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Behavior of boundary layer ozone and its precursors over a great alluvial plain of the world: Indo-Gangetic Plains

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[1] We investigate the special behavior in the distribution of boundary layer ozone and its precursors over world's most extensive tract of uninterrupted alluvium and intensively farmed zones situated in the foothills of Himalayas as major river basin, known as Indo-Gangetic Plains (IGP). The study makes use of a Chemistry-Transport Model forced with dynamical fields and new emission inventories of pollutants established for 2001. It is found that the IGP region is highly vulnerable to human induced pollutant emissions due to conducive synoptic weather pattern which make it a source regions of ozone precursors within which these tracers remain confined and reinforce photochemical production of ozone. In addition, the continental tropical convergence zone and long range transport play a vital role. As a result, elevated levels of ozone concentration (maximum up to 80 ppbv) and its precursors with cellular structure of spatial variation with large seasonality are noticed. **Citation:** Beig, G., and K. Ali (2006), Behavior of boundary layer ozone and its precursors over a great alluvial plain of the world: Indo-Gangetic Plains, *Geophys. Res. Lett.*, *33*, L24813, doi:10.1029/2006GL028352.

1. Introduction

[2] Increasing contribution of atmospheric pollutants like nitrogen oxide (NO_x), carbon monoxide (CO), and volatile organic compounds to global and regional environmental changes has received much attention in recent years especially over the tropical region [*Intergovernmental Panel on Climate Change*, 2001]. These pollutants are precursors of ozone production in the troposphere. Sources of these precursors are mainly anthropogenic and lightning activities. It is a widespread concern in recent time that elevated concentration of ozone in the boundary layer has implications for human health and vegetation growth. Breathing ozone, even at relatively low abundances, is correlated with pulmonary damage and asthma attacks [*Prather et al.*, 2003]. Global chemical transport models [e.g. *Prather et al.*, 2003; *Brasseur et al.*, 2006] suggest that surface ozone concentration could increase by as much as 25–30 ppbv in tropical India between years 2000 and 2100, assuming an economic growth described by the IPCC/SRES A2 scenario. Recent studies have suggested that on account of certain specialty in the geographical locations of the regions of major river basins like IGP, boundary layer ozone and its precursors show an elevated concentration in these regions as compared to those in the rest of the surrounding regions [*Beig and Brasseur*, 2006; *Ali et al.*, 2004]. Thus, the predicted future scenario of these species over other regions appears to occur in present time over the IGP region. If we assume it as specific feature of major river basins then it should be an immediate concern to our society due to their known adverse impacts. Hence such feature should be investigated in detail which is attempted in this work. The IGP region is an area of about 700,000 km^2 with flat terrain which varies in width by several hundred kilometers stretching from the Indus River system in Pakistan to the Punjab Plain and the Haryana Plain to the delta of the Ganga in Bangladesh (shaded region in Figure 1). It is the world's most extensive tract of uninterrupted alluvium and one of the most intensively farmed zones in the world. The processes responsible for above mentioned unusual behavior in such regions are not properly understood and hence efforts should be made to understand them. Notably, the emissions of pollutants which are poorly documented especially for the South Asian region play an important role in the distribution of these tracers. Recently, emission inventory of these pollutants are made available with finer resolution [*Dalvi et al.*, 2006] which is used in the present work.

[3] In this paper, we assess, for the first time, the special features in the distribution of ozone and its precursors in different seasons over the IGP region (shown by shaded region in Figure 1) and discuss the possible processes responsible for it. For the purpose, we use the MOZART (Model for Ozone and Related Tracers) with a newly established emission inventory along with the observed winds.

2. Model Simulations

[4] The MOZART-2 chemical-transport model [*Horowitz et al.*, 2003], which is used to study the distribution of ozone and its precursors, provides the distribution of 63 chemical compounds at a horizontal resolution of ~1.8 degrees in longitude and latitude, and on 31 vertical levels extending from the surface to approximately the 10 hPa pressure level. It takes into account the surface emissions of several chemical compounds. The emissions due to various sectors used in the model for 2001 are taken similar to the work by *Beig and Brasseur* [2006]. Over the Indian subcontinent, high-resolution emission estimates from the Indian national inventory [*Dalvi et al.*, 2006] have been used which account for the rapid temporal and small-scale geographical variability. It considers discrete mixture of modern urban population and traditional rural and agro-dominated population with diverse socio-economic differences. In the adopted Indian emission inventory, total CO emission for 2001 in India (approximately 69,376 Gg/yr) contains about 50% contribution from bio-fuel sources and

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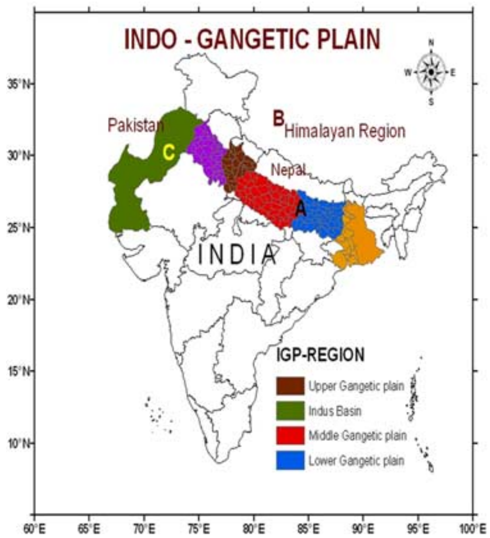

Figure 1. Geographical map showing different parts of the IGP regions (shaded area).

consists of several hotspots including those in the IGP region. The total surface NO_x emissions in the Indian region for 2001 are estimated to be 4,260 Gg NO_2/yr which contain maximum contribution by coal followed by fossil fuel combustion, bio-fuel and biomass burning. In the present study, the model simulations have used meteorological data for one specific year, i.e., 2001. It may be noted that, on account of uncertainty in emission estimates, the errors introduced in the simulated absolute concentrations of ozone and other species is likely to be less than 2–5%.

3. Results

[5] Figure 2 presents model results for pre-monsoon month (May) on the average spatial pattern, over Indian subcontinent, of the concentration of O_3, NO_x and CO near the ground surface which best represents the characteristics of ambient air. Model results also show wind vector superimposed on this plot to qualitatively explain their horizontal advection. It may be seen in Figure 2 that there are three segments of the tract of land along the IGP and the Himalayan region (marked A, B and C in Figure 1) over which the pattern of spatial distribution of ozone concentration looks cellular, that is, an area in which there is a location of maximum concentration of ozone surrounded by locations of decreasing values. The first cell (marked A in Figure 1) covers upper and middle Gangetic plains wherein the ozone level ranges 45–80 ppbv with a maximum (∼80 ppbv) around 25°N, 88°E. To the north of this part of IGP lies a large region of nearly uniform concentration of ozone in the range of 45–54 ppbv. The second cell (marked B in Figure 1) which shows relatively less pronounced cellular pattern of ozone variation forms over northern Himalayan region of India and northern Pakistan. The range of variation in the ozone concentration over this region is 45–60 ppbv. *Ali et al.* [2004] have studied surface ozone at two Himalayan locations- Mohal (31.5°N, 77°E) and Kothi (31.5°N, 77°E) and at a nearby plain station Delhi (28.4°N, 77°E). They have reported roughly the same average concentration level. Ozone concentration over the

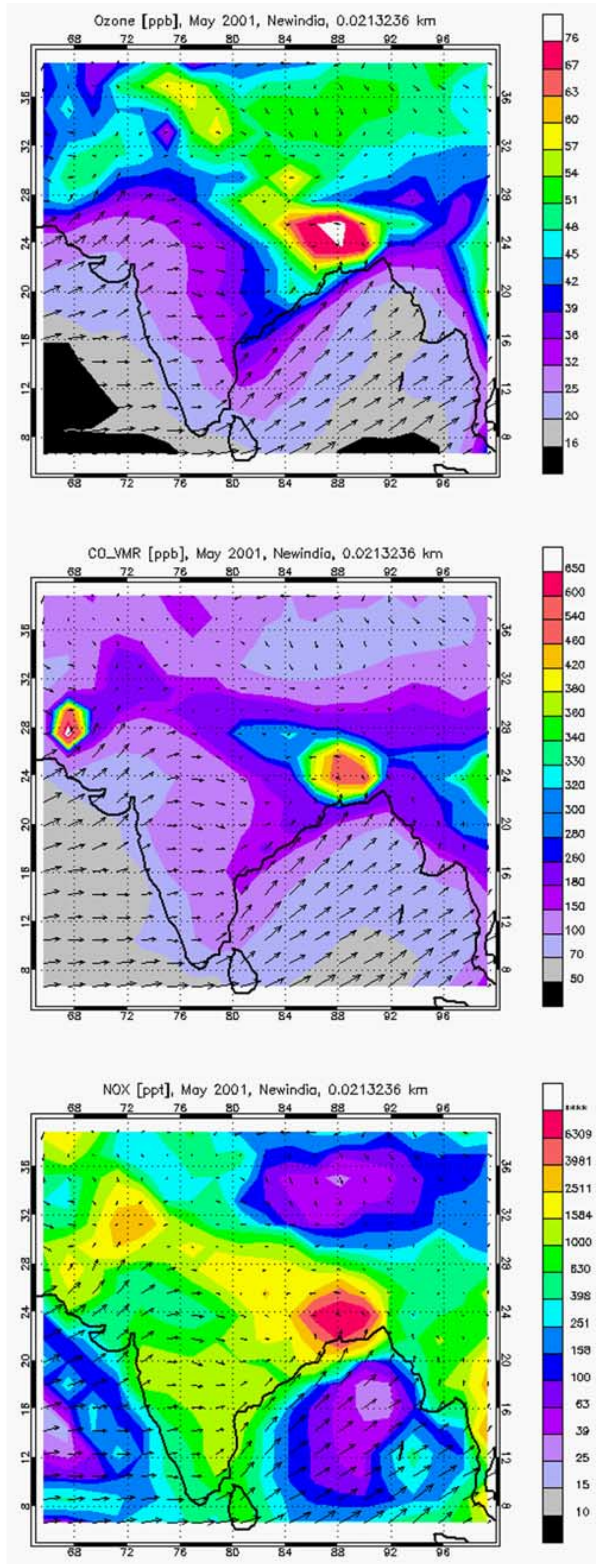

Figure 2. Distribution of O_3 (ppbv), CO (ppbv) and NO_x (pptv) at the boundary layer as simulated by MOZART for the Indian subcontinent during May (pre-monsoon season).

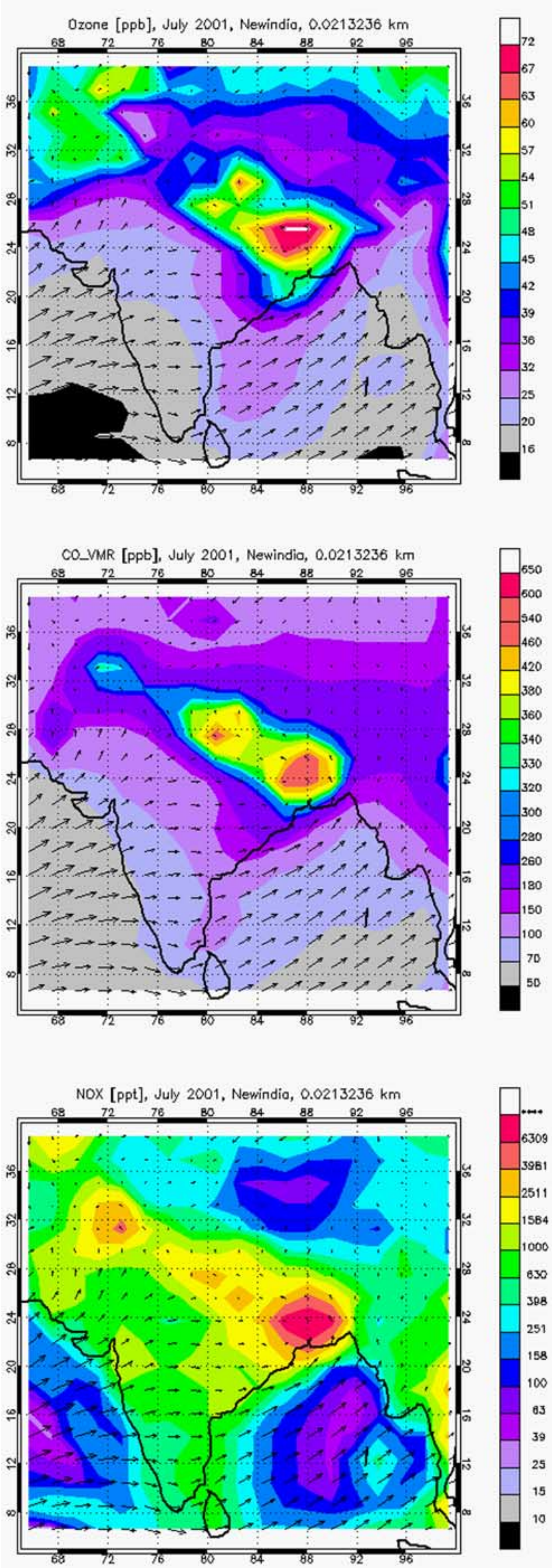

Figure 3. Same as Figure 2 but for July (monsoon season).

region constituting third cellular pattern (marked C in Figure 1) of ozone variation is further diminished. This cell includes the Indus region of northeastern Pakistan. The range of variation of ozone over this region is 45–51 ppbv. Model results for NO_x and CO also show almost similar pattern over these regions with NO_x maximum (~6.3 ppbv) and CO maximum (~600 ppbv) near the boundary between middle and lower Gangetic plains.

[6] Indian Southwest monsoon activity peaks in July and hence model results on spatial distribution of O_3 and its precursor have been obtained for July which best reflect the characteristic features for the monsoon season of 2001. This spatial pattern is shown in Figure 3. The important feature observed in this plot is two distinct regions of elevated level of ozone concentration, i.e., in the lower and middle Gangetic plains with maximum value of ozone (> 72 ppbv) around the location 26°N, 87°E and the other in the northern Pakistan region with maximum value of ozone (>51ppbv) around 34°N, 70°E location. The NO_x and CO variations over Indian region also show elevated concentration level in the same region with maximum of NO_x (~6.3 ppbv) around 24°N, 88°E and of CO (~600 ppbv) around 25°N, 88°E. This kind of pattern of variation is specific to monsoon.

[7] Spatial distribution of ozone and of its precursor gases during October, which is the representative month for post-monsoon season, is shown in Figure 4. The maximum concentration of these gases occurs over a region from middle to lower Gangetic plains with ozone maximum of around 72 ppbv and minimum of around 45 ppbv. North of the Gangetic plains, a vast region stretched between latitudes 32°N and 38°N and between longitudes 72°E and 97°E shows relatively less spatial variation in ozone concentration (45–60 ppbv). Similar feature is observed to the South of the Gangetic plains also. Variation of NO_x over IGP shows maximum value (~7.5 ppbv) around 23°N, 88°E and minimum (~0.4 ppbv) around 25°N, 75°E. The distribution of NO_x over rest of the Indian land shows variation in the range 1.6–4.0 ppbv. Spatial distribution of CO over lower and middle Gangetic Plains shows maximum around 850 ppbv and minimum around 300 ppbv. Over rest of the Indian subcontinent it shows variation in the range around 150–330 ppbv. Model calculations on the distribution of the concentration of O_3, NO_x and CO over Indian subcontinent have also been made for other different individual years. It has been found that the results for individual years do differ on minor scale in quantitative terms but the broad patterns of the trend for the chemical species are roughly similar due to specific geographical location of IGP region where seasonal synoptic weather patterns are well defined.

4. Discussion

[8] In this section an attempt has been made to understand the above mentioned specific features found in the distribution of ozone and its precursors over the IGP region during different seasons which are distinctly different from that of surrounding region. Figures 2–4 indicate relatively higher level of ozone and its precursors with sharp gradient over the IGP as compared to other parts of India. This specific feature can be attributed to several common factors.

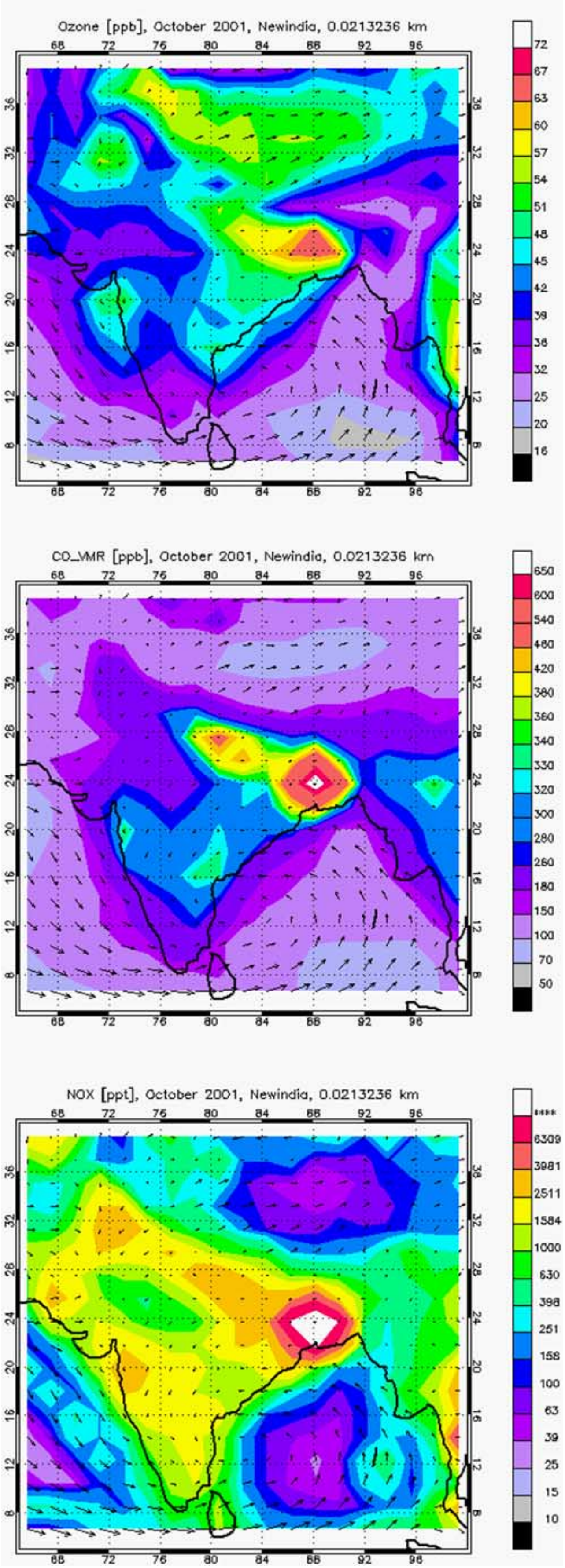

Figure 4. Same as Figure 2 but for October (post-monsoon season).

The regions of major agricultural activity in India lie along the IGP. People living in north India from the extreme east to the west mostly use coal or wood for domestic cooking. These activities add to the source of CO emissions. It may also be noted that 30 years mean number of occurrence of thunderstorm and lightning, being a minor source of NO_x in the Planetary Boundary Layer, are reported to be maximum (62% of the total number of occurrences over Indian sub-continent) over north Indian region [*Kandalgaonkar et al.*, 2005] which includes majority of the IGP region. However, the elevated levels of these trace gases indicate strong seasonal special patterns over the IGP, interpretation of each pattern is marked by different processes as discussed below.

[9] In addition to the above sources common to all seasons in IGP region, the other major local source which is responsible for emission of ozone precursor gases over north Indian region during summer months is burning of weeds and remains of the previous agricultural plants during April and May. Spraying of manures in the farm and increased lightning flashes during May are also the minor sources of ozone precursors during this season. It may be noted that monthly average lightning flash count over Gangetic West Bengal has been found maximum in May [*Kandalgaonkar et al.*, 2006]. It is normally the hottest month of the year in most parts of India, particularly in the North India, caused by intense solar flux. Thus the region, being rich in ozone precursors in this season, also provides favorable thermal condition for more local photochemical production of ozone in these regions than production in any other regions of India. However, the spatial distribution pattern of ozone and its precursors over Indian subcontinent during this season is mainly controlled by the dynamics involved in the season's synoptic weather pattern prevailing over the region. During May 2001, east-west troughs in the lower level of troposphere prevailed over regions extending either from middle or from upper Gangetic plains to Northeastern Himalayan regions. These troughs were normally effective up to a height of 0.9 km and occasionally up to 1.5 km asl. During the first week of the month, low-level cyclonic circulations were seen first over a region to the south of upper and middle Gangetic plains and then over middle to lower Gangetic plains. Also, the Trans-Gangetic Plains, northern Himalayan region of India and the Indus region recorded cyclonic circulation on a number of different occasions throughout this month [*India Meteorological Department*, 2001]. These low level troughs and the cyclonic circulations caused convergence of wind along IGP and the Northern Himalayan region resulting in trapping there of locally emitted NO_x and CO and photochemically produced ozone. Wind plots superimposed on the spatial variation of ozone and its precursor gases support this argument.

[10] During the monsoon season, the only additional contribution to the concentration of ozone precursor gases over the north Indian region is that due to increase in the NO_x concentration caused by increased frequency of lightning flashes in this season. Season-wise analysis of thunderstorm activity and associated lightning flashes over north Indian regions has revealed that their frequency of occurrence is maximum during monsoon season [*Kandalgaonkar et al.*, 2005]. However, on account of the increased frequency of lightning flashes there is only a

minor increase in the concentration of NO_x in the Planetary Boundary Layer as the lightning flashes in this season is mostly due to cloud-to-cloud discharge. Hence, this activity causes only a minor increase in the boundary layer ozone concentration. On the other hand, less availability of solar flux due to cloud cover and active washout of aerosol (containing ozone deposited onto it) through rain tend to potentially diminish the ozone level. Under the prevailing source and sink mechanisms, the most striking synoptic feature in the monsoon month of July which controls the spatial distribution of ozone and its precursors over Indian subcontinent is the continental part of the tropical convergence zone (CTCZ). This zone is characterized by a trough of low pressure extending from the Bay of Bengal through IGP to its northwestern extent of India and adjoining Pakistan. The CTCZ causes strong convergence of wind around it which results in trapping of locally generated NO_x, CO and O_3. It also triggers horizontal advection of ozone deficient moist marine winds from the Arabian Sea and the Bay of Bengal to the Indian continental region which diminish the boundary layer ozone mixing ratio there. The winds also steer the distribution pattern and tend to push it to the north of the peninsular India. Thus it is seen in Figure 3 that although there is no major change in the distribution pattern and the location-wise concentration level of NO_x during July from those during May (Figure 2), ozone concentration is less in July than in May over most of the Indian region.

[11] It is clear from Figure 4 that the maximum value of the concentration of NO_x and CO gases over IGP is more in October than those in the other two months (Figures 2 and 3). This is mainly due to occurrence of low level temperature inversion during October and also due to enhanced NO_x emissions from chemical fertilizers used in the cultivated fields. On the other hand, the maximum value of ozone in October over the IGP is lower than those in the other two months. This is mainly because of decrease in photochemical production of ozone which is attributed primarily to the availability of relatively less number of photons in October due mainly to the slant solar beams reaching over regions of northern hemisphere and also due to shorter duration of the days. In addition, high abundance of NO_x during this season may enhance the ozone loss due to titration. It is also noted that the dominant weather system during October is Western Disturbance (WD) which occurred on five occasions as an upper air system [*India Meteorological Department*, 2001] and played an important role in the spatial distribution of ozone. On account of those systems northwesterly winds, which brings cold wave lying in the rear side of the WD, prevailed over northern India and the Arabian Sea. They caused lowering of ambient air temperature bringing the temperature inversion layer to a lower level and so increasing the concentration level of all the chemical pollutants. Apart from this, the prevailing wind in this season is responsible for spreading the gases over whole land and sea areas.

5. Conclusions

[12] The IGP region records higher concentration of ozone and its precursors than the surrounding regions due primarily to its being rich in ozone precursors forced by conducive synoptic condition and due to convergence of wind along the region caused by seasonally distinct synoptic features. Mild convergence of wind during pre-monsoon season and strong convergence during monsoon season cause trapping of ozone and its precursors in the IGP region, the source region, during these seasons, whereas there is spreading of these gases from the IGP region to the other regions during post-monsoon season. During pre-monsoon, the distribution pattern of these trace species over Indian region is controlled by frequent occurrence of low level troughs and the cyclonic circulation over IGP, during monsoon by continental tropical convergence zone and during post-monsoon by western disturbances and associated low level temperature inversion.

[13] The observational study for IGP regions are sparse but the vulnerability of the region to such an escalated level of ozone and its precursors which cause adverse impact on human health and vegetation, make it important to explore further. Hence, it is stressed that a network of stations over IGP and Himalayan regions should be established to ensure its scope for future applications.

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