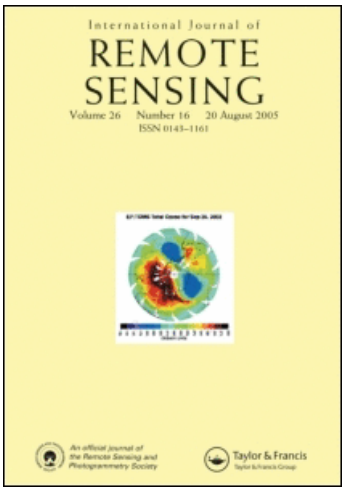

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

Annual and seasonal variations in tropospheric ozone concentrations around Varanasi

Supriya Tiwari [a]; Richa Rai [a]; Madhoolika Agrawal [a]
[a] Department of Botany, Banaras Hindu University, Varanasi, India

Online Publication Date: 01 January 2008

To cite this Article Tiwari, Supriya, Rai, Richa and Agrawal, Madhoolika(2008)'Annual and seasonal variations in tropospheric ozone concentrations around Varanasi',International Journal of Remote Sensing,29:15,4499 — 4514
To link to this Article: DOI: 10.1080/01431160801961391
URL: http://dx.doi.org/10.1080/01431160801961391

International Journal of Remote Sensing
Vol. 29, No. 15, 10 August 2008, 4499–4514

Taylor & Francis
Taylor & Francis Group

Annual and seasonal variations in tropospheric ozone concentrations around Varanasi

SUPRIYA TIWARI, RICHA RAI and MADHOOLIKA AGRAWAL*
Department of Botany, Banaras Hindu University, Varanasi, India

(*Received 12 April 2007; in final form 21 January 2008*)

This study examines the annual, seasonal and diurnal variations in the ambient concentrations of ozone at a suburban site of Varanasi, India, during 2002–2006. Prominent seasonal variations in ozone concentrations were recorded. Ozone concentrations were higher during the warmer months. Daytime 12-hourly mean monthly ozone concentrations varied from 45.18 to 62.35 ppb during summer, from 28.55 to 44.25 ppb during winter and from 24 to 43.85 ppb during the rainy season from 2002 to 2006. Distinct diurnal variations in ozone concentrations were also observed. Daytime maxima in ozone concentration were recorded between 1200 and 1400 h, whereas morning and evening hours showed lower concentrations of ozone. Ozone concentrations in the atmosphere depended on several meteorological factors. Monthly average ozone concentration was significantly correlated with maximum temperature ($p<0.001$) and mean monthly temperature ($p<0.05$), maximum relative humidity ($p<0.001$), minimum relative humidity ($p<0.001$) and mean monthly relative humidity ($p<0.001$), and sunshine hours ($p<0.001$). Ozone concentrations in the ambient air have shown an increase in the past decade that was more in the winter and rainy seasons than in the summer. This study suggests that ozone concentrations around Varanasi were sufficiently high to cause significant damage to agricultural production. The present work can be extended to a regional level by incorporating modelling studies using recent remote sensing tools.

1. Introduction

Tropospheric ozone (O_3) is considered to be the most widespread and damaging air pollutant to which living organisms are exposed (Fuhrer *et al.* 1997, Musselman and Massman 1999, Ollerenshaw *et al.* 1999, Smidt and Herman 2004). It occurs naturally at low concentrations ranging from 5 to 15 ppb (Marenco *et al.* 1994). However, in the past few decades, anthropogenic activities have led to an increase in the level of tropospheric O_3 beyond the critical limit throughout the world (Ashmore 2005, Karnosky *et al.* 2005).

The current level of O_3 is high enough to exceed the tolerance threshold of many plants, thus impairing plant growth, reducing crop yields and altering the composition of plant community (Davison and Barnes 1998). Background concentration of O_3 in the troposphere has doubled in the past decade and there is also evidence of an increase in annual mean values ranging from 0.1 to 1 ppb per year (Coyle *et al.* 2003).

*Corresponding author. Email: madhoo58@yahoo.com

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160801961391

Ozone concentration builds up in the atmosphere by several natural and anthropogenic sources. These include (1) downward transport of stratospheric O_3 through the free troposphere to near ground level, (2) *in situ* O_3 production from methane emitted from swamps and wetlands reacting with natural nitrogen oxides (NO_x), (3) production of O_3 from reaction of volatile organic compounds (VOCs) with NO_x and (4) long-range transport of O_3 from distant pollution sources (EPA 1993, Kondratyev and Varotsos 2001a,b, Varotsos *et al.* 2004). Ozone is a secondary air pollutant that is formed by the transformation reactions of primary air pollutants, especially nitrogen dioxide (NO_2). Over the past decades, motor vehicles have emerged as a crucial source of air pollutants emitting hydrocarbons and nitrogen oxides (Faiz 2000, Kondratyev and Varotsos 2002). Nitrogen oxides are rapidly oxidized to NO_2 in the atmosphere and act as a precursor to O_3, thus increasing its concentration (Dibbs *et al.* 2003). High temperature and sunlight intensity found in tropical countries are ideal conditions for O_3 formation (Varotsos *et al.* 2001*a*, 2005).

In India, despite the favourable tropical conditions for O_3 formation, very few systematic simultaneous measurements of surface O_3 have been performed. Pandey and Agrawal (1992) recorded O_3 concentrations (24 h annual mean) ranging from 6.12 to 10.2 ppb during 1989–1990 around Varanasi. During the same period O_3 concentrations (daytime 9 h mean) were reported to vary from 9.4 to 128.31 ppb at an urban site in Delhi (Varshney and Aggarwal 1992). Singh *et al.* (1997) observed that 10 h ground level mean O_3 concentrations in Delhi varied between 34 and 126 ppb during the winter season in 1993. An annual average daytime O_3 concentration of 27 ppb and hourly concentrations of 2–69 ppb at Pune during August 1991 to July 1992 were reported by Khemani *et al.* (1995). Lal *et al.* (2000) studied the patterns of O_3 concentration from 1991 to 1995 at an urban site at Ahemedabad and reported that daytime mean O_3 concentrations exceeding 80 ppb were rarely observed. A more detailed monitoring result from Delhi was reported by Jain *et al.* (2005). Increasing O_3 concentrations have been implicated as leading to severe losses in agricultural yields. Ozone affects several physiological and biochemical processes in plants, including reduction in photosynthesis (Fangmeier *et al.* 1993) and alteration in carbon and nitrogen metabolism (Agrawal and Agrawal 1990, Soja and Soja 1995), which ultimately leads to a reduction in yield (Fumagalli *et al.* 2001, 2003, Fuhrer and Booker 2003, Ishii *et al.* 2004, van Tienhoven *et al.* 2006). Field experiments conducted under the National Crop Loss Assessment Network (NCLAN) in the USA in the early 1980s and the European Open Top Chamber (EOTC) studies during 1987–1991 showed that elevated surface O_3 concentrations can substantially reduce grain yield (EPA 1996, EEA 1999). Based on the NCLAN results, yield losses of 10% were calculated for about one-third of crop species in the USA at ambient O_3 concentrations by the US Environmental Protection Agency (EPA 1996). MOZART-2 model simulation studies have predicted that because of increased levels of O_3, grain yield loss may increase from 1990 to 2020 by 2–16% for wheat, rice and corn and 28–35% for soybean in China, Japan and South Korea (Wang and Mauzerall 2004). A Community Multiscale Air Quality model has calculated highest O_3 concentrations ranging from 55 to 70 ppb during May and June in the boundary layer over East China and Japan (Yamaji *et al.* 2006). Ozone monitoring conducted in Pakistan showed that average (8 h) O_3 concentrations were 72 ppb during December 2003 to April 2004 (Wahid 2006*a*) and 71 ppb during December 2004 to April 2004 (Wahid

2006b). Ozone concentrations were investigated using the Urban Airshed Model in the Kanto area of Tokya, Japan during 1978–1994 and the highest hourly O_3 concentration during this period was 223 ppb in 1994 (Wakamatsu *et al.* 1999). In Hong Kong, when O_3 concentrations were monitored during 1994–1999, the Hong Kong Air Quality objective for O_3 (122 ppb) was violated six times, with the highest O_3 concentration being 170 ppb during August 1999 (Lee *et al.* 2002). Average summer O_3 concentrations at 28 locations in the south of the Spanish Mediterranean basin ranged from 40.8 ppb to 51 ppb depending on the distance from the urban centre (Caballero *et al.* 2007).

The European approach to determining the impact of O_3 on crops has centred around the concept of a 'critical level' (CL), which is based on a cumulative exposure above a cutoff concentration, below which only an acceptable level of harm is incurred. Based on the experimental results of the EOTC, the yield reductions were found to be highly correlated with cumulative exposure to O_3 above a threshold of 30–40 ppb during daylight hours (Fuhrer 1994). A cumulative indicator of O_3 exposure above a 40 ppb threshold (AOT40) was therefore established. AOT40 was set at 3000 ppbh accumulated during daylight hours for three months (May, June and July) when clear-sky radiation is greater than 50 W/m^2 (Fuhrer *et al.* 1997). Currently, the AOT40 parameter exceeds 3000 ppbh in most of the European Union (EU), with the exception of northern Scandinavia and the UK (Fuhrer *et al.* 1997).

Apart from phytotoxic effects, O_3 has important climatic implications because it acts as a greenhouse gas, and also has an important role in the radiative and chemical balance in the atmosphere. The development of remote sensing techniques to measure O_3 and its precursors from the Earth's surface to the tropopause is an important achievement in measuring tropospheric O_3 (TROZ) variability. It has now become possible to analyse global scale TrOZ dynamics as well as specific features of the O_3 concentration vertical profile. Several modelling studies using remote sensing as a monitoring device have predicted an increase in TROZ concentrations (Kondratyev and Varotsos 2001a,b, 2002). Saraf and Beig (2004) analysed tropospheric column ozone (TCO) data derived from an ozonesonde and the Nimbus 7 Earth Probe TOMS over three different tropical stations in India from 1972 to 2001. The average surface volume mixing ratios of O_3 during 1972–2001 were 5–100 ppb over Delhi, 5–80 ppb over Pune and 5–60 ppb over Trivandrum (Saraf and Beig 2004). To validate the modelling results, however, ground level monitoring of O_3 is also required. The present work was therefore an attempt to analyse the increasing trends in ozone concentrations over an area in the Gangetic plains of India for more than three years.

India is an agricultural country and its economy is dependent on agricultural production. A survey conducted by the Ministry of Agriculture reported that the total foodgrain production showed an increment of 12% during 1993–2005 (Indian Statistical Data 2005). However, data from the Indian Census Board reported an increase of 21.24% in the population during 1991–2001. Thus the increase in foodgrain production does not match the demands of the increasing population. Increasing air pollution is one of the factors responsible for the poor agricultural production. Ozone has emerged as the most damaging air pollutant in recent years, with plants exposed to elevated O_3 concentrations showing severe yield reductions in various crops (Wahid *et al.* 1995a,b, Reinert *et al.* 1997, Zheng *et al.* 1998, Ollerenshaw *et al.* 1999, Agrawal *et al.* 2003, Tiwari *et al.* 2006). Transect studies

conducted by Agrawal *et al.* (2003) along varying pollution load showed significant reductions in yield of mung at a suburban site of Varanasi experiencing high seasonal mean O_3 concentrations (55.7 ppb) during summer. At the same site, during winter, the yield of wheat and mustard did not vary significantly as compared to the reference site when the O_3 concentration was low (15.4 ppb).

In view of the reports of the negative impact of O_3 on crop productivity from different parts of the world and the lack of O_3 monitoring data from suburban and rural areas supporting agriculture, the present study was undertaken with the objective of long-term assessment of O_3 concentrations in the ambient environment of an agricultural area situated in the lower Gangetic plains of India experiencing a tropical monsoonic climate. Annual, seasonal and diurnal variations in O_3 concentrations were monitored from November 2002 to May 2006. Correlation of O_3 concentrations with different meteorological parameters such as temperature, relative humidity, sunshine hours and wind speed were also computed to understand their role in O_3 formation.

2. Study area

Varanasi is situated in the eastern Gangetic alluvial plains on the bank of river Ganga at 25°78′ N latitude and 83°1′ E longitude at an elevation of 76.19 m above mean sea level. The weather in Varanasi is characterized by a dry tropical monsoonic climate with three distinct seasons: summer (March–June), the rainy season (July–August) and winter (November–February). The summer season is dry, associated with strong hot winds, high temperature during the day and infrequent premonsoon rains during the late summer months. During the study period from November 2002 to May 2006, the mean monthly maximum temperature during the summer season varied from 30.25°C to 42°C and the mean minimum was between 15.75°C and 28.57°C. The mean monthly maximum relative humidity varied from 40.8% to 77% and the minimum from 20.20% to 56.75%. The rainy season starts with the onset of heavy monsoons towards the end of June and continues to mid-October, with 90% of the annual rainfall falling within four months. During this season, the mean monthly maximum temperature varied from 30.9°C to 33.66°C and the mean minimum from 19.3°C to 26.7°C. The mean monthly maximum relative humidity varied from 88.6% to 93.4% and the mean minimum from 59.4% to 74.6%. During winter, the mean monthly maximum temperature ranged from 17°C to 28.8°C and the mean minimum from 7.7°C to 15.72°C. During this season, the mean maximum relative humidity varied from 84.25% to 90% and the mean minimum from 40% to 67%. Occasional light rains result from the retreating western monsoon. Table 1 shows the meteorological conditions during the study period. The wind direction shifts from predominantly westerly and northwesterly in October to April to easterly and northwesterly in the remaining months.

In the present study, the monitoring site Susuwahi was selected in the southern region of Varanasi, about 5.8 km from the city (figure 1). Susuwahi is a suburban area characterized by large agricultural lands and lies about 3 km away from the Allahabad–Howrah highway. As such, there is no specific source of pollution except transport of primary pollutants from the city and highway. Earlier studies have shown that during most of the year, the wind flows in the direction from north to south and thus accumulation of O_3 precursors leads to higher O_3 formation at this site (Rajput and Agrawal 2004). Most of the population of this area depends on farming as their main source of livelihood.

Table 1. Meteorological parameters recorded in different seasons during the study period.

	2002–2003			2003–2004			2004–2005			2005–2006	
	S	W	R	S	W	R	S	W	R	S	W
Total rainfall (mm)	218.88	104.8	859.4	184	73.2	404.4	207	81.4	410.4	65.2	00.00
Mean maximum temperature (°C)	36.88	24.31	32.13	36.77	21.69	32.92	38.40	25.27	32.22	36.74	26.41
Mean minimum temperature (°C)	22.81	11.50	25.12	23.47	11.35	24.49	23.10	12.76	24.56	20.78	11.08
Mean maximum relative humidity (%)	70.17	82.56	88.60	63.25	86.17	86.83	58.52	82.37	87.33	64.73	85.27
Mean minimum relative humidity (%)	31.38	52.11	71.06	34.05	52.18	65.00	29.17	50.40	69.90	34.60	40.41
Mean monthly sunshine (h)	8.92	5.44	6.01	9.13	5.23	6.18	9.19	6.36	6.99	8.86	5.83
Average wind speed ($km\,h^{-1}$)	5.11	1.79	3.39	5.30	2.70	3.64	4.51	2.10	4.63	3.85	1.76

S, summer; W, winter; R, rainy season.

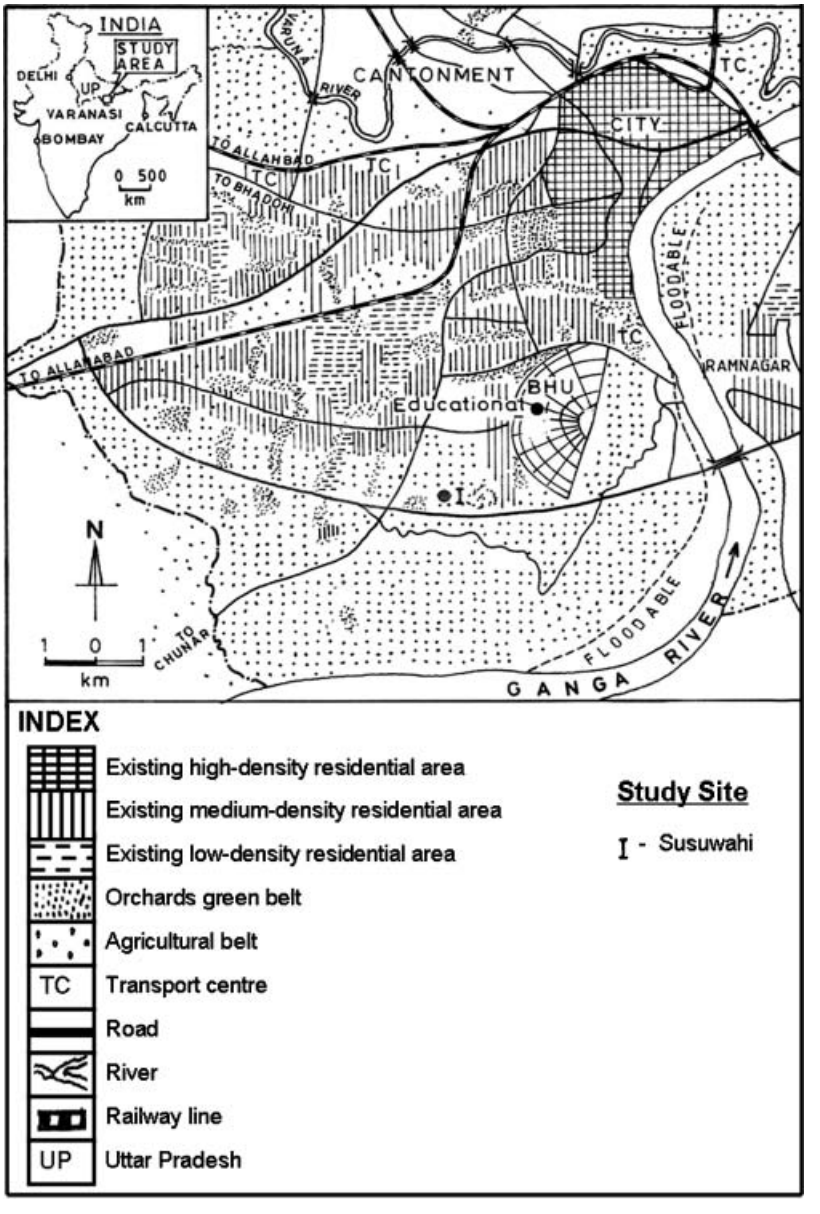

Figure 1. Map of Varanasi showing the experimental site.

3. Methodology

Air quality monitoring for O_3 was carried out using a Photometric Ozone Analyzer (Model 400A, API, Inc., USA). The detection of O_3 molecules in this instrument is based on absorption of 254 nm UV light due to the internal electronic resonance of the O_3 molecule. The Model 400A uses a mercury lamp constructed so that most of the light emitted is at 254 nm. Light from the lamp passes down a hollow quartz tube that is alternately filled with the sample gas and then the gas scrubbed to remove O_3. The ratio of the intensity of light passing through the scrubbed gas to that of the

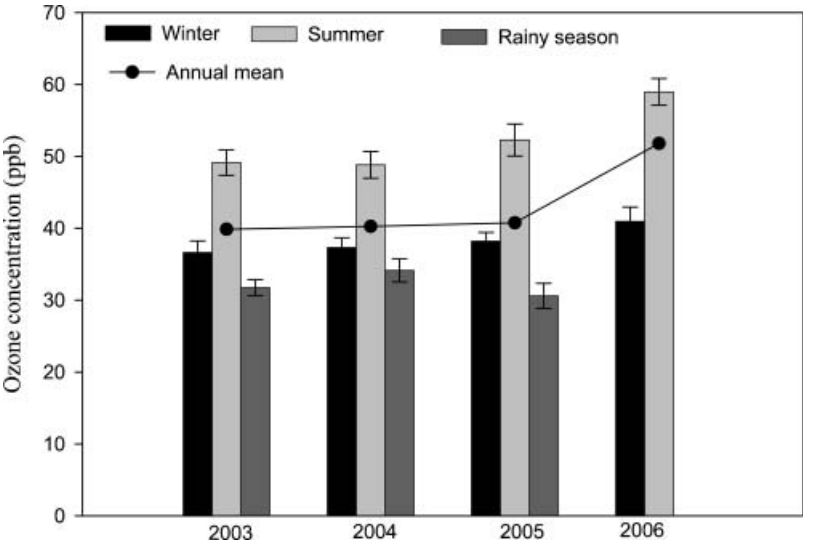

Figure 2. Seasonal and annual variations in ozone concentration in 2003–2006 (mean $\pm$ 1 standard error).

sample (I/I_o) forms the basis for the calculation of the O_3 concentrations using the Beer–Lambert law.

Air quality monitoring was conducted for 12 h from 0700 to 1900 h. During this time period the O_3 concentration reaches its daytime maxima because of favourable meteorological conditions. Furthermore, at this time the plants are metabolically most active. High O_3 concentrations during this time adversely affect various physiological and biochemical processes and ultimately the productivity of plants. Twenty-four-hour monitoring of O_3 was also conducted on selected days in 2003.

4. Results and discussion

Seasonal variations in O_3 concentration from 2002 to 2006 are shown in figure 2. Elevated O_3 concentrations ranging from 45.18 to 62.35 ppb have frequently been observed during the summer months between 0700 and 1900 h. However, O_3 concentrations were lower during the winter (28.55–44.25 ppb) and rainy (24.09–43.85 ppb) seasons. The formation of O_3 in the troposphere depends upon several meteorological factors such as temperature, sunshine hours, wind velocity and relative humidity. Elevated O_3 levels during the summer months can be attributed to high temperature, which favours photochemical production of O_3. During the monsoon periods, minimum O_3 levels were observed. This may be due to non-availability of sufficient solar radiations and washout of primary pollutants. Relatively low levels of O_3 during the winter might be due to greater atmospheric stability and an increased incidence of nocturnal inversions, which might enhance the chemical scavenging of O_3 and dry deposition (Stephens 1969). During the summer season, the 12-h mean seasonal O_3 concentration was much higher than 40 ppb (the critical level for O_3 set by the EU), which proves to be harmful to plant growth and development. Hourly O_3 concentrations during the summer months were often in excess of 100 ppb and reached as much as 142 ppb in the year 2005. High temperature favours O_3 formation, and peak O_3 concentrations were recorded

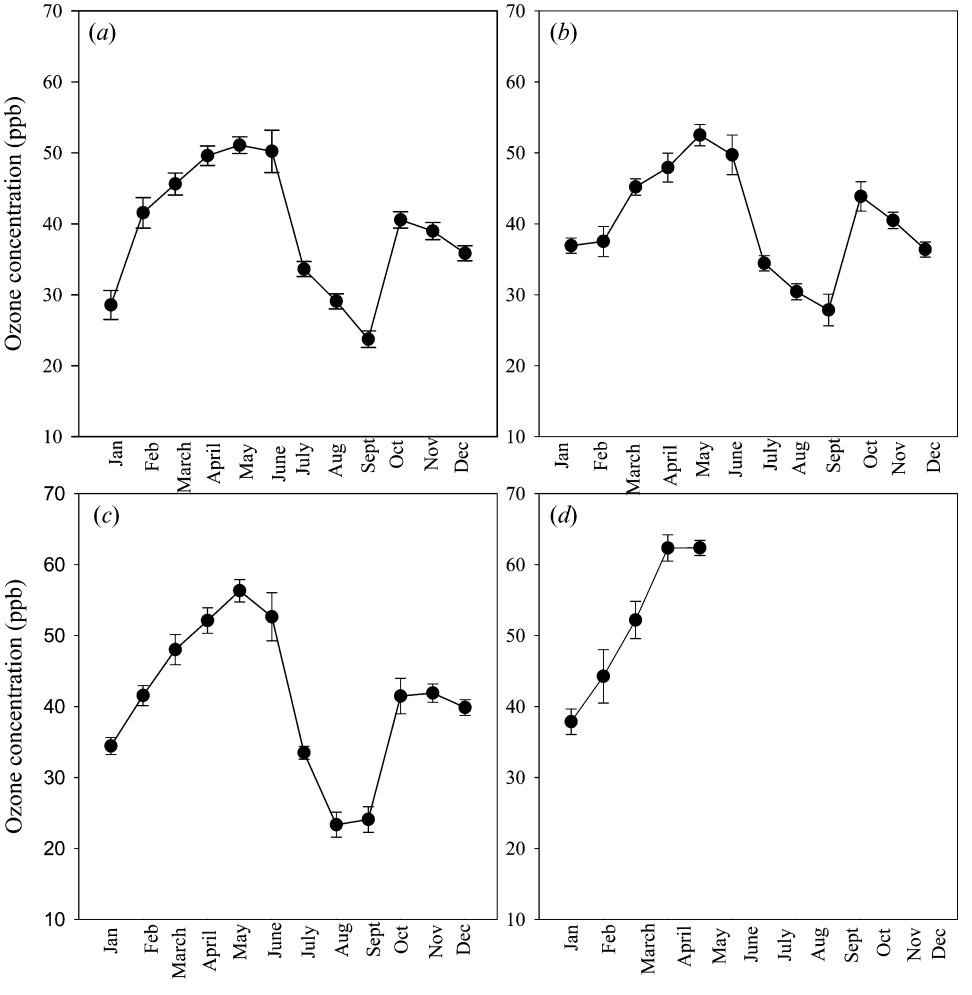

Figure 3. Mean monthly variations in ozone concentration (12 h mean) of (*a*) 2003, (*b*) 2004, (*c*) 2005 and (*d*) 2006 (mean $\pm$ 1 standard error).

during the summer months. Figure 3 shows the monthly variations in O_3 concentrations, and clearly indicates the effect of the different meteorological factors on O_3 concentration. The mean temperature remains low (8.9–20.5°C) during January and February but rises rapidly in March, reaching maxima of more than 33°C in May and June. A significant positive correlation was observed between maximum temperature (R=0.55) and mean monthly temperature (R=0.32) with mean monthly O_3 concentrations (figure 4). This indicates a temperature-dependent O_3 formation resulting in high O_3 maxima during the summer season as compared to the winter months. Besides temperature, O_3 concentrations also depend upon relative humidity. A significant negative correlation was found between mean relative humidity (R=−0.85) and mean monthly O_3 concentration (figure 5). O_3 concentrations were also significantly correlated with maximum relative humidity (R=−0.79) and minimum relative humidity (R=−0.81). Relative humidity was lowest during the summer months. The high temperature and low humidity observed during the dry summer months are favourable for O_3 formation. The

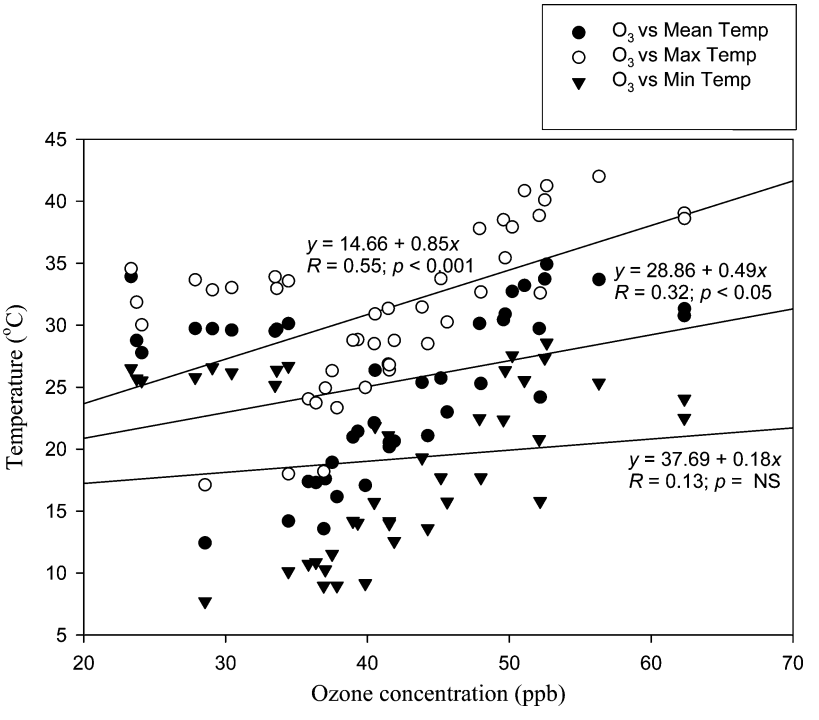

Figure 4. Correlation between mean minimum, maximum and monthly temperature and mean monthly ozone concentration during the study period. NS, not significant.

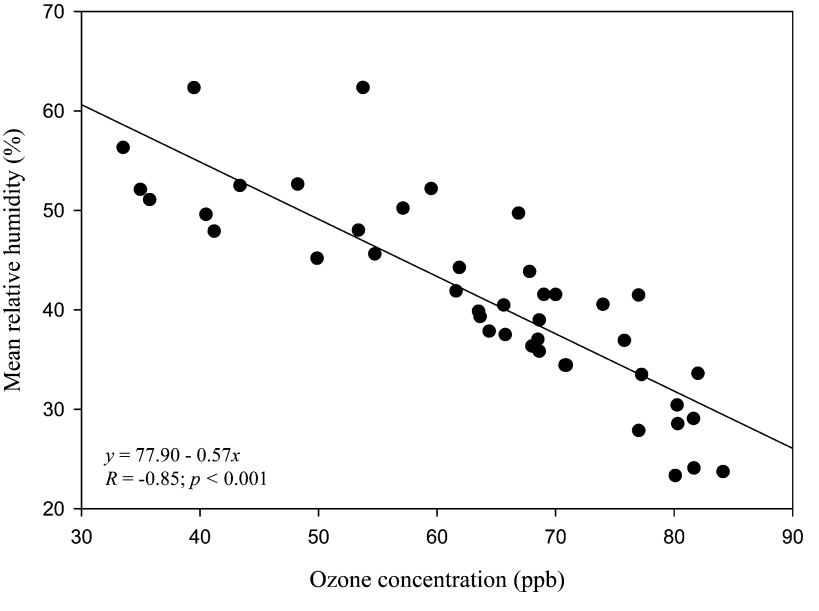

Figure 5. Correlation between mean monthly relative humidity and mean monthly ozone concentration during the study period.

condition is reversed during the winter and rainy seasons. The relative humidity is high and the temperature and sunshine hours are reduced, which explains the low O_3 concentrations during these seasons.

A similar seasonal dependence of O_3 has been reported in several other studies conducted in the USA (Cooper and Peterson 2000, Vingarzan 2004), Europe (Varotsos *et al.* 2001b, 2003), Canada (Monks 2000, Vingarzan 2004) and Korea (Ghim and Chang 2000, Kim *et al.* 2006). In Bulgaria, the average O_3 concentration during the summer was recorded in the range 46–50 ppb (Dovnev *et al.* 2002), which was slightly less than the average value of O_3 concentrations in the present study. In India, several studies have also recorded seasonal variations in O_3 concentrations (Pandey and Agrawal 1992, Varshney and Aggarwal 1992, Agrawal *et al.* 2003, Jain *et al.* 2005). Jain *et al.* (2005) observed that, in Delhi, the average monthly O_3 concentrations during the summers of 1997–2003 were in the range 62–95 ppb whereas they varied between 50 and 82 ppb in autumn (October–November) during the same time period. These values were higher than those recorded in the present study. Agrawal *et al.* (2003) reported that daytime mean O_3 concentration (6 h) was 15.44 ppb during winter and 55.70 ppb during summer of 1989 to 2000 at a suburban site of Varanasi, similar to the site selected in the present study.

The present study has also shown distinct diurnal variations in O_3 concentrations. Daytime O_3 concentrations were much higher than night-time O_3 concentrations. The hourly maxima were observed between 1200 and 1400 h whereas the evening and morning hours showed lower O_3 concentrations (figure 6). A positive correlation ($R=0.76$) between sunshine hours and mean monthly O_3 concentrations recorded in the present study explains the high O_3 concentrations during the daytime (figure 7). The daytime maxima were much higher during the summer months than the winter months (figures 8 and 9). During May, the hottest month of the year, hourly maxima reached as high as 131 ppb in 2003, 139 ppb in 2004, 142 ppb in 2005 and 150.9 ppb in 2006, whereas in January, which is the coolest month of the year, the O_3 concentration maxima were recorded to be 47.7 ppb in 2003, 49 ppb in 2004 and 47 ppb in 2005. Hourly O_3 levels often exceeded 100 ppb in

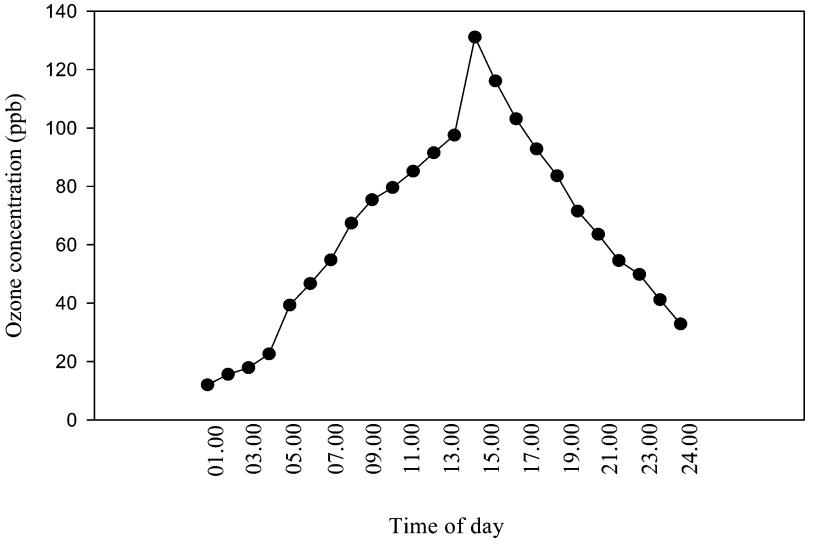

Figure 6. Diurnal variations in hourly ozone concentration during May 2003.

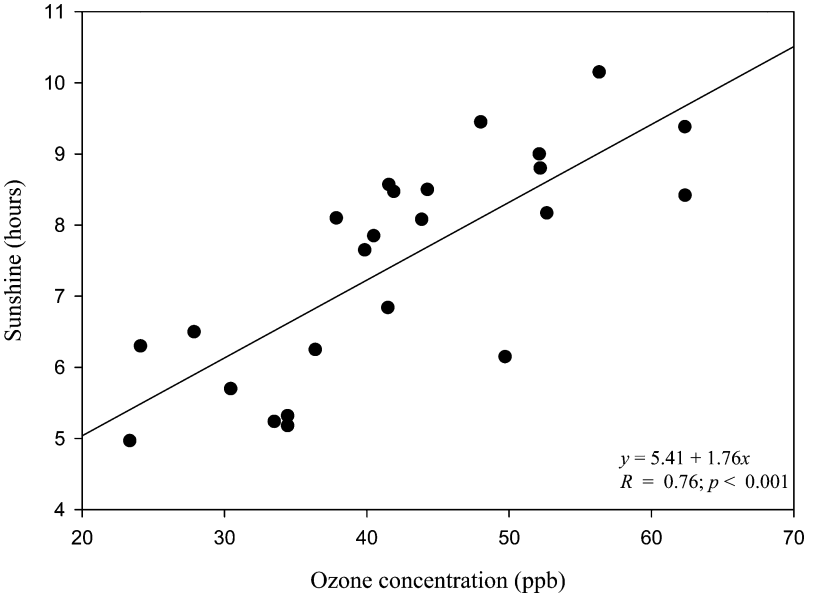

Figure 7. Correlation between mean monthly sunshine hours and mean monthly ozone concentration during the study period.

the Mediterranean region (Cartalis and Varotsos 1994, Danalatos and Glaves 1996). The maximum urban O_3 concentrations in Bulgaria during summer 2000 were reported to be 212 ppb and 248 ppb for May and June, respectively (PTL/AQ 2000). Khemani *et al.* (1995) observed that, at an urban site in Pune, the hourly O_3 concentrations during the winter period increased from a minimum value of 8 ppb to a value of 49 ppb. However, in summer the minimum O_3 value was 11 ppb, rising to

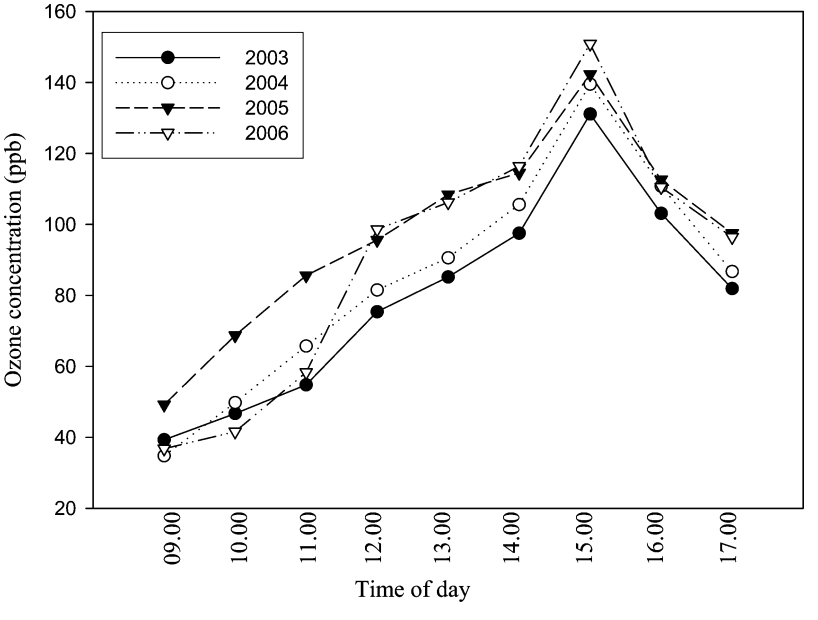

Figure 8. Daytime variation in ozone concentration on 22 May, during 2003–2006.

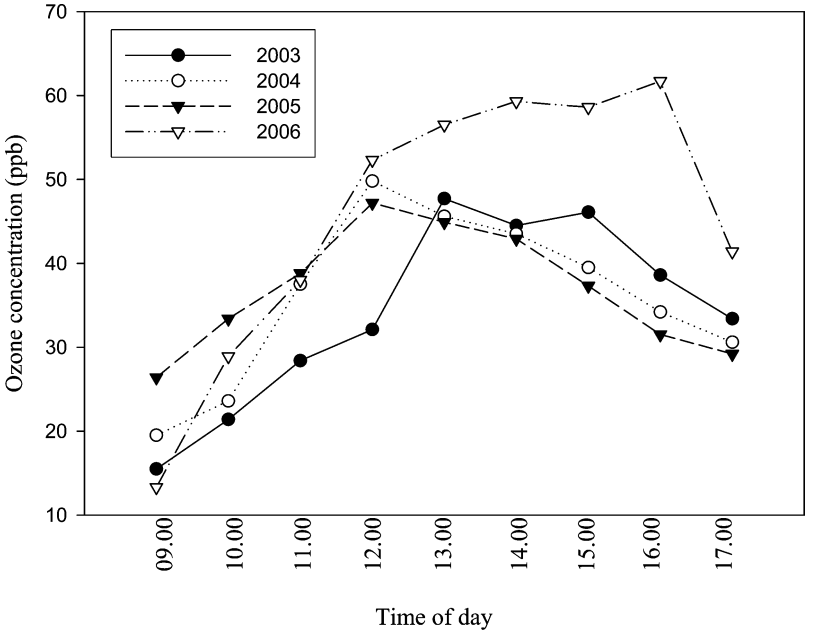

Figure 9. Daytime variation in ozone concentration on 28 January, during 2003–2006.

a maximum value of 40 ppb. These results are not in accordance with the results of the present study as the highest O_3 concentrations were recorded in the winter and not in the summer season. Similar observations were reported at Ahmedabad, where during the winter period surface O_3 concentrations increased from 18 ppb in the early morning to 55–60 ppb during noontime, whereas during the summer period they increased from 11 ppb to 30–33 ppb (Subbaraya *et al.* 1994). The higher concentration of hourly O_3 during the winter season represents characteristics of a polluted region as well as a region with high dynamical activity of the atmosphere, such as an increase in wind speed and in convective mixing height (Khemani *et al.* 1995). There is also the possibility of enhanced transport from the stratosphere, which is most effective during the winter season (Levy *et al.* 1985, Danielsen and Mohnen 1997).

This study found that the concentrations of O_3 showed an increasing trend during the course of monitoring from 2002 to 2006. The increase, however, is more in the winter and rainy seasons than in the summer season.

5. Conclusions

The mean monthly O_3 concentrations in Varanasi exceeded the limit that has been shown to cause significant damage to plant life. Maximum O_3 concentrations are found during the summer followed by the winter and rainy seasons. The O_3 concentration reached its maximum during hot and sunny days. Hourly maxima were recorded near noontime, which was found to be higher during the summer months as compared to the winter months. Ozone concentrations have shown an increasing trend in the past few years. Most crops in the developed countries are grown in summer when the O_3 concentrations are elevated and are frequently sufficiently high to reduce yields.

The present work was an attempt to assess the variations in tropospheric O_3 concentrations on a local scale. However, the monitoring network may be expanded to study the variability in O_3 concentrations over a regional scale. Remote sensing techniques need to be used to model O_3 concentrations over wider areas to predict climatic change and its impact on plant and human life.

Acknowledgements

We are grateful to the Department for International Development (DFID), UK for providing the ozone monitoring system. Financial assistance from the University Grants Commission, India and fellowships to S.T. by CSIR, New Delhi and R.R. from CAS, Botany, BHU are also acknowledged.

References

AGRAWAL, M. and AGRAWAL, S.B., 1990, Effects of ozone exposure on enzymes and metabolites of nitrogen metabolism. *Scientia Horticulturae*, **43**, pp. 169–177.

AGRAWAL, M., SINGH, B., RAJPUT, M., MARSHALL, F. and BELL, J.N.B., 2003, Effect of air pollution on periurban agriculture: a case study. *Environmental Pollution*, **126**, pp. 323–329.

ASHMORE, M.R., 2005, Assessing the future global impacts of ozone on vegetation. *Plant Cell and Environment*, **28**, pp. 949–964.

CABALLERO, S., GALLENDO, N., VAREA, M., GIL-MOLTO, J., ESCLAPEZ, R., PASTOR, C. and CRESPO, J., 2007, Spatial distribution of the tropospheric ozone concentration in a region located in the south of the Spanish Mediterranean basin. *Geophysical Research Abstracts*, **9**, pp. 03582.

CARTALIS, C. and VAROTSOS, C., 1994, Surface ozone in Athens, Greece, at the beginning and at the end of the 20th century. *Atmospheric Environment*, **28**, pp. 3–8.

COOPER, S.M. and PETERSON, D.L., 2004, Spatial distribution of tropospheric ozone in Western Washington, USA. *Environmental Pollution*, **107**, pp. 339–347.

COYLE, M., FLOWER, D. and ASHMORE, M.R., 2003, New directions: implications of increasing tropospheric background ozone concentrations for vegetation. *Atmospheric Environment*, **37**, pp. 153–154.

DANALATOS, D. and GLAVES, S., 1996, Diurnal and seasonal variations of surface ozone in a Mediterranean coastal site, Patras, Greece. *Science of the Total Environment*, **177**, pp. 291–301.

DANIELSON, E.F. and MOHNEN, V.A., 1997, Project dust storm report: ozone transport, in situ measurements and meteorological analysis of tropopause folding. *Journal of Geophysical Research*, **82**, pp. 5867–5877.

DAVISON, A.W. and BARNES, J.D., 1998, Impact of ozone on wild plants. *New Phytologist*, **139**, pp. 135–151.

DIBBS, J.E., TALBAT, R.W., SCHEUER, E., SEID, G., DEBELL, L., LEFER, B. and RIDLEY, B., 2003, Stratospheric influence on the northern North American free troposphere during TOPSE: ^{7}Be as a stratospheric tracer. *Journal of Geophysical Research*, **108**(D4), pp. 8363–8371.

EEA, 1999, *Environment in the European Union at the Turn of the Century*, Environmental assessment report No. 2 (Copenhagen: European Environmental Agency).

EPA, 1993, *Air Quality Criteria for Ozone and Related Photochemical Oxidants*, Vol. I-III. External Review Drafts. US Environmental Protection Agency, Washington, D.C. (EPA-6001P-93-004 aF-cF).

EPA, 1996, *Air Quality Criteria for Ozone and Related Photochemical Oxidants*, US Environmental Protection Agency, Office for research and development, National Centre for Environmental Alienment, Washington, D.C.

FAIZ, A., 2000, New directions: air pollution and road traffic in developing countries. *Atmospheric Environment*, **34**, pp. 4745–4746.

FANGMEIRER, A., KANBACH, F. and JAGER, H.J., 1993, Response of wheat photosynthesis to ozone: exposure response relationships achieved in greenhouse chamber fumigations. *Angewandte Botanik*, **67**, pp. 199–203.

FUHRER, J., 1994, The critical level for ozone to protect agricultural crops – an assessment of data from European open top chamber experiments. In *Critical Levels for Ozone*, UNECE Workshop Report, J. Fuhrer and B. Achermann (Eds), pp. 42–57 (Berne-Liebefeld: Swiss Federal Research Station for Agricultural Chemistry and Environmental Hyglerie).

FUHRER, J. and BOOKER, F., 2003, Ecological issues related to ozone: agricultural issues. *Environment International*, **29**, pp. 141–154.

FUHRER, J., SKARBY, L. and ASHMORE, M.R., 1997, Critical levels for ozone effects on vegetation in Europe. *Environmental Pollution*, **97**, pp. 91–106.

FUMAGALLI, I., GIMENO, B.S., VELISSARIO, D., DE TEMMERMEN, L. and MILLS, G., 2001, Evidence of ozone induced adverse effects on crops in the Mediterranean region. *Atmospheric Environment*, **35**, pp. 2583–2587.

FUMAGALLI, I., MIGNANEGO, L. and MILLS, G., 2003, Ozone monitoring with clover clones: yield loss and carry over effects under high ambient ozone levels in Northern Italy. *Agriculture Ecosystems and Environment*, **95**, pp. 119–128.

GHIM, Y.S. and CHANG, Y.S., 2000, Characteristics of ground level ozone distributions in Korea for the period of 1990–1995. *Journal of Geophysical Research*, **105**, pp. 8877–8890.

INDIAN STATISTICAL DATA, 2005, http://www.indiastut.com/india/ShowData.asp?secid=225ptid=2&level=2.

ISHII, S., MARSHALL, F.M. and BELL, J.N.B., 2004, Physiological and morphological responses of locally grown Malaysian rice cultivars (*Oryza sativa* L.) to different ozone concentrations. *Water Air and Soil Pollution*, **155**, pp. 205–221.

JAIN, S.L., ARYA, B.C., KUMAR, A., GHUDE, S.D. and KULKARNI, P.S., 2005, Observational study of surface ozone at New Delhi, India. *International Journal of Remote Sensing*, **26**, pp. 3515–3524.

KARNOSKY, D.F., PREGITZER, K.S., ZAK, D.R., KUBISKA, N.E., HENDREY, G.R., WEINSTEIN, D., NOSAL, M. and PERCY, K.E., 2005, Scaling ozone responses of forest trees to the ecosystem level in a changing climate. *Plant Cell and Environment*, **28**, pp. 965–981.

KHEMANI, L.T., MOMIN, G.A., RAO, P.S.P., VIJAYKUMAR, R. and SAFAI, P.D., 1995, Study of surface ozone behaviour at urban and forested sites in India. *Atmospheric Environment*, **29**, pp. 2021–2024.

KIM, J.H., LEE, H.J. and LEE, S.H., 2006, The characteristic of tropospheric ozone seasonally observed from ozone soundings at Pohang, Korea. *Environmental Monitoring and Assessment*, **118**, pp. 1–12.

KONDRATYEV, K.Y. and VAROTSOS, C., 2001a, Global tropospheric ozone dynamics. Part I: Troposopheric ozone precursors. *Environmental Science and Pollution Research*, **8**, pp. 57–62.

KONDRATYEV, K.Y. and VAROTSOS, C., 2001b, Global tropospheric ozone dynamics. Part II: Numerical modelling of tropospheric ozone variability. *Environmental Science and Pollution Research*, **8**, pp. 113–119.

KONDRATYEV, K.Y. and VAROTSOS, C., 2002, Remote sensing and global tropospheric ozone observed dynamics. *International Journal of Remote Sensing*, **23**, pp. 159–178.

LAL, S., NAJA, M. and SUBBARAYA, B.H., 2000, Seasonal variations in surface ozone and its precursors over an urban site in India. *Atmospheric Environment*, **34**, pp. 2713–2724.

LEE, Y.C., CALORI, G., HILLS, P. and CARMICHAEL, G.R., 2002, Ozone episodes in urban Hong Kong 1994–1999. *Atmospheric Environment*, **36**, pp. 1957–1968.

LEVY, M., MAHLMAN, J.D., MOXIM, W.J. and LIN, S.C., 1985, Tropospheric ozone: the role of transport. *Journal of Geophysical Research*, **90**, pp. 3753–3772.

MARENCO, A.H., GOUGET, P.N. and PAGES, J.P., 1994, Evidence of a long term increase in tropospheric ozone from Pic Du Midi data series, consequences, positive radiative forcing. *Journal of Geophysical Research*, **99**, pp. 166–177.

MONKS, P.S., 2000, A review of the observations and origins of the spring ozone maximum. *Atmospheric Environment*, **34**, pp. 3545–3561.

MUSSELMAN, R.C. and MASSMAN, W.J., 1999, Ozone flux to vegetation and its relationship to plant response and ambient air quality standards. *Atmospheric Environment*, **33**, pp. 65–73.

OLLERENSHAW, J.H., LYONS, T. and BARNES, J.D., 1999, Impacts of ozone on growth and yield of field grown oilseed rape. *Environmental Pollution*, **104**, pp. 53–57.

PANDEY, J. and AGRAWAL, M., 1992, Ozone: concentration variabilities in a seasonally dry tropical climate. *Environment International*, **18**, pp. 515–520.

PTL/AQ, 2000, *Phare Topic Link on Air Quality (PTL/AQ) Ozone Exceedances Summary Table, Summer Season 2000*, Available online at: www.chmi.ez/uoco/isko/ptl/about.html.

RAJPUT, M. and AGRAWAL, M., 2004, Physiological and yield response of peaplants to ambient air pollution. *Indian Journal of Plant Physiology*, **9**, pp. 9–14.

REINERT, R.A., EASON, G. and BARTON, J., 1997, Growth and fruiting of tomato as influenced by elevated CO_2 and O_3. *New Phytologist*, **137**, pp. 411–420.

SARAF, N. and BEIG, G., 2004, Long term trends in tropospheric O_3 over the Indian tropical region. *Geophysical Research Letters*, **31**, pp. L05101 (doi: 10.1029/2003GL018516).

SINGH, A., SARIN, S.M., SHANMUGAM, P., SHARMA, N., ATTRI, A.K. and JAIN, V.K., 1997, Ozone distribution in the urban environment of Delhi during winter months. *Atmospheric Environment*, **31**, pp. 3421–3427.

SMIDT, S. and HERMAN, F., 2004, Evaluation of air pollution related risks for Austrian mountain forests. *Environmental Pollution*, **130**, pp. 99–112.

SUBBARAYA, B.H., LAL, S., MODH, K.S. and NAJA, M., 1994, Monitoring of surface ozone at Ahemedabad. In *Proceedings of the International Conference on Regional Environment and Climate Changes in East Asia*, Taipei, Taiwan, November–December 1994, pp. 195–198.

TIWARI, S., AGRAWAL, M. and MARSHALL, F., 2006, Evaluation of ambient air pollution impact on carrot plants at a suburban site using open top chambers. *Environmental Monitoring and Assessment*, **119**, pp. 1–15.

VAN TIENHOVEN, A.M., ZUNCKEL, M., EMBERSON, L., KOOSAILEE, A. and OTTER, L., 2006, Preliminary assessment of risks of ozone impacts to maize (*Zea mays*) in Southern Africa. *Environmental Pollution*, **140**, pp. 220–230.

VAROTSOS, C., ALEXANDRIS, D., CHRONOPOLUS, G. and TZANIS, C., 2001a, Aircraft observations of the solar ultraviolet irradiance throughout the troposphere. *Journal of Geophysical Research: Atmospheres*, **106**, pp. 14843–14854.

VAROTSOS, C., CARTALIS, C., VLAMAKIS, A., TZANIS, C. and KERAMITSOGLOU, I., 2004, The long term coupling between column ozone and tropopause properties. *Journal of Climate*, **17**, pp. 3843–3854.

VAROTSOS, C., EFSTATHIOU, M.N. and KONDRATYEV, K.Y., 2003, Long term variation in surface ozone and its precursors in Athens, Greece. A forecasting tool. *Environmental Science and Pollution Research*, **10**, pp. 19–23.

VAROTSOS, C., KONDRATYEV, K.Y. and EFSTATHIOU, M., 2001b, On the seasonal variations of surface ozone in Athens, Greece. *Atmospheric Environment*, **35**, pp. 315–320.

VAROTSOS, C., ONDOV, J. and EFSTATHIOU, M., 2005, Scaling properties of air pollution in Athens, Greece and Baltimore, Maryland. *Atmospheric Environment*, **39**, pp. 4041–4047.

VARSHNEY, C.K. and AGGARWAL, M., 1992, Ozone pollution in the urban atmosphere of Delhi. *Atmospheric Environment*, **26**, pp. 291–294.

VINGARZAN, R., 2004, A review of surface ozone background levels and trends. *Atmospheric Environment*, **38**, pp. 3431–3442.

WAHID, A., 2006a, Influence of atmospheric pollutants on agriculture in developing countries: a case study with three new wheat varieties in Pakistan. *Science of the Total Environment*, **371**, pp. 304–313.

WAHID, A., 2006b, Productivity losses in barley attributable to ambient atmospheric pollutants in Pakistan. *Atmospheric Environment*, **40**, pp. 5342–5354.

WAHID, A., MAGGS, R., SHAMSI, S.R.A., BELL, J.N.B. and ASHMORE, M.R., 1995a, Air pollution and its impacts on wheat yield in Pakistan Punjab. *Environmental Pollution*, **88**, pp. 147–154.

WAHID, A., MAGGS, R., SHAMSI, S.R.A., BELL, J.N.B. and ASHMORE, M.R., 1995b, Effect of air pollution on rice yield in Pakistan Punjab. *Environmental Pollution*, **90**, pp. 323–329.

WAKAMATSU, S., ITSUSHI, U., TOSHIMASA, O. and KENNETH, S.L., 1999, A study of the relationship between photochemical ozone and its precursor emissions of nitrogen oxides and hydrocarbons in Tokyo and surrounding areas. *Atmospheric Environment*, **33**, pp. 3097–3108.

WANG, X. and MAUZERALL, D.L., 2004, Characterizing distribution of tropospheric ozone and its impacts on grain production in China, Japan and South Korea: 1990 and 2000. *Atmospheric Environment*, **38**, pp. 4348–4402.

YAMAJI, K., OHARA, T., UNO, I., TANIMOTO, H., KUROKAWA, J. and AKIMOTO, H., 2006, Analysis of seasonal variation of ozone in the boundary layer in East Asia using the Community Multiscale Air Quality model: what controls surface ozone level over Japan? *Atmospheric Environment*, **40**, pp. 1856–1868.

ZHENG, Y., STEVENSON, K.J., BARROWCLIFFE, R., CHEN, S., WANG, H. and BARNES, J.D., 1998, Ozone levels in Chongqing: a potential threat to crop plant commonly grown in the region? *Environmental Pollution*, **99**, pp. 299–308.