CHAPTER- 6

Summary with general conclusions and outlook

Tropospheric ozone plays an important role in the chemistry and radiation budget of the atmosphere. It is a major source of OH radicals and was also a greenhouse gas. Measurements over the northern tropical region are very limited. The aim of this work is to study the variability in the distribution of ozone in the tropical troposphere over different sites representing different environments.

Fortnightly measurements of ozone profile were made at Ahmedabad, an urban location in the western part of India during 2003-2007 using a standard ECC ozonesonde coupled with a radiosonde (RS80). As a part of a major campaign over the Indo-Gangetic Plain (IGP) in December 2004, similar measurements were made from Kanpur, which is located in central IGP, using these sondes. The aim of this campaign was to study effects of foggy conditions on the distributions of trace gases including ozone. Another major campaign was conducted over the marine regions surrounding India namely, Bay of Bengal (BOB) and Arabian Sea (AS). A total of 30 balloon flights carrying these two sondes were launched from the ship, which covered both these marine region during March-May 2006. This study provided an opportunity to study the effects of dynamics on the distribution of ozone. These results are used to get the average distribution of ozone in the troposphere as well as to study the effects of advection, convection, and transport from the stratosphere on ozone distribution. Results from the three sets of measurements are summarized below.
6.1. Variations in vertical distribution of ozone over Ahmedabad

Ahmedabad is a semi-arid region in western India (23.03 N, 72.54 E). While, ozone soundings do not give information on the day-to-day changes associated with a particular synoptic event they provide a quantitative measure of variation in ozone throughout the troposphere. Over 80 profiles on the vertical distribution of ozone were obtained over this site from June 2003 to July 2007. These data obtained over Ahmedabad are classified into four major seasons viz winter (DJF), pre-monsoon (MAM), monsoon (JJAS) and post-monsoon (ON). Boundary layer ozone was maximum during winter and minimum during monsoon. This observation could be due to shallow boundary layer height during winter and wash out of pollutants during monsoon. The summer monsoon ozone minimum in the lower troposphere is attributed to the onset of summer monsoon when polluted air from the Asian continent is replaced by cleaner air from the tropical Indian Ocean.

The middle troposphere ozone was at its highest during the rainy season and at a minimum during post-monsoon. Near tropopause, large variability was observed during pre-monsoon and winter due to intrusion of ozone from the stratosphere. A frequently observed feature during pre-monsoon and winter was high ozone (80-170 ppbv) in the upper troposphere (from about 9 to 16 km). Integrated ozone increase due to STE for the month of March was 5 DU (Dobson unit) and for April it was 15 DU. This phenomenon is generally observed at higher latitudes in the months of March and April. However, this phenomenon was also observed at the study location. This is the first experimental study to estimate the contribution of ozone due to STE process over Ahmedabad. In the stratosphere highest peak ozone concentration was observed during rainy season and minimum during winter.

Average integrated total ozone was 261 DU and average integrated tropospheric ozone was 39.4 DU. Higher lifetime of ozone in the free troposphere increases the importance of long range transport. In the lower and mid-troposphere, higher concentrations of O₃ in the spring season could be due to long-range transport of pollutants by northwesterly
winds associated with the winter monsoon circulation. This circulation transports the ozone-rich polluted air masses from the Asian continent to this site. Conversely, low ozone (as low as 15 ppbv) values are observed over Ahmedabad during summer season (July to September). This is related to summer monsoon circulation, advecting cleaner and moist air from the Indian Ocean.

Elevated O$_3$ values of around 100-450 ppbv were observed in the middle and upper troposphere (10-14 km) during the spring season over Ahmedabad. Occurrences of high O$_3$ tongues in the spring season follow the propagation of dry air with low relative humidity, suggesting that O$_3$ is transported from higher heights, probably of stratospheric origin.

Case study of vertical profiles over Ahmedabad reveals significant day-to-day variability in the vertical structure of O$_3$ and relative humidity. These studies also revealed influences of convection and advection of various air masses within the troposphere.

Dynamics plays a major role in the seasonal distribution over Ahmedabad. In the lower and middle regions of the troposphere, low O$_3$ values with high water vapor concentrations in the summer monsoon season are pronounced. While in the upper region of the troposphere, high O$_3$ values with very low amount of water vapor in the spring season are pronounced. In the spring season, elevated O$_3$ levels over this location reflect the influence of photochemical production from precursors. Back trajectory analysis suggests that this enhancement resulted from the transport of air masses arriving at the altitudes of O$_3$ peaks in the middle troposphere passed over regions of biomass burning during this season.

6.2. Study of ozone distribution over the Indo-Gangetic Plain (IGP) during a winter month

Vertical distributions of ozone and other meteorological parameters were measured at Kanpur, an urban site in the Indo-Gangetic Plain (IGP) during December 2004 to study
the processes affecting their levels. This campaign was organized to study the effect of fog/haze on tropospheric ozone and other pollutants. During the foggy days, wind speed was very low along with shallow boundary layer height. In general, the winters in the North Indian region are dry. Six balloon flights were conducted from this site during December 2004. Three were on clear days (December 11, 15 and 29) while the remaining were on foggy days (December 18, 22 and 25).

Large variability in tropospheric ozone was observed from flight to flight. Temperature profile suggested that the average boundary layer height was about 800 m on foggy day and 1.5 km on non-foggy days. The average tropopause height was observed to be 17 ± 0.7 km. The average tropospheric column ozone was 41 ± 3 DU. It increased to 53 DU on December 25 due to intrusion of air mass from the stratosphere, which accounted for 15 – 20% of the total tropospheric ozone column.

In the lower troposphere (3-7 km) ozone concentration was higher (70 ppbv) as compared to an average of 50 ppbv based on the six balloon profiles. Back-trajectory analysis suggests that the air parcels in the enhanced ozone layers over Kanpur passed over the region of intensive seasonal burning in Africa and higher pollutant region of the Gulf.

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 data. The peak in the TTL region (14-18 km) showed an enhancement of ozone by 35-55 ppbv over the average ozone profile. The peaks at lower heights of 12 and 10 km show enhanced ozone by 20 ppbv and 35 ppbv respectively from the average ozone profile. Seven day back trajectories for the height range of 9-15 km obtained from HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model suggest that the air came from high latitudes at this site. Further, the Potential Vorticity (PV) values indicate that a jet stream came from the mid latitude in the southeast direction towards this site through the isentropic surface of 350K. Noticeably, there was a sharp PV gradient along the subtropical jet stream around 20-30 N, which is the location of active stratospheric-
tropospheric exchange. Cross-sectional view of PV shows 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 has its origin in the stratosphere. Lower ozone levels by 35-40 ppbv as compared to the average profile in the height range of 11 to 14 (December 29) were observed. Back trajectory analysis suggests that the air mass originated from a pristine marine region near the equator and traveled across the Indian Ocean, where generally low ozone values were observed as reported in earlier studies. Since ozone lifetime is higher in the free troposphere, it can get transported far away from the source regions.

A comparison of vertical profile of ozone obtained from ozonesonde with that obtained from MATCH-MPIC (Model of Atmospheric Transport and Chemistry - Max Planck Institute for Chemistry version) model was made. Among all the six profiles, model was able to reproduce large variations in the ozone profiles (e.g., high ozone on 25th December and low ozone on 29th December).

6.3. Cruise study of ozone distributions over the marine regions

Simultaneous measurements of vertical distributions of ozone and meteorological parameters were made to study variations in ozone distribution and its relationship with meteorology over the Bay of Bengal (BOB) and Arabian Sea during a cruise from 18 March to 9 May, 2006. This is the first systematic study of the vertical distribution of ozone covering both these marine regions fully during the pre-monsoon season. The northern and western Arabian Sea regions are the least studied. Most of the earlier studies e.g. INDOEX (Indian Ocean Experiment) focused on the eastern/southern Arabian Sea and attention was only on winter season (NE monsoon).

Variations in the vertical distribution of ozone and meteorological parameter show evidence of deep convection on 30 March over the central BOB (12.39N, 87.92E). The average integrated tropospheric ozone over the BOB was 36.7 ± 5.7 DU, while on 30 March at the location 12.39N, 87.92E it was only 22.4 DU (which is approximately 60%
of the average value) due to strong convective activity. Depleted ozone profile with mixing ratio of 20 ppbv up to around 6 km of altitude and 35 ppbv in the height range of 10 to 16 km were observed. However, high ozone concentrations (50-60 ppbv) from 6 - 10 km were observed. Outgoing Long wave Radiation (OLR) and the presence of clouds from satellite images indicated significant convective activity during this period, while seven day back-trajectories showed that superimposition of long range transport on this activity. The confluence of deep convection with advected dry air was a new observation. Computation of surface ozone estimated using MATCH -MPIC model also showed low ozone concentrations in this region.

The wind field analysis and back trajectory analysis did not reveal any evidence of transport from the land on 30 March except at 1 km height from India and for the height range of 7-9 km from Africa. For the height range of 7-9 km, these results show long range transport from Africa (non convective region), on the contrary trajectories for the height range of 2 to 6 km and 10 to 18 km show transport from the Pacific Ocean where a small cyclonic formation took place during that time. The back trajectories computation show lateral transport for 1 to 6 km and downward transport in the height range of 6 to 10 km whereas from 10 to 18 km it shows uplift of air mass from 4 to 5 km altitude range.

Surface ozone in north-west Arabian Sea was observed to be higher as compared to south-east Arabian Sea, while the reverse was true for ozone precursors like CO, and CH$_4$. These observations in combination with simultaneously observed dust levels suggest the loss of ozone through heterogeneous chemistry on dust particles. However, the anti-correlation between ozone and dust concentrations was weak.

Higher concentration of ozone in the upper troposphere was observed in the north Arabian Sea during first week of May. This increase was due to intrusion from the stratosphere and transport of air from the higher latitudes. It is known that incidence of stratospheric contribution is frequent and strong during spring. Average integrated
tropospheric ozone is found to be 42.5 DU which was higher than that obtained over the Bay of Bengal.

Comparison of the day-night profiles of ozone does not show any difference in the free troposphere but showed differences in the boundary layer for the profiles near the coast only. These results indicate that photochemistry played a minor role compared to the dynamics of the free troposphere.

Figure 6.1 shows average tropospheric ozone profiles observed Ahmedabad for the entire period of measurements (May 2003-September 2007), over Kanpur for the campaign period of December 2004 and over the two marine regions, Bay of Bengal and Arabian Sea during 18 March -12 April 2006 and 18 April - 10 May 2006 respectively. Even though these are for different periods, average ozone over Arabian Sea is clearly higher not only compared to over the BOB but also over urban sites of Ahmedabad and Kanpur. Higher ozone values over the Arabian sea appears to be due to transport from the stratosphere/ higher latitudes during the observation period.
6.4. Future directions and scope

The present study characterized the spatial and temporal distributions of ozone in the lower atmosphere and provided an unique opportunity to study the influence of meteorological events and long range transport. Ozone together with the meteorological parameters helps in the elucidation of stratosphere-troposphere exchange across the tropopause. Tropopause structure, temperature profile and potential vorticity are required to calculate the increase in tropospheric ozone flux from the stratosphere and its implication to its tropospheric budget.

Ozone together with available relative humidity and temperature profiles help to study the effects of convection events and change in photochemistry. Since lifetime of ozone in the free troposphere is large, once ozone gets lifted from the boundary layer into the troposphere, it can get transported to long distances. This can have significant implications on a global scale. It is also observed that in the free troposphere dynamical processes dominate over photochemistry in altering the distribution of ozone while in the boundary layer photochemistry dominates the dynamical processes. Regular measurements of ozone and its precursors in the tropical troposphere are needed to study the integrated effects of stratospheric tropospheric transport, long range transport and convection events.

This study also brings out the need to validate models to understand quantitative contribution of different chemical and dynamical processes. Due to regional nature of the sources/sinks, there is a significant spatial variability in tropospheric ozone, which makes modeling of tropospheric ozone extremely difficult. It is necessary that observations and modeling studies should complement each other for further improvement in our understanding of chemistry-transport coupling, long term changes and influence of ozone on the climate.

The marine regions are affected by transport of pollutants from the continental regions. It is also important to make regular measurements of ozone along with its precursors in the
troposphere. Limited observations during INDOEX campaign were made using aircraft borne sensors. Aircraft based studies are needed over the Indian subcontinent to understand chemistry and transport.

Numerical models in combination with field measurements have proven to be useful tools in studying the complex interactions of chemical species and meteorology in the atmosphere. Development of photochemical air quality models, which will be helpful to predict spatially and temporally resolved ambient pollutant concentrations are essential.

A network of stations for long term, simultaneous measurements of ozone and its precursor gases will be important to account for the regional contributions in the model simulations. As tropical data are still scarce, measurements at Ahmedabad should continue for a long period.

So far the focus of ozone research was mainly on stratospheric ozone, but during the last decade it has changed to tropospheric ozone. While ozonesondes provide high-resolution vertical profiles from limited sites there is a need for satellite measurements of tropospheric ozone for global coverage.


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