CHAPTER - 4

Distributions of ozone and other trace gases over the Indo-Gangetic Plain during a winter month

In December 2004, a land campaign with a multi-institutional scientific effort was carried out in the Indo-Gangetic Plain (IGP) in North India to understand the distribution and dynamics of the atmospheric pollutants during a winter month. The main goal of the research work presented in this chapter was to understand the ozone chemistry and to study the effect of fog/haze on tropospheric ozone and other pollutants. Simultaneous measurements of surface $O_3$, $CO$, $NO_x$ and $CH_4$ along with vertical distribution of ozone and other meteorological parameters were made during December 2004 at Kanpur (26.03N, 80.04E), an urban site in the IGP. Such extensive simultaneous measurements have not been made over this region. During the winter season mainly in December and January, the whole part of the northern India experiences western disturbances moving eastward which leads to intense fog and haze in this region. In winter, the relationship between ozone and westerlies is found to be positive especially in locations which are more influenced by westerlies. It is suggested that these relationships reflect the importance of vertical exchange from the free troposphere/stratosphere to the surface in winter months. Previous studies have identified transport of atmospheric pollutants from the IGP during winter and occasionally these pollutants are transported downwards and result in substantial ozone concentrations at the surface.
4.1. Significance of the study site

Asia is one of the most anthropogenically active areas in the world and provides an interesting study field for tropospheric ozone build up. The aged air masses associated with the continental outflow from the IGP carry with them anthropogenic air pollutants emitted from the industrial and urban neighborhoods of Kanpur under favorable meteorological conditions for photochemical ozone formation. Emissions of ozone precursors are expected to multiply in the next few years in India and the level of photo-oxidants may increase substantially.

There have been several field campaigns to study the transport of pollutants over the marine regions surrounding India such as INDOEX, BOBEX, and BOBPS [Lelieveld et al., 2001; Chand et al., 2003; Lal et al., 2006; Sahu et al., 2006; Lal et al., 2007]. However, there were limited measurements by individual groups to study levels of aerosols and trace gases over the IGP [Singh et al., 1997; Fishman et al., 2003; Jain et al., 2005; Sahoo et al., 2005; Beig and Ali, 2006; and Tripathi et al., 2006]. In view of the importance of this region, a campaign was organized by Indian Space Research Organization-Geosphere Biosphere Programme (ISRO-GBP) to study levels and variations of pollutants (aerosols and trace gases) at eight different sites covering wide regions of the IGP from west to east during December 2004. The month of December was chosen, as it is the period when both clear days and foggy days occur. Thus, the changes in trace gases and aerosols could be studied during clear as well as foggy days. These measurements were made by a large number of groups covering all these sites.

Measurements using balloon-borne ozonesonde provide a unique data set to study the vertical changes in the troposphere and effects of transport. This is the first time that vertical distribution of ozone was made from this site over the Gangetic basin, except the measurements made by the Indian Meteorological Department (IMD) from Delhi regularly. There are some measurements of ozone as a part of MOZAIC (measurement of ozone by air bus in-service aircraft) at Delhi. However, they are highly irregular in frequency and limited to a height below 300 mb [Kunhikrishnan et al., 2006]. Results of
distribution of surface level CO, NO\textsubscript{x}, and CH\textsubscript{4} and vertical profiles of ozone are presented in this chapter.

4.2. Site description

The balloon flight experiments were conducted at the Indian Institute of Technology (IIT) campus at Kanpur in North India (Fig. 4.1). This campus is located about 16 km away from the city centre in the upwind direction. It is an industrially polluted city with a population of about 2 million. Foggy conditions often prevail during the winter season in this region [Tripathi et al., 2006].

![Figure 4.1. Geographical location of Kanpur city and location of Indian Institute of Technology (IIT), where measurements were made during December 2004.](image)

4.3. Experimental details

Continuous surface level measurements of \text{O}_3 were made using an analyzer (Table 4.1), which is based on the absorption of UV radiation at 253.7 nm by O\textsubscript{3}. The absolute accuracy of this analyzer is 5%. Detailed description of the analyzer, including
calibration methodology, is given by Lai et al. [1998]. A Teflon tube was used as an inlet line for air sample, which was taken from the top of the building. Ozone data, averaged for every 5-min interval, were stored in a data acquisition system. A total of nearly 60 air samples were collected in glass bottles through a 2 m long stainless steel tube (1/4" OD) using an oil free compressor (Metal Bellow, USA). Analyses of CH$_4$ and CO were performed by a gas chromatograph (Varian Vista 6000, USA) using a molecular sieve packed column of 5 m length. Calibration mixtures supplied by NIST (Gaithersburg, USA) (1.0-0.01 ppmv; Sample 1223-E) and Matheson (Texas, USA) (2.1 0.01 ppmv; Lot 04-96-07670) were used to calibrate CH$_4$ and CO, respectively. Analyses of CH$_4$ and CO showed better than 1% and 3% of reproducibility, respectively. A detailed description of calibration and measurement methodology for analyses of CO and CH$_4$ are given by Sahu and Lal [2006b]. Instruments and parameters measured during land-campaign at Kanpur by PRL group are given in Table 4.1.

Table 4.1. Instruments operated and parameters measured during land-campaign at Kanpur

<table>
<thead>
<tr>
<th>Instruments used</th>
<th>Company</th>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone analyzer</td>
<td>Environment S.A, France</td>
<td>Ozone</td>
<td>Surface</td>
</tr>
<tr>
<td>CO analyzer</td>
<td>Environment S.A, France</td>
<td>CO</td>
<td>Surface</td>
</tr>
<tr>
<td>NO$_x$ analyzer</td>
<td>Environment S.A, France</td>
<td>NO and NO$_2$</td>
<td>Surface</td>
</tr>
<tr>
<td>Gas chromatograph</td>
<td>Varian, USA</td>
<td>CO and CH$_4$</td>
<td>Surface</td>
</tr>
<tr>
<td>Radiation flux</td>
<td>Solar Light, USA</td>
<td>UVB</td>
<td>At ground</td>
</tr>
<tr>
<td>Ozonesonde</td>
<td>EN-SCI, USA</td>
<td>Ozone</td>
<td>Maximum 35 km</td>
</tr>
<tr>
<td>Radiosonde</td>
<td>Vaisala, Finland</td>
<td>T, RH, and P</td>
<td>Maximum 35 km</td>
</tr>
</tbody>
</table>
4.4. Meteorological conditions, back trajectory and potential vorticity analysis

The regional surface winds, based on the National Center for Environmental Prediction (NCEP) reanalysis data, were found to be mainly northwesterly (Fig. 4.2). However, the surface winds varied from northwesterly to southwesterly [Tripathi et al., 2006].

Figure 4.2. Synoptic monthly averaged wind at 925 hPa from NCEP showing northwesterly wind direction at Kanpur.

Very low wind speeds along with shallow boundary layer height during the foggy days were observed. Although, the winter season in the North India is dry, when the cold air from higher latitudes mixed with the moist air from surrounding marine regions, strong haze and fog conditions were observed in the Gangetic basin. The relative humidity (RH) soared above 75% during nighttime and in the early morning hours during these events. During foggy days, RH remained high (46%) throughout the day but it dipped down to about 40% during clear sky mid-day period. Transport of air and local meteorological conditions play an important role in changing the weather condition in this region. Low surface temperature (down to 8°C) and high humidity (up to 95%) made favorable
conditions for fog formation during 18–25 December 2004 at this site (Fig. 4.3). The average boundary layer height, based on temperature profiles from radiosonde data, was about 800 m on foggy days while it reached up to about 1.5 km on non-foggy days. The isentropic seven-day back air trajectories used in this study were obtained from Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), version 4 [Rolph and Draxler, 2003]. Back trajectory analyses are used to examine potential source regions of the air parcel and transport pathways, although the exact origin of a specific air parcel cannot be determined. The European Centre for Medium-Range Weather Forecasts (ECMWF) data are used to estimate potential vorticity (PV). This parameter is used to trace the origin of the air. PV is expressed in PV units where one PV unit is $10^6 \text{m}^2\text{s}^{-1}\text{Kkg}^{-1}$. Air with potential vorticity of 2 PV units or more is taken to be of stratospheric origin [Appenzeller and Davies, 1992; Holton et al., 1995; Newell et al., 1997].

![Figure 4.3](image)

**Figure 4.3.** Surface temperature and relative humidity observed over Kanpur during the land campaign (11–29 December 2004).
4.5. Results and discussion

4.5.1. Time series analysis

Figure 4.4a depicts the variation of hourly averaged O₃ mixing ratios observed during the entire campaign. Ozone mixing ratios showed a large range (10–60 ppbv) of variability during the campaign. During the first half of the campaign its average value was ~55 ppbv and then it decreased to 20 ppbv during the foggy days.

Figure 4.4. Time series of surface ozone, CO and NOₓ along with UVB flux (in arb units) observed at Kanpur during December 2004.
Figure 4.4b depicts the variations in CO mixing ratios. CO varied from 200 to 1000 ppbv. High CO concentrations were observed on 12 December and 16 December.

Variations in concentrations of NOx are shown in Figure 4.4c. It varied between 5 to 50 ppbv during the campaign. Except for some small variations, the overall trend in NOx is somewhat similar to those in CO mixing ratios. The mixing ratios of NOx showed peaks on 12 and 16 December as for CO. Figure 4.4d shows the variations in pyro-measured flux. The flux ranged from 20 to 350. It depicts lows on 18, 24, and 26 December when heavy fog events were observed.

4.5.2. Frequency distributions

Frequency distributions of O3, NOx, and CO based on the data averaged for 5 minutes are shown in Figure 4.5, in bins of 2, 1, and 25 ppbv, respectively. A total of about 7500 data points were obtained. Most of the data points of ozone lied in the range of 5 to 25 ppbv. Out of the total data points, maximum numbers of data points in a single bin were in the 8 ppbv bin. Similarly most of the data points for CO were in the range of 25 to 400 ppbv. The maximum number of data points lied in the 25 ppbv bin. In case of NOx, most of the data points are in the range of 0 to 20 ppbv, however the 10 ppbv bin had the highest number (550) of data points.

4.6. Diurnal variations in ozone and its precursors

Average mixing ratios of surface O3, CO and NOx at Kanpur during clear sky days were 34.99 ± 15.12 ppbv, 337.68 ± 169.9 ppbv, and 13.86 ± 2.5 ppbv, respectively while on foggy days these were 14.35 ± 8.7 ppbv, 191.87 ± 135.6 ppbv, and 7.93 ± 1.7 ppbv.

4.6.1. Foggy days

From 18 –26 December 2004, there was an intense fog over Kanpur as well as over the Indo-Gangetic Plain [Gupta et al., 2007]. Atmospheric visibility was very poor during the morning and evening hours. Diurnal variations of ozone show a very different pattern from its normal pattern since no afternoon peak was observed during the foggy days. This observation suggests high suppression in ozone concentration due to heavy fog.
Figure 4.5. Frequency distribution of ozone (ppbv), carbon monoxide (ppbv) and NOx (ppbv) at Kanpur during December 2004.
There were no changes in the diurnal patterns of CO and NOx except that there was a decrease in the concentrations compared to clear sky days (Fig. 4.6). These results indicate that in spite of significant levels of precursors, ozone does not show its diurnal pattern due to the absence of photochemistry during heavy foggy condition. Pyro flux was reduced to 2 μWcm\(^{-2}\) compared to 6 μWcm\(^{-2}\) on a clear sky day. Measurements during clear sky days showed stronger diurnal variations in the trace gas distributions as compared to foggy days. The levels and variabilities of trace gases were suppressed on foggy days due to the lack of photochemical production.

4.6.2. Clear days

Concentrations of trace gases at Kanpur also show large diurnal variations like other urban and industrial sites. Typical diurnal distributions of O\(_3\), CO and NOx are shown in Figure 4.7. The maximum amplitudes of about 75 ppbv, 3.5 ppmv and 80 ppbv were observed for O\(_3\), CO, and NOx concentrations, respectively. The diurnal variation in O\(_3\) showed a maximum in the afternoon with low values during early morning and late night hours. An increasing trend was observed between early morning hours and noon, while a decreasing trend was observed between noon and evening. Day-to-day variations in ozone increasing and decreasing trends were negligible. The diurnal variations in CO and NOx were opposite to that of ozone. Observed diurnal and day-to-day variabilities in the distributions of anthropogenically emitted trace gases like CO and NOx could be due to significant differences in their local emissions considering that solar irradiance induce variations are minimal during clear days within a month.

Average diurnal variations of O\(_3\), CO, NOx and UVB measured during clear sky of observations are shown in Figure 4.6. The diurnal peak in ozone occurs at 1500 hrs in the afternoon, while the radiation peaks around 1300 hrs. Mixing ratio of ozone was observed to be lowest at 0900 hrs. These is an increase in ozone mixing ratio due to lifting of boundary layer height in the forenoon and due to photochemical production of ozone and after 1500 hrs, loss of ozone starts dominating due to decrease in solar radiation. Diurnal patterns observed in CO and NOx shows two peaks in the morning and
evening hours. Morning peak occurs at around 0800-0900 hrs and evening peak at around 2100 hrs. Both of these peaks coincidence with the morning and evening rush hours as well as decrease in boundary layer height. These variations are typical of an urban/semi-urban site [Sahu and Lal, 2006a].

**Figure 4.6.** Diurnal variations of ozone, CO, NO & NOx and UVB flux on (a) a foggy day (b) and on a clear day at Kanpur
4.7. Vertical distribution of ozone

4.7.1. Average vertical profiles of ozone and temperature over Kanpur

Six balloon flights were conducted of which three were on clear days (December 11, 15 and 29) while the other three were on foggy days (December 18, 22 and 25). Average peak ozone concentration of 140 nb was observed around 25 km (Fig. 4.7). The cold point tropopause temperature ranged from -70 °C to -77 °C and the tropopause height ranged from 16.5 to 18.9 km with an average and standard deviation of 17 ± 0.7 km as shown in Figure 4.8. Large variability in tropopause height was observed from flight to flight (Fig. 4.8). A layer of high ozone was observed in the free troposphere from 3 to 7 km on December 18. Similarly, three sharp layers of high ozone were observed in the height range of 10–18 km on December 25. On the contrary, depleted ozone was observed in the height range of 11–14 km on December 29. These results are discussed in detail in the following section.

Figure 4.7. Mean vertical profile of ozone (nb) and temperature up to 35 km observed from six balloon flights made from Kanpur during December 2004.
4.7.2. Observed features

Columnar total ozone was obtained by integrating individual profiles up to the balloon burst altitude which was generally around 32–35 km, and further extending it up to 60 km using the method described by McPeters et al. [1997]. These integrated columnar ozone for the balloon flight days show good correlation \( r = 0.74 \) with the corresponding total ozone values obtained from total ozone mapping spectrometer (TOMS) (Fig. 4.9). The average TOMS total ozone for six flights was \( 249 \pm 20 \text{ DU} \), whereas the average balloon flight total ozone was \( 266 \pm 13 \text{ DU} \). There was a bias of about 22 DU in the satellite data.

The average of all the observational tropospheric ozone content was obtained by integrating individual observed profiles up to the tropopause height, which was calculated from the temperature profile measured by the radiosonde. Total columnar and tropospheric columnar ozone variability are shown in Figure 4.10. The average tropospheric column ozone was \( 41 \pm 3 \text{ DU} \) but it was much higher (53 DU) on 25 December.

Figure 4.8. Tropopause temperature and height over Kanpur during December 2004.
**Figure 4.9.** Comparison between total columnar ozone computed from balloon data and TOMS columnar ozone.

**Figure 4.10.** Total columnar and tropospheric columnar ozone amounts computed from ozonesonde data.
4.7.3 Case 1: Higher ozone concentration in the lower troposphere

Higher ozone (70 ppbv) with respect to the average of six balloon profiles on December 18 was observed in the altitude region of 3–7 km (Fig. 4.11). Average ozone concentration of all the six balloon flights in the height range of 3–7 km was 50 ppbv. The strong inversion at the bottom of the layer suggests that the higher concentration was not due to mixing upwards from the local boundary layer (Fig. 4.12). Seven-day back trajectories were calculated at the altitude levels of 3, 4, and 5 km. This trajectory analysis clearly indicates that the air parcel in the enhanced ozone layer over Kanpur passed over the region of intensive seasonal burning in Africa and higher pollutants (e.g., CO, CH₄) region of the Gulf as seen from the MOPITT data (Fig. 4.13a). The humidity in the enhanced layer was found to be lower, which indicates that the air mass passed through a dry region. CO data obtained from measurements of pollution in the troposphere (MOPITT) at 850 hPa shows higher concentration of CO along the trajectory path for 18 December 2004 (Fig. 4.13b).

![Figure 4.11. Vertical distribution of ozone (ppbv) with ± 1σ standard deviation along with six balloon profiles.](image-url)
Figure 4.12. Vertical profile of ozone, temperature and RH for December 18, 2004.

Figure 4.13. CO obtained from MOPITT (measurements of pollution in the troposphere) at 850 hPa shows higher concentration of CO along the trajectory path for 18 December, 2004 (a). Seven day back trajectory analysis from HYSPLIT model at 3, 4 and 5 km for December 18. The upper plate shows the horizontal movement of air parcel while the lower plate shows the vertical movement of air parcel (b).
During this month northern tropics experience a dry season where precipitation is rare and biomass burning is frequent in regions like Central Africa and Southeast Asia as shown in the Figure 4.13a.

The NASA earth observatory (http://earthobservatory.nasa.gov/NaturalHazards/) has captured this intense burning during 1-12 December 2004. Although back trajectory analysis is a tool to track the path of air mass, it is not possible to locate the origin and exact location of the source. Both the meteorological data obtained along with ozone profile and the air parcel trajectory information were consistent in showing that the layer of high ozone values could be due to transport of ozone as well as its precursors and subsequent photochemical production of ozone. PV data obtained from ECMWF do not show any evidence of its origin from the stratosphere (not shown here). Local pollutants measured simultaneously with the balloon launchings at this location i.e. surface ozone, (25 ppbv) carbon monoxide (300 ppbv) and nitrogen oxides (20 ppbv) could not get mixed from the local boundary layer to the free troposphere due to the strong boundary layer inversion. These observations further suggest that this ozone rich air can only be due to lateral transport.

4.7.4. Case 2: Ozone intrusion from the stratosphere

Enhanced ozone peaks were observed between 10 and 18 km on December 25, compared to the average ozone profile based on all the six balloon flights. The peak in the Tropical Tropopause Layer (TTL) region (14–18 km) shows enhanced ozone by 35–55 ppbv compared to the average ozone profile values, while the peaks at lower heights of 10 and 12 km show enhanced ozone by 20 and 35 ppbv, respectively (Fig. 4.14).
Figure 4.14. Vertical profiles of ozone, relative humidity and temperature observed on 25 December 2004 over Kanpur.

The temperature profile on this day showed double tropopause (Fig. 4.14), which suggest that these high ozone layers below the tropopause may be due to its transport from the stratosphere resultant of the weakening of the tropopause.

Wind data obtained from NCEP show extremely high (60 ms$^{-1}$) wind around 12 km of altitude on this day (Fig. 4.15). Seven-day back trajectories for the height range of 9–15 km obtained from HYSPLIT model suggest that wind was coming from higher latitudes at this site (Fig. 4.16).
Figure 4.15. Vertical profile of mean wind speeds along with the U and V components.

Figure 4.16. Seven-day back trajectory analysis from HYSPLIT model at 10, 11 and 12 km for 25 December 2004. The upper plate shows the horizontal movement, whereas the lower plate shows the vertical movement of air parcels.
There was a very dense fog event on December 25. Furthermore, due to low convective activity over this region, vertical transport from the polluted continental boundary layer was less likely. PV from the ECMWF analyzed wind and temperature fields was estimated at 0600 GMT on December 25 (Fig. 4.17). A jet stream was observed to be coming from the mid latitude in the southeast direction towards this site through the isentropic surface of 350 K. Noticeably, there was a sharp PV gradient along the subtropical jet stream around 20–30N, which is the location where active stratosphere–troposphere exchange can occur [Chan et al., 2004]. Cross-sectional view of PV (Fig. 4.18) showed a tongue of air with PV of more than 2 PV units between about 300 hPa (9.5 km) and 100 hPa (17 km). These altitudes coincide with the ozone enhanced peak levels and indicate that the air at these altitudes had its origin in the stratosphere. Enhanced ozone layers were also observed by Chan et al. (2004) over Xining (36.4N, 101.4E), Beijing (39.8N, 116.4E) and Hong Kong (22.3N, 114.2E) in January, 2002. These observations suggested that these enhancements were due to intrusion of stratospheric ozone from the Indo-Burmese region of Southeast Asia, where subsidizing downward motion were observed during winter. A study by Waugh and Polvani [2000] using NCAR/NCEP (National Center for Atmospheric Research/National Center for Environmental Prediction) reanalysis data for the period between 1980 and 1997 also showed that in the northern hemisphere, stratospheric intrusions occur mainly during the northern winter.
Figure 4.17. Latitude–longitude cross-section of potential vorticity (PV) derived from ECMWF for 06 UT on 25 December 2004 at 350K potential temperature.
Figure 4.18. Longitude–pressure cross-section view of potential vorticity at 26.5N for 25 December 2004.

The Atmospheric Infrared Sounder (AIRS) data were also able to capture this event of ozone transport from high latitude to low latitude on 25 December 2004 (Fig. 4.19). Figure 4.18 depicts the Latitude-Pressure cross sectional view of ozone variation on 80 E longitude on 25 December 2004. This indicates a subsidence of airmass at 100 hPa pressure level at 26 N to 30 N.
4.7.5. Case 3: Lower ozone concentration

Lower ozone concentrations by 35–40 ppbv compared to the average concentrations in the height range of 11–14 km were observed on December 29. Back trajectory analysis (Fig. 4.20) suggest that the air mass originated from a pristine marine region near the equator and had traveled across the Indian Ocean, where generally low ozone values were observed as reported in earlier studies [deLaat et al., 1999; Taupin et al., 1999; Zachariasse et al., 2000]. Since ozone lifetime is long in the free troposphere it can get transported far away from the source regions. The back trajectory analysis suggests that the low ozone air on December 29 originated from the free troposphere over the Arabian Sea and the Indian Ocean.

Figure 4.19. Latitude-pressure cross section of ozone at 80 E longitude on 25 December, 2004 at Kanpur based on the results from AIRS.
Figure 4.20. Back trajectories at 11, 12 and 13 km for 29 Dec. 04. Upper panel shows the horizontal movement while the lower panel shows the vertical movement.

4.8. Comparison with MATCH-MPIC model

4.8.1. Surface ozone

The global atmospheric off line model, MATCH-MPIC (Model of Atmospheric Transport and Chemistry - Max Planck Institute for Chemistry version), was developed for studies of atmospheric photochemistry. The, MATCH-MPIC is driven by wind, temperature, pressure, surface heat flux, and wind stress data from the NCEP-GFS analysis, at T42 horizontal resolution (roughly 2.8 degrees in latitude and longitude), and with 42 vertical levels (from the surface to about 2 hPa). The details of this model are discussed elsewhere [Lawrance et al., 1999, 2003; Von Kulmann et al., 2003]. Diurnal
cycle obtained from MATCH-MPIC modeled output agrees quite well with the observational data for Kanpur (Fig. 4.21). However, it is not able to reproduce low ozone during foggy days. This observation is due to the fact that these are short term local effects and the model is a global model.

Figure 4.21. Comparison of surface ozone measured at Kanpur during December 2004 and MATCH-MPIC model simulated results.

4.8.2. Vertical distribution of ozone

The vertical profiles of ozone obtained from ozonesonde were compared with the profile obtained from MATCH-MPIC model (Fig. 4.22). Among all the six profiles, model was able to reproduce major features in the ozone profiles which were observed in ozonesonde profiles. However, model was not able to reproduce the small features observed in the ozone profiles. Model did a poor job in reproducing the STE and LRT enhancements on 25 as well as on 18 December although there was a weak signal in both of them. The model did a much better job with the 29 December low ozone in the upper troposphere.
Figure 4.22. Comparison of the vertical profiles of ozone measured from ozonesonde and MATCH-MPIC model computed for December 2004 over Kanpur.

4.9. Summary of the results
As a part of a major campaign, six balloon flights carrying ozone and radiosondes were conducted from Kanpur during December 2004. Measurements showed large variability in tropospheric ozone distributions over this subtropical site. Average total ozone from the six balloon flights data was 262 ± 16 DU. But the TOMS data had a bias and gave
lower total ozone by about 22 DU. The average columnar tropospheric ozone estimated was 41 ± 3 DU which accounted for about 16% of the total column ozone. The average profile based on six balloon flights showed 60 ppbv below 2 km height and about 50 ppbv upto about 13 km. Thereafter there was a sharp increase in ozone. The average available MOZAIC profile for December 1999 over Delhi showed mixing ratios of about 60–80 ppbv within 1–2 km of altitude and about 50 ppbv in the free troposphere [Kunhikrishnan et al., 2006]. This average profile closely matched the profile observed over Kanpur. There are significant variations in ozone profiles observed on December 18, 25 and 29. On December 18, there was a broad layer of higher ozone in the height range of 3 – 7 km. This increase was by 40% as compared to the average profile. The PV analysis on this day did not show any evidence of air coming from the stratosphere, also the strong boundary layer temperature inversion ruled out the convection from the boundary layer. Hence, this increase seemed to be due to lateral transport from Africa and the Gulf countries as indicated by back trajectory. The results also revealed multiple layers of enhanced ozone on December 25 in the upper troposphere. These enhancements from the average profile range from 2.4 to 1.3 for height 10 to 17 km. Based on PV analysis, these peaks are linked to transport from the stratosphere. These observations confirmed that this region was susceptible to the influence of stratospheric intrusions, which can lead to large ozone enhancements in the upper troposphere in winter. However, there is a need to quantify the impact of such intrusions on ozone distribution. In addition to the elevated events, one event of lower ozone (60%) compared to the average in the height range of 10–14 km was also observed on December 29. This was a result of transport of pristine air from the free troposphere over the Arabian Sea and the Indian Ocean. These are the first observations of ozone distribution from this site in the Indo-Gangetic plain in India. This data set is valuable for validating models and satellite ozone profiles for this region. Ozone data on 25 December 2004, retrieved from AIRS was also able to capture the intrusion of stratospheric air to the troposphere. However, for better understanding of these variations in ozone and role of transport, there is a need to make measurements for a longer period to quantify the occurrence and exchange
amount of ozone in different seasons over the Indian region. This study has also indicated the fact that surface ozone is not affected by the elevated ozone concentrations in the upper troposphere but it is mainly affected by the local meteorological conditions due to strong temperature inversion. Isentropic back trajectory analyses were applied to sort out the influence of the air mass exchange in the winter month and the regional scale photochemical build up of ozone.

A comparison of these results was made with that of MATCH-MPIC results. The model is able to reproduce general features of the observed ozone profiles but it is not able to capture local effects.