Hill. 1974. Arizona Climate, 1931-1972. Tucson, Arizona: The University of Arizona Press.

21. Simpson, J.E. 1997. Gravity Currents in the Environment and the Laboratory. Cambridge: Cambridge University Press.

22. URBAIR. 1997. Urban Air Quality Management Strategy in Asia: Kathmandu Valley Report. eds. J. Shah, T. Nagpal, World Bank Technical Paper No. 378. Kathmandu: World Bank.