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Measurements of ozone and its precursor nitrogen dioxide and crop yield losses due to cumulative ozone exposures over 40 ppb (AOT40) in rural coastal southern India

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Abstract Measurements of ground level ozone (O_3), nitrogen dioxide (NO_2) and meteorological parameters (air temperature, relative humidity and wind speed and direction) has been made for 3 years from March 2007 to February 2010 at Nagercoil (8.2°N, 77.5°E, 23 m above sea level), an equatorial rural coastal site of southern India. The monthly average of daytime maximum of O_3 concentrations ranged from 28 to 50 parts per billion (ppb) with an annual average of 19.8 ppb. Similarly, monthly average of NO_2 concentration ranged from 3.4 ppb to 7.7 ppb with an annual average of 5.3 ppb. The monthly variation of meteorological parameters shows the little changes being a coastal site. The estimated summer crops yield losses by 1.1–15.6 % from present O_3 concentration level associated with AOT40 index 3.1–5 ppm h.

Keywords Ground level ozone · Precursor · Atmospheric conditions · Crop damage

1 Introduction

Ground level ozone (O_3) is increasing at the rate of 0.5–2 % year^{-1} over the Northern Hemisphere due to increase in anthropogenic activities on the earth surface (Vingarzan 2004). The O_3 on which attention has becoming increasingly focused in the context of its negative impacts on human and vegetation (Ashmore et al. 2006; Amann et al. 2008). Amann et al. (2008) reported that exposure to high O_3 levels greater than 90 parts per billion (ppb) (permissible limit) hourly averages is linked to respiratory problems. Similarly, due to phytotoxic nature of O_3 greater than 40 ppb (threshold limit) has the potential to cause adverse impacts on growth and yield of agriculture and horticulture crops (Fuhrer 2009 and references

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therein). Further, O_3 has undesirable effects on yield quality of crops that directly affect seed and fruit chemistry as well as forage nutritive value (Royal Society 2008; Booker et al. 2009).

O_3 is the most important oxidant in the troposphere. It is formed through the photochemical oxidation of precursor pollutants such as nitrogen oxides (NO_x=NO+NO_2), volatile organic compounds (VOC), methane (CH_4) and carbon monoxide (CO) in the presence of sunlight. The formation O_3 is controlled by NO_x in India indicates that the O_3 concentration increases with increase of NO_x concentration (Lelieveld et al. 2001). The O_3 precursor gases emission are mainly increasing due to increase of automobile sector. Streets et al. (2003) reported that the emission of NO_x is increasing at the rate of 6.5 % year^{-1} over the Indian region. The automobile contributes highest 34 % of the total NO_x emission (4.6 Tg) in India between year 2000. Similarly, Ohara et al. (2007) reported that the NO_x Asian emissions increased by 3 times in the year 1980–2003 with highest increase in China followed by in India. The information on O_3 measurements is limited in India; the available studies have suggested that O_3 concentrations can reach potentially damaging levels of crops (Mittal et al. 2007; Engardt 2008; Debaje et al. 2010). Model studies by Mittal et al. (2007) and Engardt (2008) have shown that the daytime monthly mean of O_3 concentration ranges between 30 ppb and 45 ppb for the year 2000 over the Indian region and exceeds AOT40 index critical limit of 3 ppm h of 3-months growing period of agriculture crops responsible for 5 % crops yield losses by O_3 damage. Further, Debaje et al. (2010) estimated that the winter wheat and summer crops yield losses by 10 % and 15 %, respectively using AOT40 index from present measured O_3 pollution level in the rural India.

Emberson et al. (2009) reported that crops respond differently to O_3 exposure in Asia (India in particular) than in USA and Europe underestimating crop yield losses occur at the present O_3 concentration. A recent synthesis of experimental data from Asia shows that today's concentrations (40–80 ppb) of O_3 cause yield losses of three staple Asian crops (wheat, rice and legumes) that vary between 5 % and 48 %, 3–47 % and 10–65 % respectively. Similarly, Feng and Kobayashi (2009) reported wheat yield losses by 9.7 % at O_3 concentration 31–50 ppb using meta-analysis study and 5 % yield losses in number of crops. Wang and Mauzerall (2004) calculated that in China, Japan and South Korea 1–9 % of wheat, rice and corn yields and 23–27 % of soybean yield were lost due to 1990 levels of O_3 and that losses may exceed 30 % by 2020 using MOZART-2 model simulation. Van Dingenen et al. (2009) estimate economic loss for four crops (wheat, rice, maize and soybean) for the world and largest losses are found in India between US$3 and US$6 billion for the year 2000 and ranking highest economic losses about 22 % (US$ 4.5 billion) followed by 21 % (US$ 4.3 billion) in China.

A few scattered O_3 measurements are available over the Indian southern coastal region (Nair et al. 2002; Debaje et al. 2003; David and Nair 2011; Nishanth et al. 2012). The daytime maximum of O_3 concentration reaches greater than 48 ppb during the summer season at Thumba (Trivandrum) and Kannur sites (Nair et al. 2002; David and Nair 2011; Nishanth et al. 2012). Similarly, the average maximum O_3 concentrations greater than 40 ppb at Tranquebar was reported by Debaje et al. (2003).

In this study, we present ground level ozone (O_3), nitrogen dioxide (NO_2) and meteorological parameters (air temperature, relative humidity and wind speed and direction) measured for 3 years from March 2007 to February 2010 (study period) for the first time in this region at Nagercoil, an equatorial rural coastal site on the Arabian Sea and Bay of Bengal, a southern extreme continental part of India. Diurnal, monthly and seasonal variations of O_3 were studied in the light of NO_2, temperature, relative humidity, wind speed and direction and prevailing atmospheric conditions. The crops yield losses estimated in summer season due to cumulative O_3 exposures over 40 ppb using AOT40 index is discussed.

2 Location of site, measurement techniques and method

2.1 Description of site

Figure 1 presents a map of India showing measuring site-Nagercoil (8.2°N, 77.5°E, 23 m above sea level), and a few other sites which are located around it and mentioned in the present study. The population of the Nagercoil town was around 0.35 million as per 2011 census. There is no industrial complex located in the town. However, registered vehicles about 0.25 million in district Kanyakumari, Tamil Nadu state as on 1 April 2010 (STA 2010).

2.2 General meteorology

The month April is the representative for the summer season (March-May). The bright sunshine hours are experiences during these 3 months. The sunshine duration was longer (12.74 h/day)

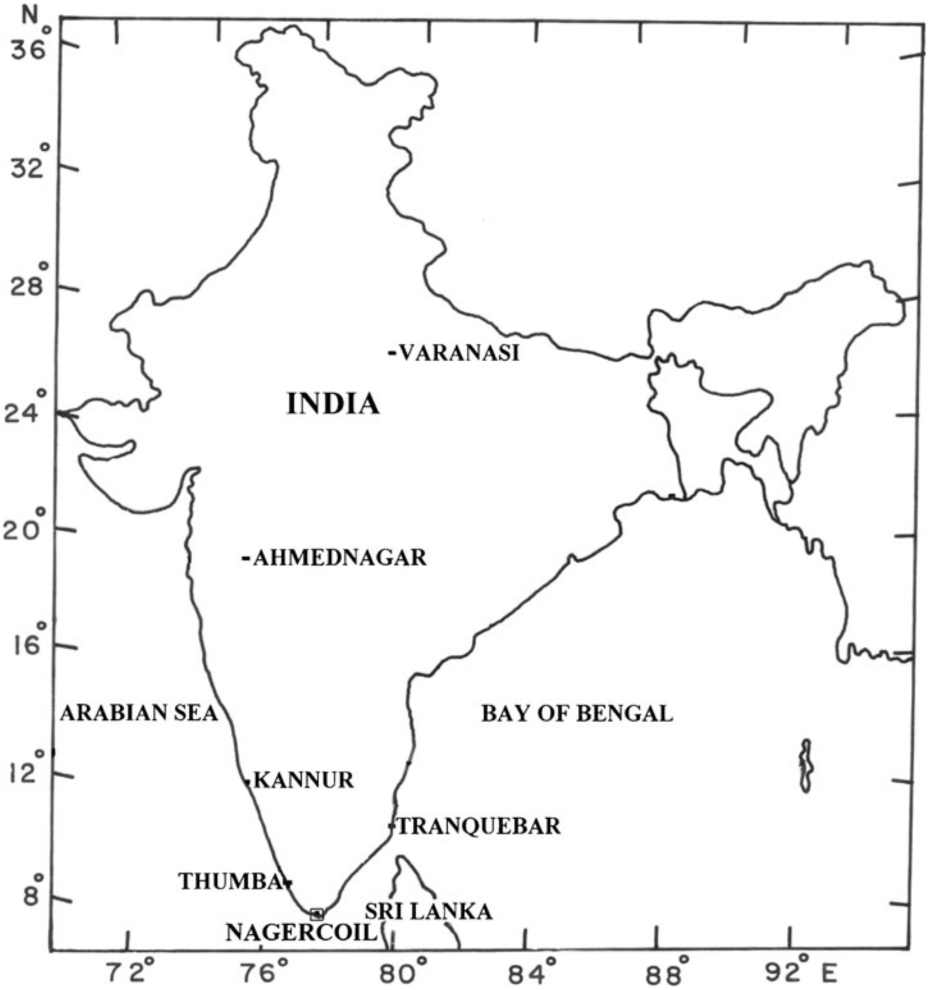


Fig. 1 Map of India shows the measurements site-Nagercoil and some other adjacent sites used in the study

during April and shorter (5.74 h/day) during November (CGWB 2008). Table 1 shows the atmospheric conditions observed during the study period at Nagercoil. The average highest maximum (minimum) temperature 31.5 °C (26.4 °C) in April, and lowest 30 °C (24.3 °C) was in January during winter season indicating less variation in temperature being a coastal site. The hot and cloudy weather with moderate rainfall prevails during pre-monsoon season (June–September). Nagercoil receives rainfall both from northeast (NE) monsoon (October–December) and southwest (SW) monsoon (June–September); however, it seems that NE monsoon is more active than the SW monsoon. The month November is a rainiest month during NE monsoon season. The total annual normal rainfall is 83 cm reported by the nearest observatory Kanyakumari (8.1°N, 77.5°E, 37 m above sea level), India Meteorological Department (IMD) (http://www.imd.gov.in). Fair weather conditions prevail in the month of February is the representative for the winter season (January–February). The surface meteorological parameters such as cloud cover and rainfall are used from Kanyakumari observatory to explore their role on O_3 formation (Debaje et al. 2003; IMD 2010).

2.3 Measurement techniques

Measurement of O_3, NO_2 in parts per billion (ppb) and meteorological parameters were carried out using the Aeroqual Series 200 Handheld Monitor (Aeroqual Limited, New Zealand) at Nagercoil, India. The more details about the instrument are available at website www.aeroqual.com. Gas Sensitive Semiconductor (GSS) technology is used to measured the gases. The sensor head is controlled by intelligent data logger. The operating chemical parameters are O_3 (detection range 0–500 ppb) and NO_2 (detection range 0–200 ppb). The lower detection limit for O_3 and NO_2 is 1 ppbv and response time for O_3 less than 70 s and NO_2 less than 60 s. The meteorological parameters such as air temperature (°C), relative humidity (%) and wind speed (ms^{-1}) and direction (16 points compass) are also measured using different sensors. The lower detection limit for temperature sensor is 0.01 °C and for relative humidity sensor 1 % and response time less than 1 s. All times are given in Indian Standard Time (IST), which is ahead of the GMT by 05:30 h. The O_3 sensor was calibrated with the ultraviolet (UV) photometric O_3 analyzer (Model: $O_3$42M, Environmental S. A., France) by running them together with averaging time interval of 1 h, and correlation coefficient is found to be 0.86–0.94. Similarly, NO_2 sensor was calibrated with the chemiluminescence's technique (Model: APNA 365 analyzer, Horiba, Japan) by running them together with averaging time interval of 1 h, and correlation coefficient is 0.84–0.91.

All data analyses in this study are based upon the hourly averaged of O_3, NO_2, temperature, relative humidity and wind speed and direction. The daily means of O_3, NO_2, temperature, relative humidity and wind speed and direction was calculated from the hourly average. The monthly average of O_3, NO_2, temperature, relative humidity and wind speed and direction was calculated from the daily mean for each month. The monthly average daytime maximum value of O_3 was calculated from averaging daily single maximum values of O_3 concentration for each month. The monthly diurnal means of O_3, NO_2, temperature and relative humidity was computed by averaging for all days of a month for specific hour. The annual and seasonal diurnal means of O_3 are computed by averaging for all months of a year.

2.4 Method

Crop yield losses due to cumulative O_3 exposures over 40 ppb was estimated using AOT40 index (accumulated O_3 concentration over a threshold of 40 ppb) (Mills et al. 2007). AOT40 is the hourly mean O_3 concentration accumulated over a threshold O_3 concentration of

Table 1 Monthly variation of air temperature (minimum/maximum), relative humidity (minimum/maximum) and wind speed and direction measured for 3 years from March 2007 to February 2010 at Nagercoil

	Air temperature (°C)				Relative humidity (%)				Wind speed (ms^{-1})/Direction		
	2007–08	2008–09	2009–10	Avg.	2007–08	2008–09	2009–10	Avg.	2007–08	2008–09	2009–10
March	25.3/31.1	25.4/30.4	26.6/31.3	25.6/30.9	59/81	55/77	60/79	58/79	1.9/W	1.9/WSW	1.7/W
April	26/31.8	26.6/31.2	27.3/31.7	26.4/31.5	61/83	59/79	58/79	59/80	2/W	1.8/WNW	2.3/W
May	26.7/31.4	26.8/31.1	27.5/30.9	27/31.1	65/86	63/82	64/80	64/83	2.2/NW	2/WNW	2/WNW
June	24.4/29.5	25.8/30	26.3/30	25.5/29.8	72/89	70/88	73/86	72/88	1.5/NW	2.2/WNW	2.2/WNW
July	24.4/28.9	25.2/29.4	25.4/29.7	25/29.3	75/90	75/91	76/90	75/90	2.5/WNW	2.6/NW	3/NW
August	25.5/29.5	25.1/29.8	25.4/29.8	25.3/29.7	70/87	74/88	74/90	73/88	2.7/NW	2.6/WNW	2.6/NW
September	24.8/29.1	25.3/29.5	25.9/29.6	25.3/29.4	71/91	72/88	75/89	73/89	2.2/NW	2.2/NW	2.3/WNW
October	25.9/29.7	25.4/29.6	26.0/29.8	25.7/29.7	68/89	71/88	71/85	70/87	1.6/W	1.9/W	2.9/WNW
November	24/30.3	25.6/29.9	25.5/29.5	25/29.9	64/91	69/92	72/92	68/92	1.5/N	1.7/NE	1.6/NE
December	25/30.5	24.7/30.4	25.7/29.8	25.1/30.2	63/83	65/87	63/84	64/85	1.3/W	2.3/SW	1.4/SW
January	24.5/30.7	23.6/29.8	24.8/29.6	24.3/30	52/80	56/81	62/80	57/80	1.6/WSW	1.2/SW	1.5/WSW
February	24.3/30.9	24.7/29.9	25.9/30.9	24.9/30.5	54/79	56/81	55/76	55/79	2/W	1.5/W	1.3/W
Avg.	25.2/30.2	25.4/30.2	25.8/30.2	25.4/30.2	65/86	66/85	66/84	66/85			

40 ppb during daylight hours for 3-months of growing (November-December) to harvesting (March–April) period for agricultural and horticulture crops and is linearly correlated with crop yield reduction, unit's parts per million hours (ppm h, hourly average). AOT40 is calculated mathematically as (Engardt 2008):

$$\mathrm{AOT40} = \sum_{i=1}^{n} ([\mathrm{O_3}]-40)\mathrm{i}\ \mathrm{for}[\mathrm{O_3}] > 40\ \ \mathrm{ppb\ during\ daylight\ hours}$$

$[O_3]$ = hourly averaged O_3 concentration in ppb; 40 = threshold limit of O_3 and n is the number of hours from growing to harvesting season of crop.

3 Results and discussion

3.1 Diurnal variation

Figure 2a shows the annual average diurnal variations of O_3 for the 3 years 2007, 2008 and 2009. The highest and lowest concentration of O_3 was observed in April and November, respectively; hence, it is investigated separately in Fig. 2b. The annual average daytime maximum of O_3 concentration 33.3±8, 30.3±8 and 34.6±10 ppb in the afternoon around 15:00 h and minimum of O_3 9.1±5, 9±5 and 9.8±7 ppb at the sunrise 06:00 h with 1σ standard deviation in 2007, 2008 and 2009, respectively (Fig 2a). The highest maximum of O_3 concentration 49.7±17 ppb (27.7±8 ppb) (average for 3 years) was observed in the afternoon and minimum of O_3 16.5±11 ppb (8.1±6 ppb) at the sunrise in April (November) (Fig. 2b). It was observed that hourly averaged daytime highest maximum of O_3 exceeds 75 ppb in the afternoon in April attributed to the high temperature and clear sky along with high NO_2 concentration (favorable conditions for O_3 formation).

The daytime maximum of O_3 concentration was observed between 14:00 h and 16:00 h, and corresponding maximum air temperature attained between 13:00 h and 15:00 h indicating peak O_3 concentration lagged behind nearly by 1–2 h from peak air temperature (Figs. 2 and 4). Debaje and Kakade (2009) reported the similar time lag from peak air temperature to peak O_3 concentration at continental rural site. Similarly, the maxima of O_3 concentration were always observed in the afternoon in all seasons similar to other coastal rural sites in southern India, a characteristic of rural site (Nair et al. 2002; Debaje et al. 2003; David and Nair 2011; Nishanth et al. 2012).

Figure 3a, b shows the annual average diurnal variation of NO_2 for 3 years 2007, 2008 and 2009, and diurnal variation in April and November. It is seen from the Fig. 3a that highest NO_2 concentration 6.5, 6.5 and 6.6 ppb was observed at around midnight 24:00 h and minimum of NO_2 1.7, 1.8 and 2.8 ppb in the afternoon at 15:00 h in 2007, 2008 and 2009, respectively. The maximum of O_3 concentration formed at around 15:00 h, and corresponding minimum of NO_2 observed at the same time indicate that NO_2 utilized in the O_3 formation. The significant year to year differences in annual diurnal NO_2 variation were not observed in 3 years period, however, higher NO_2 concentration was observed in 2009 than NO_2 concentration in 2007 and 2008. The maximum NO_2 concentration 8.5 ppb (4.2 ppb) was observed in the midnight and the minimum of NO_2 3.2 ppb (0.9 ppb) in the afternoon in April (November) (Fig. 3b). It is to be noted that the small upper side kink in the diurnal pattern of NO_2 were observed at around 9:00 h due to morning rush hours of traffic emission.

The high concentration of NO_2 in April was due to biomass burning and low NO_2 in November because of rainy season. The biomass burning from March to May in India results

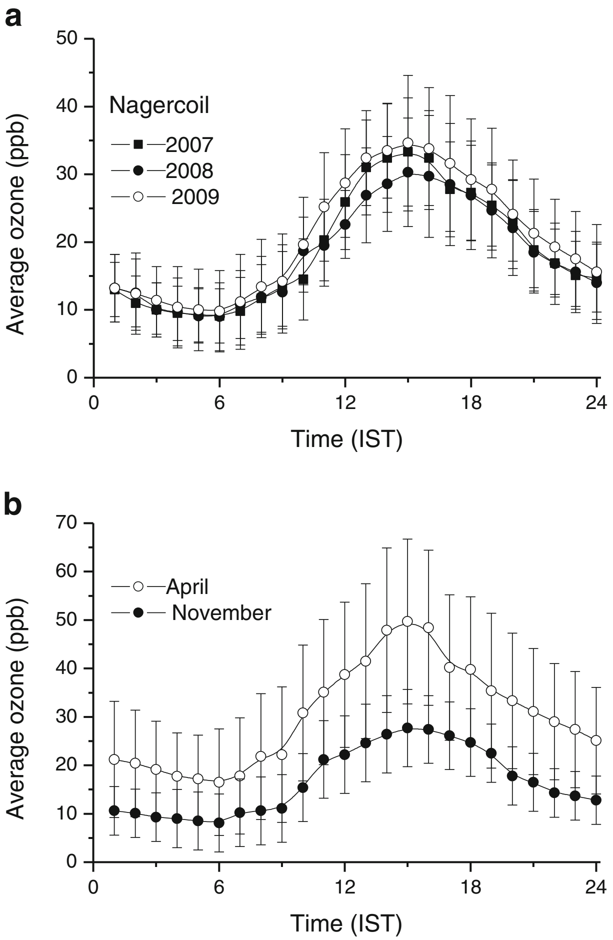
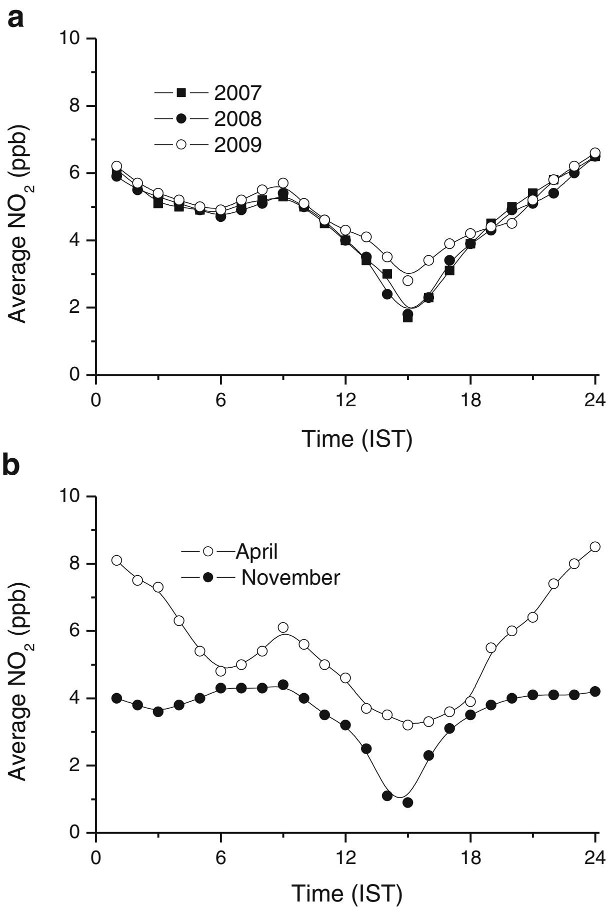


Fig. 2 Annual average diurnal variations of ozone concentration (ppb) observed at Nagercoil for 2007, 2008 and 2009 (**a**) and average diurnal variations of ozone concentration in April and November (**b**). Note that Y-axis scale is different for b

in emission of NO_x and VOC lead to more photochemical buildup of O_3 in rural areas (Galanter et al. 2000). Further, the emissions of biogenic hydrocarbons (e.g. isoprene) increases with increase of temperature help produce more O_3 in summer season (Velasco 2003). Similarly, Figs. 4a, b and 5a, b show the annual average diurnal variation of temperature and relative humidity, respectively, and diurnal variation in April and November. The annual maximum temperature around 30.1 °C, 30.2 °C and 30.4 °C was observed in the afternoon (14:00–15:00 h) and minimum of 25.5 °C, 25.4 °C and 25.6 °C in the morning (6:00 h) in 2007, 2008 and 2009, respectively (Fig. 4a). The maximum temperature 31.7 °C (29.8 °C) was observed in the afternoon around 15:00 h and minimum of 27.3 °C (25.5 °C) in the morning 6:00 h in April (November) (Fig. 4b). The highest temperature greater than 36 °C were also observed on clear sky days in April, related to highest O_3 formation. The highest relative humidity was observed in November and lowest in April, related to lowest O_3 concentration in November because photochemical formation of O_3 decreases with increase of relative humidity and overcast sky (unfavorable conditions for O_3 formation) (Debaje et al. 2003). The westerly wind of the order of 2–2.3 ms^{-1} was in April favor for high O_3 concentration; while northeasterly wind 1.5-1.7 ms^{-1} in November decreases O_3 concentration (Table 1).

Fig. 3 Annual average diurnal variations of nitrogen dioxide (NO_2) concentration (ppb) observed at Nagercoil for 2007, 2008 and 2009 (**a**) and average diurnal variations of nitrogen dioxide concentration in April and November (**b**)



3.2 Seasonal variation

Table 2 shows the comparison of monthly average O_3 concentration at Nagercoil and other nearby coastal sites O_3 measured available in India. The monthly average of NO_2 measured also shown in Table 2. The highest average of O_3 concentration in the range 24.9–27.9 ppb was observed in April. The corresponding average highest NO_2 concentration 6.8 ppb was in April indicating that O_3 increases with increase of NO_2. The lowest O_3 concentration 14.4–16.9 ppb was observed in November and corresponding lowest NO_2 concentration about 4 ppb indicate that the O_3 decreases with decrease of NO_2 concentration. The annual averaged O_3 concentration was 19.8 ppb for the study period with highest annual O_3 concentration 20.6 ppb in 2009 followed by 19.7 ppb and19.2 ppb in 2007 and 2008, respectively. The rate of increase of O_3 is 2.4 % year^{-1} for the study period, which is higher than the O_3 increase rate 1.45 year^{-1} during 1954–55 and 1991–93 in Ahmedabad, India reported by Naja and Lal (1996).

Similarly, annual averaged NO_2 concentration 5.3 ppb was for 3 years period with highest annual NO_2 concentration 5.8 ppb in 2009. The higher annual average O_3 concentration in 2009 than in 2007 (4.6 ppb) and 2008 (5.6 ppb) was due to the higher NO_2 concentration in 2009. The rate of increase of NO_2 is 8.6 % year^{-1} for the study period, which is also higher

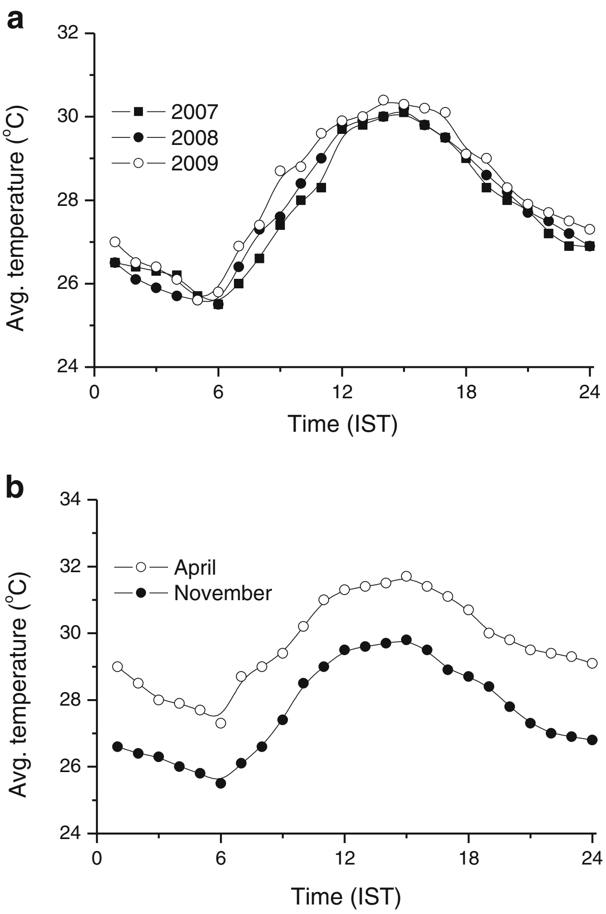


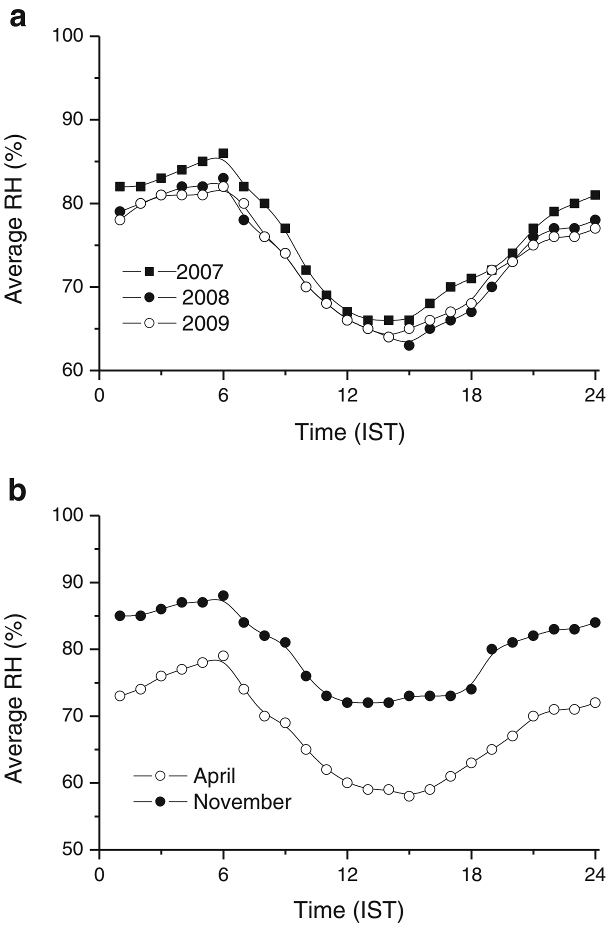
Fig. 4 Annual average diurnal variations of air temperature (°C) observed at Nagercoil for 2007, 2008 and 2009 (**a**) and average diurnal variations of air temperature in April and November (**b**). Note that Y-axis scale is different for b

than the rate of increase of NO_x 6.5 % year^{-1} in India between 2000 reported by Streets et al. (2003). The O_3 concentrations linearly depend on emission of NO_x in the rural sites (Wang et al. 2001). It is seen from the Table 2 that O_3 measured at Nagercoil is in good agreement on seasonal basis with O_3 measured at Thumba. Similarly, O_3 measured at Nagercoil are in good agreement with the O_3 measured in April and in November at Tranquebar and Kannur.

4 Crop exposure to O_3

The monthly average daytime maximum of O_3 concentration was 37.8, 42.1, 45.4, 43 and 40.2 ppb in February, March, April, May and June in 2007, respectively. The 3-months cumulative mean O_3 concentration was 41.8, 43.5 and 42.9 ppb for February–April, March–May and April–June 2007. Similarly, monthly daytime maximum O_3 concentration 39, 40.3, 43.9, 41.7 and 40.2 ppb in February, March, April, May and June in 2008, respectively. The 3-months cumulative mean O_3 concentration was 41, 42 and 41.9 ppbv for February–April, March–May and April–June 2008, respectively. The monthly daytime maximum O_3 concentration 38.4, 42.2, 59.3, 46.5 and 39.5 ppb in February, March, April, May and June in 2009, respectively. The 3-months cumulative mean O_3 concentration was 46.6, 49.3 and 48.4 ppb for

Fig. 5 Annual average diurnal variations of relative humidity (RH) (%) observed at Nagercoil for 2007, 2008 and 2009 (**a**) and average diurnal variations of relative humidity in April and November (**b**)



February–April, March–May and April–June 2009, respectively indicating crop yield losses due to O_3 exposure. The daytime hourly averaged O_3 concentration less than threshold limits of 40 ppb was observed from July to January each year for 2007, 2008 and 2009.

4.1 AOT40 index

The monthly AOT40 index value was calculated using Equation (1) from February to June in 2007, 2008 and 2009. Further, cumulative 3-months AOT40 value was calculated for different period such as February–April, March–May and April–June. Table 3 shows the summary of calculated AOT40 index values for the different period. The highest AOT40 index value was 3.1 ppm h, 2.6 ppm h and 5 ppm h in March–May 2007, March–May 2008 and March–May 2009, respectively used for estimation of crop yield losses due to O_3 damage. The AOT40 critical limits for 5 % crop yield losses for O_3 sensitive crops (watermelon, pulses (black gram (urd) and red gram (tur), green gram (moong)), cotton, wheat, onion, tomato) and moderately sensitive crops (oilseeds (groundnut, caster), potato, rice and maize) are used from Mills et al. (2007). The different AOT40 critical limits for 5 % crops losses for different crops: watermelon, pulses, cotton, wheat, onion, tomato, oilseeds,

Table 2 Monthly average ground level ozone (O_3) and nitrogen dioxide (NO_2) concentration (ppb) measured at Nagercoil for 3 years from March 2007 to February 2010 and O_3 at other site measurements available over Indian nearby coastal region

	O_3				NO_2				Thumba[a]	Tranquebar[b]	Kannur[c]
	2007–08	2008–09	2009–10	Avg.	2007–08	2008–09	2009–10	Avg.	1998–99	1997–2000	2009–10
March	24.6	22.8	24.7	24	5.5	7.1	7	6.5	22		27.4
April	26.3	24.9	27.9	26.4	5.7	7.5	7.4	6.8	20.7		23.6
May	22.7	24.5	26.8	24.7	5.2	7	7.7	6.6	17.4	22.5	21
June	19.9	21.5	22	21.1	5.1	6.8	6.4	6.1	16.4		19.8
July	20.6	19.6	21	20.4	4.7	5.8	6.3	5.6	15.7	21.1	15.3
August	18.7	17.7	18.9	18.4	4.6	5.6	5.5	5.2	15.9		13.1
September	17.4	16.6	17.6	17.2	4.3	5.1	5.2	4.8	13		14.5
October	16.3	15.6	14.7	15.5	3.4	4.4	4.7	4.1	15.1	17.5	16
November	14.4	13.9	16.9	15	3.8	4	4	3.9	16.5		20.2
December	15.8	16.7	18	16.8	3.9	5	4.8	4.5	17.8		25.4
January	17	18.4	19.2	18.2	4.2	5.1	5.1	4.8	20.5	20.7	31
February	19.1	20.2	19.1	19.9	4.4	5.6	5.7	5.2	21.4		29.7
Avg.	19.7	19.2	20.6	19.8	4.6	5.6	5.8	5.3	17.7	20.5	21.4

[a] Nair et al. (2002)

[b] Debaje et al. (2003)

[c] Nishanth et al. (2012)

Table 3 AOT40 index calculated during different months in 2007, 2008 and 2009

Period	AOT40 (ppm h)
March 2007 to May 2007	3.1
April 2007 to June 2007	1.8
February 2008 to April 2008	1.2
March 2008 to May 2008	2.6
April 2008 to June 2008	1.4
February 2009 to April 2009	3.5
March 2009 to May 2009	5
April 2009 to June 2009	2.7

potato, rice and maize are 1.6, 3, 3.1, 3.3, 4.1, 6, 8.9, 8.9, 12.8 and 13.9 ppm h, respectively. Large number of varities of agriculture and horticulture crops is grown over this area which is O_3 sensitive and moderately sensitive to O_3. In addition to the above crops, millets (bajara, ragi, jowar (sorghum, sweet sorghum), sesame, bean, jute, tea, coffee, sugarcane, mangoes, bananas, orange, grape, pepper, cardamom, chilies, cashew nut, coconut and natural rubber are also grown (http://www.tnau.ac.in/tech/acpen.pdf).

Table 4 shows the estimated crop yield losses for different crops using highest AOT40 index value in 2007, 2008 and 2009. The crops yield losses ranged from 1.1 % to 9.7 %, 0.9–8.1 % and 1.8–15.6 % in 2007, 2008 and 2009 associated with AOT40 index values 3.1 ppb h, 2.6 ppb h and 5 ppb h, respectively indicate that highest crops yield losses in 2009. The higher crop yield losses were observed for O_3 sensitive crops than for moderately sensitive crops. The crops yield losses is highest for watermelon (9.7 %), followed by pulses (5.2 %), cotton (5 %) and wheat (4.7 %) in 2007. The crops yield loss is low in 2008 compared to crops yield loss in 2007 and 2009. The highest watermelon yield losses by 15.6 %, while pulses and wheat losses by 8.3 % and 7.6 %, respectively was observed in 2009. It is seen from the above estimation that AOT40 index values exceed critical limit for 5 % yield losses of crop which are O_3 sensitive during March–May indicating that the present O_3 concentration has negative effects on crop yield due to O_3 exposure in summer season.

The stomatal conductance is higher in hot and humid environments in Asia, particularly in India poses more damage to crops due to O_3 exposure than in hot and dry environments in some

Table 4 Estimated crops yield losses (%) due to O_3 exposure using AOT40 index in 2007, 2008 and 2009

Crops/years	2007	2008	2009
Sensitive to O_3			
Watermelon	9.7	8.1	15.6
Pulses	5.2	4.3	8.3
Cotton	5	4.2	8
Wheat	4.7	4.2	7.6
Onion	3.8	3.9	6.1
Tomato	2.6	2.2	4.2
Moderately sensitive to O_3			
Oilseed	1.7	1.4	2.8
Potato	1.7	1.4	2.8
Rice	1.2	1	1.9
Maize	1.1	0.9	1.8

areas of Europe and USA (Fiscus et al. 2005). Further, crops sensitive to O_3 are at more risk due to likely co-occurrence of peak levels of O_3 and growing period of these crops from February to May. Winter wheat is especially sensitive to O_3 in India due to the likely co-occurrence of peak levels of O_3 and growing season (Emberson et al. 2003). The estimated crop yield losses by 1.1–15.6 % using AOT40 index due to O_3 damage at Nagercoil similar to other locations in India and Asia (Wahid 2006; Rai et al. 2007; Debaje et al. 2010). Wahid (2006) estimate reductions of 43 %, 39 % and 18 % in seed weight plant^{-1} of Pasban 90, Punjab 96 and Inqilab 91 varieties of wheat, respectively at seasonal mean O_3 concentration of 70 ppb by experimental study in Lahore, Pakistan. Rai et al. (2007) reported winter wheat yield losses by 21 % using open top chambers study for O_3 concentration of 42 ppb at Varanasi, India.

The NO_2 is increasing at the rate of 8.6 % year^{-1} at Nagercoil due to growth of automobiles sector, where no restrictive measures on emissions of O_3 precursors (particularly NO_x) were assumed to be implemented. The elevated O_3 concentration in future has direct negative effects on crops yield production threatening the food security in India. We use the AOT40-yield response functions obtained in Europe to estimate crop production losses in the present study. The O_3 exposure-response relationships function not established in India due to limited experiments, hence, no alternative approach is possible. Our results suggest that future crop yield reductions due to O_3 damage will be large, if no mitigation efforts for O_3 precursor are implemented.

5 Conclusions

Measurements of O_3, NO_2, temperature, relative humidity, wind speed and direction was made during 2007–2010 at Nagercoil, a rural coastal site in India clearly revealed that the O_3 concentration was higher in April than in November attributed to high NO_2 concentration, high temperature and low relative humidity. The monthly average of daytime maximum of O_3 concentrations ranged from 28 ppb to 50 ppb with an annual increase rate of O_3 is 2.4 %. Similarly, monthly average of NO_2 concentration ranged from 3.4 ppb to 7.7 ppb with an annual increase rate of NO_2 is 8.6 %. The estimated summer crops yield losses by 1.1–15.6 % associated with AOT40 index values 3.1–5 ppm h. This study suggests that ambient O_3 pollution in areas of Nagercoil has potential negative impact on crop growth and yield during the summer season. We feel that more such extensive observations of O_3 and its precursor are needed to understand the effect of O_3 on crop yield losses.

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