CrossMark

RESEARCH ARTICLE

Loss of crop yields in India due to surface ozone: an estimation based on a network of observations

Shyam Lal[1] · Sethuraman Venkataramani[1] · Manish Naja[2] ·
Jagdish Chandra Kuniyal[3] · Tuhin Kumar Mandal[4] · Pradip Kumar Bhuyan[5] ·
Kandikonda Maharaj Kumari[6] · Sachchida Nand Tripathi[7] · Ujjaini Sarkar[8] ·
Trupti Das[9] · Yerramsetti Venkata Swamy[10] · Kotalo Rama Gopal[11] · Harish Gadhavi[12] ·
Modathi Kottungal Satheesh Kumar[13]

Abstract Surface ozone is mainly produced by photochemical reactions involving various anthropogenic pollutants, whose emissions are increasing rapidly in India due to fast-growing anthropogenic activities. This study estimates the losses of wheat and rice crop yields using surface ozone observations from a group of 17 sites, for the first time, covering different parts of India. We used the mean ozone for 7 h during the day (M7) and accumulated ozone over a threshold of 40 ppbv (AOT40) metrics for the calculation of crop losses for the northern, eastern, western and southern regions of India. Our estimates show the highest annual loss of wheat (about 9 million ton) in the northern India, one of the most polluted regions in India, and that of rice (about 2.6 million ton) in the eastern region. The total all India annual loss of 4.0–14.2 million ton (4.2–15.0%) for wheat and 0.3–6.7 million ton (0.3–6.3%) for rice are estimated. The results show lower crop loss for rice than that of wheat mainly due to lower surface ozone levels during the cropping season after the Indian summer monsoon. These estimates based on a network of observation sites show lower losses than earlier estimates based on limited observations and much lower losses compared to global model estimates. However, these losses are slightly higher compared to a regional model estimate. Further, the results show large differences in the loss rates of both the two crops using the M7 and AOT40 metrics. This study also confirms that AOT40 cannot be fit with a linear relation over the Indian region and suggests for the need of new metrics that are based on factors suitable for this region.

Keywords Crop yield loss · Wheat and rice · Surface ozone · Crop loss · Loss metrics · India

✉ Shyam Lal
shyam@prl.res.in

1 Physical Research Laboratory, Ahmedabad 380009, India

2 Aryabhatta Research Institute of Observational Sciences, Nainital 263001, India

3 G.B. Pant National Institute of Himalayan Environment and Sustainable Development, Mohal-Kullu 175126, India

4 National Physical Laboratory, New Delhi 110012, India

5 Dibrugarh University, Dibrugarh 786004, India

6 Dayalbagh Educational Institute, Agra 282005, India

7 Indian Institute of Technology, Kanpur 208016, India

8 Jadavpur University, Kolkata 700032, India

9 Institute of Minerals & Materials Technology, Bhubaneswar 751013, India

10 Indian Institute of Chemical Technology, Hyderabad 500607, India

11 Sri Krishnadevaraya University, Anantapur 515003, India

12 National Atmospheric Research Laboratory, Tirupati 517502, India

13 Government Brennen College, Thalassery, Kerala, India

Introduction

Surface ozone (O_3) is mainly produced by the photochemical reactions of air pollutants emitted from anthropogenic and natural processes, and considered toxic for biological elements on the Earth's surface. The primary emissions of air pollutants include a variety of biogenic volatile organic compounds (BVOCs), carbon monoxide (CO) and oxides of nitrogen (NO_x), which react in the presence of sunlight to produce ozone in the troposphere (e.g. Crutzen 1995; Seinfeld and Pandis 2006). Major emission sources of these air pollutants are anthropogenic activities such as fossil fuel combustion and biomass burning (e.g. Ohara et al. 2007; Streets et al. 2013). Even though the urban regions are major sources of these ozone precursor gases, rural regions in the downwind could also be affected by ozone, and the balance of BVOCs and NO_x levels over the rural regions may favour higher production of ozone than over the urban regions (Chand and Lal 2003). Relatively higher levels of NO_x in the urban regions could titrate ozone. Ozone-rich air masses could also be advected from polluted regions (Lal et al. 2014) and influence remote locations (Chand et al. 2001; Naja et al. 2004; Lal et al. 2013; Kumar et al. 2013). Observations show that ozone levels at Ahmedabad in the western region of India have increased from 14.7 ppbv during 1954–1955 to 25.3 ppbv during 1991–1993, resulting in a linear increase of 1.45% per year (Naja and Lal 1996).

Since, about last one decade, global concern has increased due to positive trends in different pollutants over the Asian region, particularly in China and India. Though there are large numbers of observation sites (several thousands) across the globe, only a few tens of such observations sites are in India. India being a developing country, different emissions are shown to be increasing rapidly (Mallik and Lal 2013), which may lead to further increase in surface ozone in the future (Wild et al. 2012; Stevenson et al. 2013). Pierre et al. (2017) have estimated changes in ozone and its impact on vegetation by the year 2100 using six global atmospheric chemistry models and three Representative Concentration Pathway emission scenarios (RCP 2.6, 4.5 and 8.5). They find that for all the used models and for all the RCPs, ozone hot spots (mean concentrations >50 ppbv) are seen over Greenland and South Asia. They also find key biodiversity areas in South and North Asia as being at risk from high ozone concentrations. Based on results from 14 global chemistry transport models and using the three RCP emission scenarios, Wild et al. (2012) show that there will be a positive increase in surface ozone in the South Asian region by 2050 albeit by a few ppbv (0.2–5 ppbv).

Higher levels of surface ozone affect the future climate, human health and crop yields (Krupa et al. 1994; Chameides et al. 1999; Rai et al. 2007; Burney and Ramanathan 2014). India is the second populous country in the world after China,

and agriculture contributes a large fraction to India's economy. Therefore, any decrease in the crop yield will have serious repercussions on the country's economic growth and in securing self-sufficiency in food. Recent studies suggest a net reduction in crop yields due to ozone over the Indian region, using model-simulated ozone concentrations (Dingenen et al. 2009; Avnery et al. 2011; Ghude et al. 2014) or based on limited observations from a few sites (Debaje 2014; Sinha et al. 2015) and using concentration-based metrics. Flux-based metrics have been developed in Europe (Klingberg et al. 2014), but these need additional observations of meteorological data and information pertaining to plant conditions. So far, studies using concentration-based metrics have only been reported for India.

We present here, for the first time, a study on the effect of surface ozone on crop yields using observations from a group of 17 sites (14 from ISRO-ATCTM network and 3 from other available data) covering different parts of India. This study is aimed at better understanding of the effect of ozone concentration level and its seasonal variation on crop yields in order to reduce uncertainty in the estimations. We use two semi-empirical relations (metrics) to estimate the yield loss due to recent (2012–2013) ozone levels over India. This period is selected as there is availability of data from a large number of the network sites.

Material and methods

As a part of Atmospheric Trace Gases: Chemistry, Transport and Modelling (ATCTM) project of the Indian Space Research Organization's Geosphere Biosphere Program (ISRO-GBP), surface level measurements of ozone and related trace gases are being made at 15 locations in India (Fig. 1). Though this project started in 2008 with a few sites, the number of sites increased each year. The details of these sites are given in Table 1. Ozone monitoring at all these sites is being done continuously using ultraviolet (UV) absorption-based gas analysers. The method involves absorption of UV radiation at a wavelength of 253.7 nm by the ozone molecules. Span check is made using built-in ozone generators (Mallik et al. 2015). We calculated hourly average ozone for each month for the year 2012–2013 (except for Vallabh Vidhyanagar) for most of these sites from continuous data at 5–10-min intervals. However, if the data are not covering all the 12 months, we have utilized data from 2011 or 2014 to complete the data for all the months. In addition to these sites, we have also used published AOT40 and M7 data (described later) for Mohali (30.67° N, 76.73° E) and average monthly ozone and AOT40 data for Pune (18.54° N, 73.81° E) from Sinha et al. (2015) and Beig et al. (2008), respectively. Udaipur monthly average ozone data are taken from Yadav et al. (2014). We have distributed the measurement locations
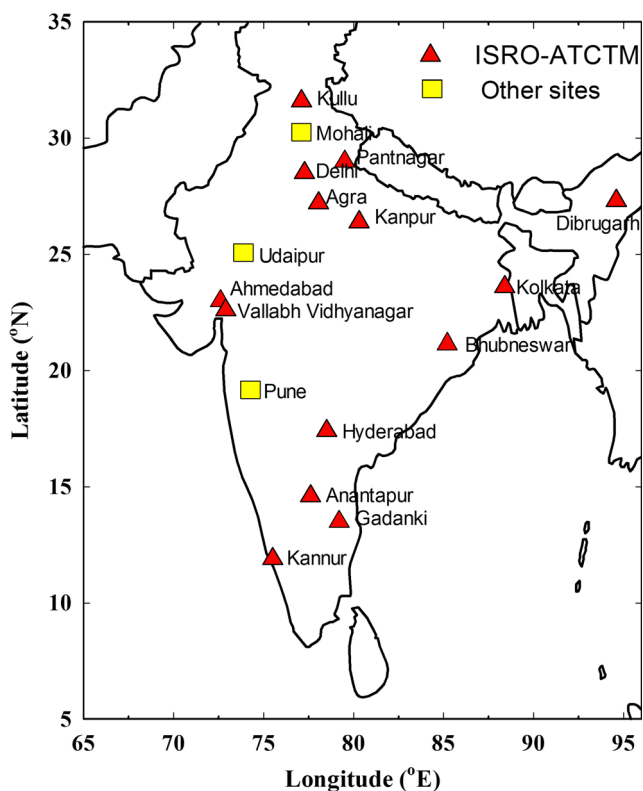
Fig. 1 Locations of observational sites of ISRO-ATCTM project and other sites for which ozone data are used

into four regions—north, east, west and south India (Table 1). Description of each site, including local meteorology and instrument details, can be seen in the related reference of each site (Table 1).

Crop yields

The annual crop yields for wheat and rice are used for the three years of 2011, 2012 and 2013 for different states of India (source http://eands.dacnet.nic.in/PDF/Agricultural-Statistics-At-Glance2014.pdf). The total average production of wheat and rice (Table 2) has been estimated for each of the four regions based on major contributing states in the respective regions for these three years. The average total production of wheat during these years has been about 94.44 million ton (Mt) of which the maximum (73.1%) contribution is from northern region (about 69 Mt) and the central-west region contributed about 17.75 Mt (18.8%). Similarly, the average total rice production during these years has been about 105.4 Mt of which the eastern region contributed maximum (40.8%) by about 43 Mt, the northern region contributed 29.3 Mt (27.8%) and the southern region contributed 21.75 Mt (20.6%). The rest is contributed by other regions and states as listed in the table.

Exposure metrics

Effect of ozone on the crops has been studied using field and laboratory measurements under controlled conditions, which are then applied to model exposure metrics or indices for upscaling the yield loss calculation at country or regional scales. There are a variety of such metrics, which are based on concentration (M7 and M12) and cumulative exposure (AOT40, SUM06 and W126). These are described in detail in Tong et al. (2009). However, it is important to know the amount of ozone uptake through the stomata to the interior of the leaf (stomatal flux), where it causes the damage. Such flux-based metrics are also becoming popular (Klingberg et al. 2014; Pierre et al. 2017). Flux-based estimates would need observations of the meteorological parameters, and due to non-availability of these parameters from all the sites, such estimates are not possible for the present study. Here, we use two most common metrics (M7 and AOT40), which have been used recently by many groups. One is known as M7, defined by the mean of daytime 7 h (0900 to 1600 h) ozone mixing ratio (ppbv) for the full duration of the crop (Eq. 1). This metric has been used widely in the USA (Adams et al. 1989; Lesser et al. 1990; Wang and Mauzerall 2004). The other widely used metric is AOT40, which is defined as the ozone mixing ratio accumulated over a threshold of 40 ppbv during the day light hours for the entire cropping period (Eq. 2). This has been widely used in the Europe (Mills et al. 2007). There are other metrics such as M12, SUM06 and W126 (see Tong et al. 2009 for details), but we restrict this study to the first two metrics only so as to have a better comparison with other studies from India. Both these metrics are given below for hourly (i) average ozone mixing ratio Ci (in ppbv):

$$M7 = \frac{1}{n} \sum_{i=0}^{n} [Ci] \tag{1}$$

From 0900 to 1559 h

$$AOT40 = \sum_{i=0}^{n} [Ci-40] \tag{2}$$

For $Ci \geq 40$ ppbv during day light hours only.

The crop response functions for relative yields (RYs) for wheat and rice crops are given as

(i) Wheat (following Lesser et al. 1990; Mills et al. 2007, respectively)

$$RY = e-(M7/137)^{2.34}/e-(25/137)^{2.34} \tag{3}$$

$$RY = -0.0000161 \times AOT40 + 0.99 \tag{4}$$

Table 1 Details of the observational sites used in the present study

Region	Site	Latitude (°N)	Longitude (°E)	Elevation (m) (amsl)	Urban/rural	Reference
North	Kullu	31.6	77.1	1154	Semi-urban	Sharma et al. (2013)
	Mohali	30.8	76.7	316	Suburban	Sinha et al. (2015)
	Pantnagar	29.0	79.5	231	Rural	Ojha et al. (2012)
	Delhi	28.5	77.2	216	Urban	Sharma et al. (2010)
	Agra	27.2	78.0	169	Suburban	Singla et al. (2011)
	Kanpur	26.4	80.3	125	Urban	Gaur et al. (2014)
East	Dibrugarh	27.3	94.6	111	Urban	Bhuyan et al. (2014)
	Kolkata	23.6	88.4	6	Urban	Ghosh et al. (2013)
	Bhubneswar	21.2	85.2	45	Urban	Mahapatra et al. (2014)
West	Ahmedabad	23.0	72.6	53	Urban	This work
	Udaipur	24.6	73.7	598	Semi-urban	Yadav et al. (2014)
	Vallabh Vidhyanagar[a]	22.6	72.9	43	Rural	This work
	Pune	18.5	73.8	560	Urban	Beig et al. (2008)
South	Hyderabad	17.4	78.5	536	Urban	Venkanna et al. (2015)
	Anantapur	14.6	77.6	331	Rural	Reddy et al. (2012)
	Gadanki	13.5	79.2	360	Rural	Renuka et al. (2014)
	Kannur	11.9	75.4	5	Rural/ Coastal	Nishanth et al. (2014)

[a] The site at Vallabh Vidhyanagar is new for ozone measurements, and the instrument at this site is similar to that being used at the Physical Research Laboratory (PRL), Ahmedabad. The data from this site are available only for 2015

(ii) Rice (following Adams et al. 1989; Mills et al. 2007, respectively)

$$RY = e{-}\left(M7\big/202\right)^{2.47}\big/e{-}\left(25\big/202\right)^{2.47} \quad (5)$$

$$RY = -0.0000039 \times AOT40 + 0.94 \quad (6)$$

Both of these metrics have been used extensively for estimating loss of crops in various parts of the world (Dingenen et al. 2009; Tong et al. 2009; Hollaway et al. 2012; Debaje 2014; Sinha et al. 2015). Ghude et al. (2014) have used only AOT40 metric. The M12 metric is similar to M7, but it is based on average ozone for 12 h during the day. However, exposure response function for M12 metric for wheat is not available. Hence, this is not used for the calculation of wheat loss.

The relative yield loss (RYL) is given by

$$RYL = 1.0{-}RY \quad (7)$$

We have used Eqs. (1) and (2) for estimating M7 and AOT40 for 14 sites of ISRO network. Additionally, we have derived relations using data from all the 14 sites for 24-h average monthly ozone and monthly average M7 (Fig. 2a)

$$M7 = 3.284 + 1.205 \times (Avg\ O_3) \quad (8)$$

as well as a relation is also derived between 24-h average monthly ozone and monthly AOT40 (Fig. 2b) for all 14 sites

$$AOT40 = 1226.6{-}165.0 \times (Avg\ O_3) + 4.797$$
$$\times (Avg\ O_3)^2 + 0.034 \times (Avg\ O_3)^3 \quad (9)$$

These Eqs. 8 and 9 are used to estimate the missing monthly M7 and AOT40 values, respectively, for the two sites, i.e. Pune (Beig et al. 2008) and Udaipur (Yadav et al. 2014) to complete the western region. M7 and AOT40 values for Mohali are used from Sinha et al. (2015).

Figure 2 shows that the 24-h average ozone has a good linear relation ($R^2 = 0.85$) with M7, but a polynomial fits better ($R^2 = 0.90$) with AOT40. It is to be noted that Debaje (2014) has used linear relationship for AOT40, similar to that by Mills et al. (2007). However, similar to our findings, Sinha et al. (2015) have also shown that AOT40 fits well with exponential curve for the northern India.

Results and discussion

The monthly (24 h) average ozone estimated for four regions (north, south, east and west) based on classification of

Table 2 Average wheat and rice yields (in million ton (Mt)) from major producing states in India during 2011–2014

Regions	Region/states	Wheat	Rice
North	Uttar Pradesh	30.28	14.35
	Punjab	16.81	11.06
	Haryana	11.87	3.91
	Rajasthan	9.06	–
	Uttarakhand	1.00	–
	North total	69.02	29.32
West/Central	Madhya Pradesh	12.87	2.60
	Gujarat	3.62	1.64
	Maharashtra	1.26	2.94
	West/Central total	17.75	7.17
East	Bihar	5.06	6.67
	West Bengal	0.91	14.96
	Odisha	–	7.35
	Chhattisgarh	–	6.45
	Assam	–	4.62
	Jharkhand	–	2.97
	East total	5.97	43.02
South	Andhra Pradesh	–	12.28
	Tamil Nadu	–	5.8
	Karnataka	–	3.67
	South total		21.75
	Others	1.7	4.14
	Total All India	94.44	105.4

Fig. 2 a Relations between 24-h average monthly ozone, monthly average M7 (*top*) and **b** monthly AOT40 based on data from all the 14 ISRO ATCTM network sites

observational sites (Table 1) in India is shown in Fig. 3a. The general pattern of ozone variability shows higher ozone in April–May, lower in August and again higher in October–November. Average ozone is highest in the northern region in May with a value of 44.3 ± 7.5 ppbv. This average ozone for the northern region does not include ozone from Mohali as we have used directly the monthly average M7 and AOT40 values for the years 2012–2013 given in Sinha et al. (2015). The seasonal variability in ozone is not very pronounced in the eastern region of India. Nevertheless, somewhat higher ozone mixing ratios are seen in late spring and late autumn and lower ozone mixing ratios in August–September. The western region shows higher ozone in March and November with values of 35.6 ± 8.2 and 35.2 ± 13.6 ppbv, respectively. Similar to the east, southern region shows a lesser pronounced seasonal variation. The eastern and the southern regions show average ozone below 30 ppbv. All the four regions show lowest ozone in August. These average ozones for different regions are presented here to get the feeling about the ozone values. These are not used directly in the calculation of crop losses, but both the metrics depend on the diurnal ozone values.

The average regional (north, east, west and south) M7 and AOT40 are also shown in Fig. 3b, c, respectively, for all the four regions based on the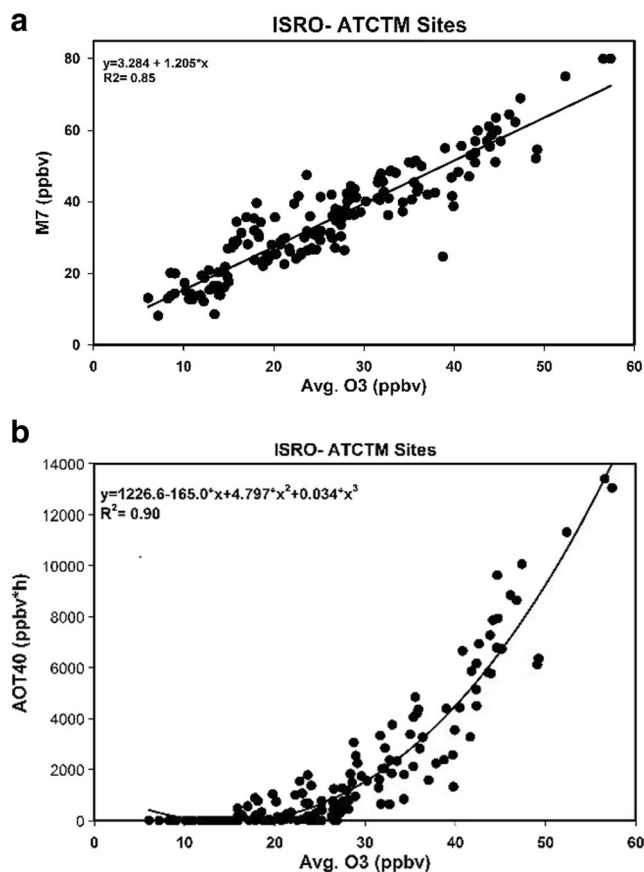 respective values for sites in these regions. The variations in regional average M7 values mimic the variations in regional average ozone except M7 values that show slightly sharper variation. As for ozone, the M7 values are also highest in May (63.2 ± 14.4 ppbv) for the northern region and in February (48.7 ± 12.2 ppbv) and November (47.8 ± 19.9 ppbv) for the western region. The eastern and southern regions show M7 values lower than 40 ppbv except in November, when it was 41.5 ± 19.1 ppbv for the eastern region.

The average AOT40 values for the four regions are shown in Fig. 3c. The AOT40 values show still sharper seasonal variation as compared to average ozone and M7. The average AOT40 values are highest for the northern region with a value of 8378 ± 4497 ppbv h in May. However, the western region shows higher values from November to March with values ranging from about 4648 ppbv h to about 5991 ppbv h. As with other metric parameters, the eastern and southern regions show monthly values below about 2150 ppbv h throughout the year.

Loss of wheat and rice crops

The average regional M7 and the integrated AOT40 values have been calculated for wheat and rice crops for their
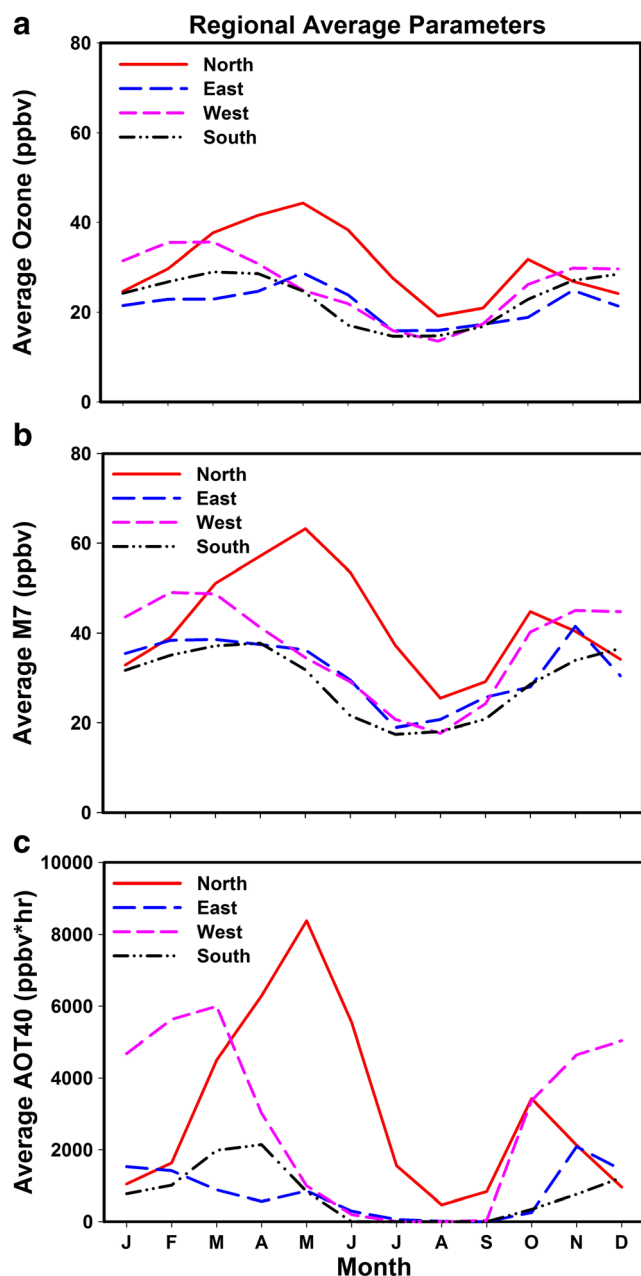
Fig. 3 a Month average ozone, **b** monthly average M7 and **c** monthly average AOT40 for the four regions of India

respective crop periods, i.e. January to March and August to October over the four regions (Table 3). These data have been further used to calculate RYLs for wheat and rice using Eqs. 3 to 7 for the four regions. Regional average M7 and AOT40 values are highest for the western region. Thereby, RYL values for wheat are highest for the western region with values of 0.06 and 0.27, respectively, for M7 and AOT40 metrics. The next higher values are for the northern region with values of 0.04 and 0.13, respectively, for M7 and AOT40. The east and south regions have almost similar RYL values. It is also observed that RYL values based on AOT40 metric are much higher than the values based on M7 metric. This difference is

also seen by Sinha et al. (2015), Debaje (2014), Hollaway et al. (2012) and Dingenen et al. (2009), who have also used both these metrics.

Based on the crop productions in different regions, we have calculated total loss of the crops. The northern region produces about 69 Mt of wheat as compared to 17.7 Mt in the western region and about 6 Mt in the eastern region. Based on this, the total all India annual loss of wheat crop ranges from 4.0 to 14.2 Mt (4.2 to 15.0%) with maximum crop loss in north (2.76–8.97 Mt). Similar calculations have been done for rice, which is mostly grown during August–October period (Table 3). Again, RYL values based on AOT40 values are much higher than based on M7. The maximum production of rice is in the eastern region (~43 Mt) followed by northern and southern regions. The western region grows only about 7 Mt of rice. The total all India rice crop loss per annum is in the range of 0.29 to 6.68 Mt (0.27–6.3%) (Table 3). Again, it is very explicit that loss estimated using the AOT40 metrics is much higher (14.2 Mt for wheat and 6.7 Mt for rice) as compared with the loss estimated using M7 metric (4.0 Mt for wheat and 0.29 Mt for rice) over India. This is consistent over all the four regions of India (Fig. 4).

Summary and Conclusions

These estimates of loss of wheat and rice crops based on surface ozone observations from 17 sites show that there is certainly loss of crops in India. While the loss of rice is in the range of 0.3 to 6.7%, the loss of wheat is higher in the range of 4.2 to 15%. Average ozone levels during the winter cropping season of wheat are highest in the western region followed by that in the northern region. Due to higher yield, both these regions contribute significantly to the total wheat loss in India. Ozone levels during the rice cropping season after the Indian summer monsoon are much lower than that in the winter season all over India. This saves the kharif season rice crop from significant damage due to ozone. As mentioned earlier, kharif season rice contributes to about 85–90% of the total annual rice production in India. These crop losses are compared with other estimates for India and presented in Table 4. Sinha et al. (2015) have estimated loss of wheat and rice in the range of 11–41% and 19–21%, respectively, for two states (Punjab and Haryana) of northern India using observational data from a single site. Debaje (2014) estimated all India wheat and rice losses in the range of 5–30 and 3–16%, respectively. His estimates are based on three sites in Maharashtra state of India, and data taken from six other locations in other states. Present estimate for the northern Indian region is in the range of 4–13 and 1–8% for wheat and rice, respectively, which are still much lower than both estimates, but estimates are done with wide network of observation sites. Further, Debaje (2014) has calculated M7 from these data, and

Table 3 M7 and AOT40 values over the four regions during 3-month crop periods for wheat (January to March) and for rice (August to October)

Crop and period	Region	Avg. O3 (ppbv)	Avg. M7 (ppbv)	AOT40 ppbv h	RYL M7	RYL AOT40	Crop yield (Mt)	Crop loss (Mt)	
								M7	AOT40
Wheat: Jan. to Mar.	North	30.7	41.0	7178.7	0.04	0.13	69.0	2.76	8.97
	East	22.4	37.5	3824.9	0.03	0.07	6.0	0.18	0.42
	West	34.2	47.1	16,299.7	0.06	0.27	17.7	1.06	4.78
	South	26.7	34.6	3770.6	0.02	0.07	0.0	0.0	0.0
	Total All India						94.4	4.0 (4.2%)	14.17 (15.0%)
Rice: Aug. to Oct.	North	24.0	33.1	4727.0	0.01	0.08	29.3	0.29	2.3
	East	17.4	24.8	264.5	0.00	0.06	43.0	0.00	2.58
	West	19.0	27.4	3403.1	0.00	0.07	7.2	0.00	0.50
	South	18.1	22.5	343.1	0.00	0.06	21.7	0.00	1.30
	Total All India						105.4	0.29 (0.27%)	6.68 (6.3%)

Relative yield loss and crop loss are also listed for four regions. Million ton is referred as Mt

AOT40 values are derived using a linear relation given by Mills et al. (2007). We find that a linear relation does not fit between 24-h average ozone or M7 and AOT40 for the Indian region. It has been shown that a polynomial only fits better between 24-h monthly average ozone and monthly AOT40. It is similar for M7 and AOT40 as 24-h average ozone and M7 are linearly related to each other. Sinha et al. (2015) also found that this relation between M7 and AOT40 is an exponential.

Fig. 4 Loss of **a** wheat and **b** rice crops in million ton (Mt) calculated using M7 and AOT40 metrics for the four regions of India

Therefore, this work confirms that AOT40 cannot be fit with a linear relation over the Indian region. Use of a linear relation by Debaje (2014) could be one possible reason for higher crop loss estimates compared to the present study.

Ghude et al. (2014) have used a regional WRF-Chem model to generate ozone levels and to estimate wheat and rice crop losses for India. They have used only AOT40 metric for the calculation of losses which are 5.0 ± 1.2 and 2.1 ± 0.9% for wheat and rice, respectively. Their estimates are within our range but lower than those based on AOT40 metric only (see Table 4). They have taken December to February as the rabi-growing season for wheat, when ozone levels are slightly lower than those during January–March period as considered in the present study. Avnery et al. (2011) have used a global chemistry transport model to calculate ozone levels. They report annual loss of wheat in the range of 9–30% for India. This is much higher than the present estimate and could be due to much higher ozone calculated by their global model as compared to observations particularly over northern India. Dingenen et al. (2009) have also estimated crop losses for India using another global chemistry transport model. They also report higher loss of wheat (13.2–27.6%) and rice (5.7–8.3%) crops compared to the present study. Again, their model also predicts higher ozone levels as compared to limited observations for India. It seems that the global models are not able to calculate surface ozone levels over India as observed. This could be due to several factors including emissions of ozone precursors such as NO_x, hydrocarbons and CO for the Indian region.

The regional model (WRF) used by Ghude et al. (2014) shows lower crop losses than the global models used by Dingenen et al. (2009) and Avnery et al. (2011). The monthly average ozone values for the Indian region resulted from these global models are higher than the observations particularly over the northern Indian region as seen from the comparison
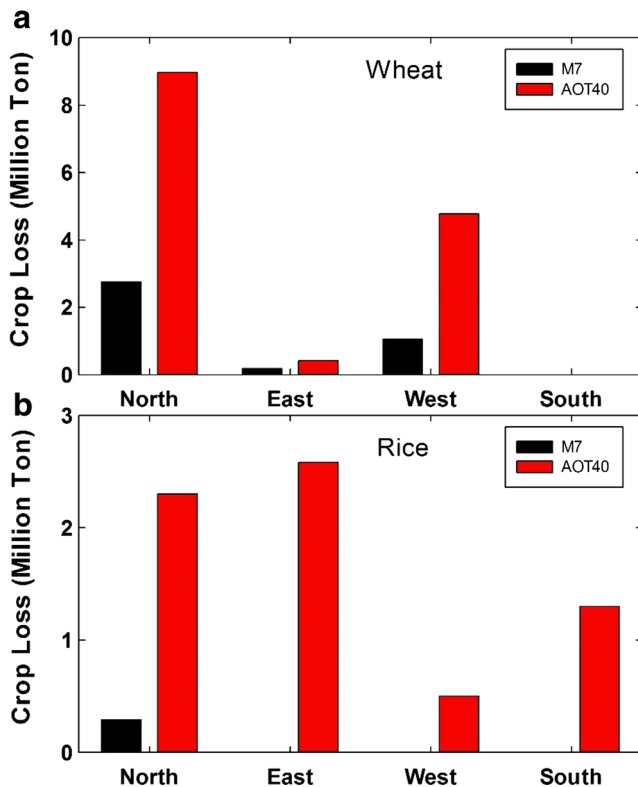
Table 4 Comparison of estimated loss of wheat and rice crops with other studies for India

Reference	Metrics used	Ozone data	Loss of wheat	Loss of rice	Comments
This work	M7 and AOT40	Observations	4.2–15%	0.3–6.3%	Observed ozone data from 17 sites throughout India.
Sinha et al. (2015)	M7 and AOT40	Observations	11–41%	19–21%	Only for Punjab and Haryana states of India.
Debaje (2014)	M7 and AOT40	Observations	5–30%	3–16%	Limited observations for M7 and a relation is used to estimate AOT40. Estimate for rice is only for the rabi season.
Ghude et al. (2014)	AOT40	WRF-Chem	5 ± 1.2%	2.1 ± 0.9%	Regional chemistry transport model.
Avnery et al. (2011)	M7 and AOT40	MOZART	9–30%	–	Global chemistry transport model.
Dingenen et al. (2009)	M7 and AOT40	TM5	13.2–27.6%	5.7–8.3%	Global chemistry transport model.

they have shown. The estimates reported by Burnery and Ramanathan (2014), based on a statistical model and taking combined effects of climate change and the direct effects of short-lived climate pollutants including ozone and black carbon due to their emissions from 1980 to 2010. They show that in 2010, yields of wheat were up to 36% lower than they otherwise would have been without such changes. Similarly, loss of rice is about 20% over this period. These are the changes over a long period and cannot be directly compared with the present estimates.

It is to be mentioned here that these metrics are for the US and European regions. Emberson et al. (2009) have pointed out that the Asian-grown wheat and rice cultivars are more sensitive to ozone than the North American metrics would suggest. Also, the two metrics give very different loss rates (Fig. 4). Therefore, it is essential to have region-specific metrics for India or South-East Asia as the seed types, agriculture practices and climate being very different in this region compared to these mid and high-latitude regions. Sinha et al. (2015) have calculated these metrics based on yields of crops spread over different periods, but actual field experiments with different levels of ozone in the local environment or in the ambient air are needed. The RYL calculation using AOT40 has a problem when these AOT40 values are very small. The minimum RY is 0.94 and hence a loss of 6% of the rice crop even if the seasonal AOT40 values are very small. It is suggested that such measurements in fields covering major crops producing states should be planned for better estimates of losses.

With increasing emissions of anthropogenic pollutants, ozone levels are likely to increase in this region in the future (Wild et al. 2012; Stevenson et al. 2013). Avnery et al. (2011) and Dingenen et al. (2009) have predicted higher losses for wheat as well as for rice for India by 2030. It is suggested that since the northern region is the main wheat-growing region (~73%) of India and since ozone is higher in March and April, the crop may be grown a bit earlier starting November itself when ozone levels are relatively lower. In addition to this, wheat and rice cultivars, which have resistance to ozone damage, need to be developed. It has been suggested that in situ ozone flux-based metrics for calculating the crop losses are more appropriate than concentration-based metrics (Klingberg et al. 2014; Pierre et al. 2017). Therefore, such field measurements need to be done over the Indian region. Finally, we would like to suggest to the policy makers to reduce the air pollution, particularly in the northern India. This will take care not only of the losses of the crops but also health of the public.

References

Adams RM, Glyer JD, Johnson SL, McCarl BA (1989) Assessment of the economic effects of ozone on United States agriculture. JAPCA J Air Waste Ma 39:960–968

Avnery S, Mauzerall DL, Liu J, Horowitz LW (2011) Global crop yield reductions due to surface ozone exposure 1: year 2000 crop production losses and economic damage. Atmos Environ 45:2284–2296

Beig G, Ghude SD, Polade SD, Tyagi B (2008) Threshold exceedances and cumulative ozone exposure indices at tropical suburban site. Geophys Res Lett 35:L02802. doi:10.1029/2007GL031434

Bhuyan PK, Bharali C, Pathak B, Kalita G (2014) The role of precursor gases and meteorology on temporal evolution of O3 at a tropical location in northeast India. Environ Sci Pollut Res 21:6696–6713. doi:10.1007/s11356-014-2587-3

Burney J, Ramanathan V (2014) Recent climate and air pollution impacts on Indian agriculture. PNAS 111:16319–16324

Chameides WL et al (1999) Is ozone pollution affecting crop yields in China. Geophys Res Lett 26:867–870

Chand D, Modh KS, Naja M, Venkataramani S, Lal S (2001) Latitudinal trend in O3, CO, CH4, SF6, over the Indian Ocean during the Indoex IFP-1999 ship cruise. Curr Sci 80:100–104

Chand D, Lal S (2003) High ozone at rural sites in India. Atmos Chem Phys Discuss 4:3359–3380

Crutzen P (1995) Ozone in the troposphere, in Composition, chemistry, and climate of the atmosphere, Editor H. International Thomson Publishing Inc, B. Singh

Debaje PK (2014) Estimated crop yield losses due to surface ozone exposure and economic damages in India. Environ Sci Pollut Res 21: 7329–7338

Dingenen RV, Dentener FJ, Raes F, Krol MC, Emberson L, Cofala J (2009) The global impact of ozone on agricultural crop yields under current and future air quality legislation. Atmos Environ 43:604–618

Emberson LD, Buker P, Ashmore M, Mills G, Jackson L, Agrawal M, Atikuzzaman M, Cinderby S, Engardt M, Jamir C, Kobayashi K, Oanh N, Quadir Q, Wahid A (2009) A comparison of North-American and Asian exposure-response data for ozone effects on crop yields. Atmos Environ 43:1945–1953

Gaur A, Tripathi SN, Kanawade VP, Tare V, Shukla SP (2014) Four-year measurements of trace gases (SO2, NOx, CO, and O3) at an urban location, Kanpur, in Northern India. J Atmos Chem 71:283–301

Ghosh D, Lal S, Sarkar U (2013) High nocturnal ozone levels at a surface site in Kolkata, India: Trade-off between meteorology and specific nocturnal chemistry. Urban Climate 5:82–103

Ghude SD, Jena C, Chate DM, Beig G, Pfister GG, Kumar R, Ramanathan V (2014) Reduction in Indian crop yield due to ozone. Geophys Res Lett 41:51971. doi:10.1002/2014GL060930

Hollaway MJ, Arnold SR, Challinor AJ, Emberson LD (2012) Intercontinental trans-boundary contributions to ozone-induced crop yield losses in the Northern Hemisphere. Biogeosciences 9:271–292. doi:10.5194/bg-9-271-2012

Klingberg J, Engardt M, Karlsson PE, Langner J, Pleijel H (2014) Declining ozone exposure of European vegetation under climate change and reduced precursor emissions. Biogeosciences 11: 5269–5283

Krupa SV, Nosal M, Legge AH (1994) Ambient ozone and crop loss: establishing a cause–effect relationship. Environ Pollut 83:269–276

Kumar R, Naja M, Pfister GG, Barth MC, Brasseur GP (2013) Source attribution of carbon monoxide in India and surrounding region during wintertime. J Geophys Res 118. doi:10.1002/jgrd.50134

Lal S, Venkataramani S, Chandra N, Cooper OR, Brioude J, Naja M (2014) Transport effects on the vertical distribution of tropospheric ozone over western India. J Geophys Res Atmos 119:10,012–10,026. doi:10.1002/2014JD021854

Lal S, Venkataramani S, Srivastava S, Gupta S, Mallik C, Naja M, Sarangi T, Acharya YB, Liu X (2013) Transport effects on the vertical distribution of tropospheric ozone over the tropical marine regions surrounding India. J Geophys Res 118:1513–1524. doi:10.1002/jgrd.50180

Lesser VM, Rawlings JO, Spruill SE, Somerville MC (1990) Ozone effects on agricultural crops: statistical methodologies and estimated dose–response relationships. Crop Sci 30:148–155

Mahapatra PS, Panda S, Walvekar PP, Kumar R, Das T, Gurjar BR (2014) Seasonal trends, meteorological impacts, and associated health risks with atmospheric concentrations of gaseous pollutants at an Indian coastal city. Environ Sci Pollut Res 21:11418–11432. doi:10.1007/s11356-014-3078-2

Mallik C, Lal S, Venkataramani S (2015) Trace gases at a semi-arid urban site in western India: variability and inter-correlations. J Atm Chem 72:143–164

Mallik C, Lal S (2013) Seasonal characteristics of SO2, NO2 and CO emissions in and around the Indo-Gangetic Plain. Environ Monit Assess 186(2):1295–1310

Mills G, Buse A, Gimeno B, Bermejo V, Holland M, Emberson L, Pleijel H (2007) A synthesis of AOT40-based response functions and critical levels for ozone for agricultural and horticultural crops. Atmos Environ 41:2630–2643

Naja M, Lal S (1996) Changes in surface ozone amount and its diurnal and seasonal patterns from 1954-55 to 1991–93 measured at Ahmedabad (23N), India. Geophys Res Lett 23:81–84

Naja M, Chand D, Sahu L, Lal S (2004) Trace gases over marine regions around India. Indian J Geo-Mar Sci 33

Nishanth T., K. M. Praseed, M. K. S. Kumar, K. T. Valsaraj (2014) Influence of ozone precursors and PM10 on the variation of surface O3 over Kannur, India, Atmos. Res., 138, 112–124, doi.org/10.1016/j.atmosres.2013.10.022

Ohara T, Akimoto H, Kurokawa J, Horii N, Yamaji K, Yan X, Hayasaka T (2007) An Asian emission inventory of anthropogenic emission sources for the period 1980–2020. Atmos Chem Phys 7:4419–4444

Ojha N, Naja M, Singh KP, Sarangi T, Kumar R, Lal S, Lawrence MG, Butler TM, Chandola HC (2012) Variabilities in ozone at a semi-urban site in the Indo-Gangetic Plain region: association with the meteorology and regional processes. J Geophys Res 117:D20301. doi:10.1029/2012JD017716

Pierre S, Alessandro A, Alessandra DM, Elena P (2017) Projected global tropospheric ozone impacts on vegetation under different emission and climate scenarios. ACPD. doi:10.5194/acp-2017-74

Rai R, Agrawal M, Agrawal SB (2007) Assessment of yield losses in tropical wheat using open top chambers, agriculture. Atmos Environ 41:9543–9554

Reddy BSK, Kumar KR, Balakrishnaiah G, Rama Gopal K, Reddy RR, Sivakumar V, Lingaswamy AP, Arafath SM, Umadevi K, Kumari SP, Ahammed YN, Lal S (2012) Analysis of diurnal and seasonal behavior of surface ozone and its precursors (NO x) at a semi-arid rural site in southern India. Aerosol Air Qual Res 12:1081–1094

Renuka K, Gadhavi H, Jayaraman A, Lal S, Naja M, Rao SVB (2014) Study of ozone and NO2 over Gadanki–a rural site in South India. J Atmos Chem 71:95–112. doi:10.1007/s10874-014-9284-y

Seinfeld J. H. and S. N. Pandis (2006) Atmospheric chemistry and physics: from air pollution to climate change, Wiley Publisher

Sharma P, Kuniyal JC, Chand K, Guleria RP, Dhyani PP, Chauhan C (2013) Surface ozone concentration and its behaviour with aerosols in the northwestern Himalaya, India. Atmos Environ 71:44–53

Sharma SK, Datta A, Saud T, Mandal TK, Ahammed YN, Arya BC, Tiwari MK (2010) Study on concentration of ambient NH3 and interactions with some other ambient trace gases. Environ Monit Assess 162:225–235

Singla V, Satsangi A, Pachauri T, Lakhani A, Kumari KM (2011) Ozone formation and destruction at a sub-urban site in North Central region of India. Atmos Res 101:373–385

Sinha B, Sangwan KS, Maurya Y, Kumar V, Sarkar C, Chandra BP, Sinha V (2015) Assessment of crop yield losses in Punjab and Haryana using 2 years of continuous in situ ozone measurements. Atmos Chem Phys 15:9555–9576

Stevenson DS et al (2013) Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP). Atmos Chem Phys 13:3063–3085. doi:10.5194/acp-13-3063-2013

Streets DG et al (2013) Emissions estimation from satellite retrievals: a review of current capability. Atmos Environ 77: 1011–1042

Tong DQ, Mathur R, Kang DW, Yu SC, Schere KL, Pouliot G (2009) Vegetation exposure to ozone over the continental United States: assessment of exposure indices by the Eta-CMAQ air quality forecast model. Atmos Environ 43:724–733

Venkanna R, Nikhil GN, Siva Rao T, Sinha PR, Swamy YV (2015) Environmental monitoring of surface ozone and other trace gases over different time scales: chemistry, transport and modelling. Int J Environ Sci Technol 12(5):1749–1758

Wang X, Mauzerall DL (2004) Characterizing distributions of surface ozone and its impact on grain production in China, Japan and South Korea: 1990 and 2020. Atmos Environ 38: 4383–4402

Wild O, Fiore AM, Shindell DT, Doherty RM, Collins WJ, Dentener FJ, Schultz MG, Gong S, MacKenzie IA, Zeng G, Hess P, Duncan BN, Bergmann DJ, Szopa S, Jonson JE, Keating TJ, Zuber A (2012) Modelling future changes in surface ozone: a parametrized approach. ACP. doi:10.5194/acp-12-2037-2012

Yadav R, Sahu LK, Jaaffrey SNA, Beig G (2014) Distributions of ozone and related trace gases at an urban site in western India. J Atmos Chem 71:125–144