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Declining trend of total ozone column over the northern parts of India

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Ozone is one of the important atmospheric trace gases that absorbs both incoming solar near-ultraviolet and outgoing infrared radiation from the Earth's surface. After the discovery of the 'ozone hole', assessment of the long-term trend of ozone in different regions of the globe has become a frontline topic of research. The present study deals with the variability in the total ozone column over the Indian subcontinent using satellite and limited ground observations. The linear regression technique was applied to the Nimbus and Earth Probe Total Ozone Mapping Spectrometer (EP-TOMS) data to study the trends during 1997–2003. The rate of decline of ozone is found to be higher in recent years over the northern parts of India, covering the Indo-Gangetic basin, compared with other parts of India.

1. Introduction

The breakdown in the stratosphere of certain anthropogenic chemicals containing chlorine and bromine are known to be responsible for the ozone depletion observed every year since the early 1980s over Antarctica as well as in the mid-latitudes of both hemispheres. Numerous studies based on various ground and satellite measurements (Stolarski *et al.* 1991, 1992, Varotsos and Cracknell 1993, Cracknell and Varotsos 1994, Cracknell *et al.* 1994, Bojkov *et al.* 1995, Chandra *et al.* 1996, Herman *et al.* 1996, 1997, McPeters *et al.* 1996, Harris *et al.* 1997, Varotsos *et al.* 2000, Singh *et al.* 2002, Varotsos, 2002, Efstathiou *et al.* 2003) have shown an overall declining trend of total ozone (TOZ) content globally during 1979–1993. These studies have led the scientific community to monitor TOZ content globally and limit the use of ozone-depleting substances to minimize the decreasing trend. After the Montreal Protocol, efforts were made throughout the globe to reduce the use of ozone-depleting chemicals and, as a result, the rate of decline of the stratospheric ozone has slowed down.

Singh *et al.* (2002) found a greater decreasing trend of TOZ in the northern Indian region compared with other parts of India where the trend is almost stable for the period 1978–1993. They also found the effect of El Niño on TOZ content for most of the cities in India, due to which the ozone trend is found to increase during the short period of 1996–2000. Similar results were found by Chakrabarty *et al.* (1998) for a few Indian cities using ground data and Nimbus-7 Total Ozone Mapping

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Spectrometer (TOMS) data. However, they did not comment on the increasing TOZ content with the limited availability of TOMS TOZ data. This paper details an analysis of TOZ data during 1997–2003, measured from TOMS over the Indian sub-continent and adjacent region. The TOZ trend was studied over various low and middle latitude stations in the southern and central part of the Indian sub-continent. The results show an increase in the rate of decline of TOZ at several locations over the western, eastern and central parts of the Indo-Gangetic (IG) basin, while the trend over rest of India is found to be stable. The causes of this declining trend of TOZ content over the IG basin are attributed to increasing pollution.

2. Sensors and datasets

The TOZ content datasets were taken from two different TOMS instruments developed by National Aeronautics & Space Administration (NASA)/Goddard Space Flight Center (GSFC) (ftp://toms.gsfc.nasa.gov/pub/). The TOMS instrument was designed to enable long-term daily mapping of the global distribution of the Earth's atmospheric ozone apart from aerosols and sulphur dioxide. There have been four such missions, and the present study deals with data obtained from TOMS on board Nimbus-7 (1979–1993) and Earth Probe (EP) (1997–2003) missions.

TOMS makes 35 measurements every 8 s, each covering a width of 30 to 125 miles (50–200 km) on the ground, strung along a line perpendicular to the motion of the satellite. Almost 200 000 daily measurements cover every single spot on the Earth except areas near one of the poles, where the Sun remains close to or below the horizon during the entire 24-hour period. Table 1 gives details about the TOMS ozone data.

The ground-based data observed by a Dobson photometer for a single station (Delhi) are obtained from the World Meteorological Organization (WMO) archive. These data have not been used from other stations because of a lack of availability during the period of study. The details of this dataset are discussed in table 2.

Table 1. Characteristics of the total ozone content datasets.

Satellites	Nimbus-7 and Earth Probe
Instrument	Total Ozone Mapping Spectrometer (TOMS)
Parameter	Total ozone concentration
Temporal coverage	1979–1993, 1997–2003
Temporal resolution	Monthly data
Spatial coverage	Global
Spatial resolution	1.25° (Longitude) $\times$ 1.0° (Latitude)
Data file format	ASCII
Data source	ftp://toms.gsfc.nasa.gov/pub/

Table 2. Characteristics of the WMO ground-observed total ozone content datasets.

Parameter	Total ozone concentration
Temporal coverage	1979–2003
Temporal resolution	Monthly data
Spatial coverage	Station data (Delhi, India)
Data file format	ASCII
Data source	http://www.woudc.org/

TOMS uses the ratio of backscattered Earth radiance to solar irradiance at specific wavelengths to infer TOZ content. In this ratio, all instrument-related changes are cancelled, except for degradation of the diffuser plate, which is used to reflect diffuse solar light into the instrument optics. The degradation of the diffuser plate is related directly to exposure to sunlight. The Nimbus-7 TOMS diffuser plate becomes degraded after continuous exposure to UV light. A non-diffused-based technique, termed spectral discrimination, was used to calibrate the TOMS data and generate the TOZ content data used in the present study.

Stations located in the IG basin and in other low-latitude regions of India have been chosen to compare the ozone trend. Most of the stations were picked as a result of the significance of the observed trend (p-values<0.10 for a two-tailed Student t-test at 90% confidence level). The IG basin is prone to dust storms coming from the Saharan deserts and Pakistan. This results in an increase in aerosol concentration in the IG basin (Dey *et al.* 2004, Singh *et al.* 2004) which is likely to affect the ozone concentration. The pollution level of the IG basin was found to increase significantly which will obviously influence the TOZ content. Numerous urban cities (Delhi, Kanpur, Varanasi, Patna and Kolkata, which lie in the IG basin; Madras, Trivandrum, Bangalore and Nagpur, which lie in the central and southern parts of India) were chosen to study the ozone trend.

3. Results and discussion

The monthly averaged TOZ content values were corrected for missing values by a 3×3 pixels spatial moving average filter. The time series at each grid location was de-seasonalized by calculating the deviations from the climatological mean annual cycle. Figure 1 shows the TOZ anomaly plots for different stations in northern India for the period 1979–2003 from two different instruments (except during 1994–1996, when no TOZ data were available). A regression time series model was fitted to the de-seasonalized monthly mean values after smoothing by a five-month moving average filter. The fine dotted trend lines in figures 1(a)–(k) are the extrapolated trends for the TOZ content from 1979–1993. The thick dotted lines show the recent trend for the period 1997–2003. Figure 1 indicates clearly that the observed trends (thick dotted lines) are significantly lower than the trends predicted based on 1979–1993 for the stations in the IG basin. The trend from the ground-observed data (figure 1(k)) confirms the trend found from the satellite-observed data for Delhi and supports the observation based on satellite TOZ data. De-seasonalized Nimbus TOZ (1979–1992) together with the WMO ground-observed ozone data for Delhi (figure 2) shows a good agreement with the correlation coefficient value of 0.9924. This validates the satellite-observed TOZ data which have been used for this trend analysis study. The declining trend over numerous stations lying in the northern part of India is found to be very significant and important in view of the Montreal Protocol that is supposed to restrict ozone-depleting substances world-wide.

Figure 3 shows the TOZ anomaly over stations lying in other parts of India, which show a very stable trend. The decadal trend estimates for each station and their location are given in table 3, while the difference between predicted and observed values for the corresponding stations are shown in figure 4. The thick dotted line in figure 4 separates the IG basin from the Southern Peninsula.

The present results show a significant declining TOZ content trend over major cities in the IG basin. This declining trend is a serious threat, especially to the 400 million people who live in the basin. The declining trend can be due to numerous

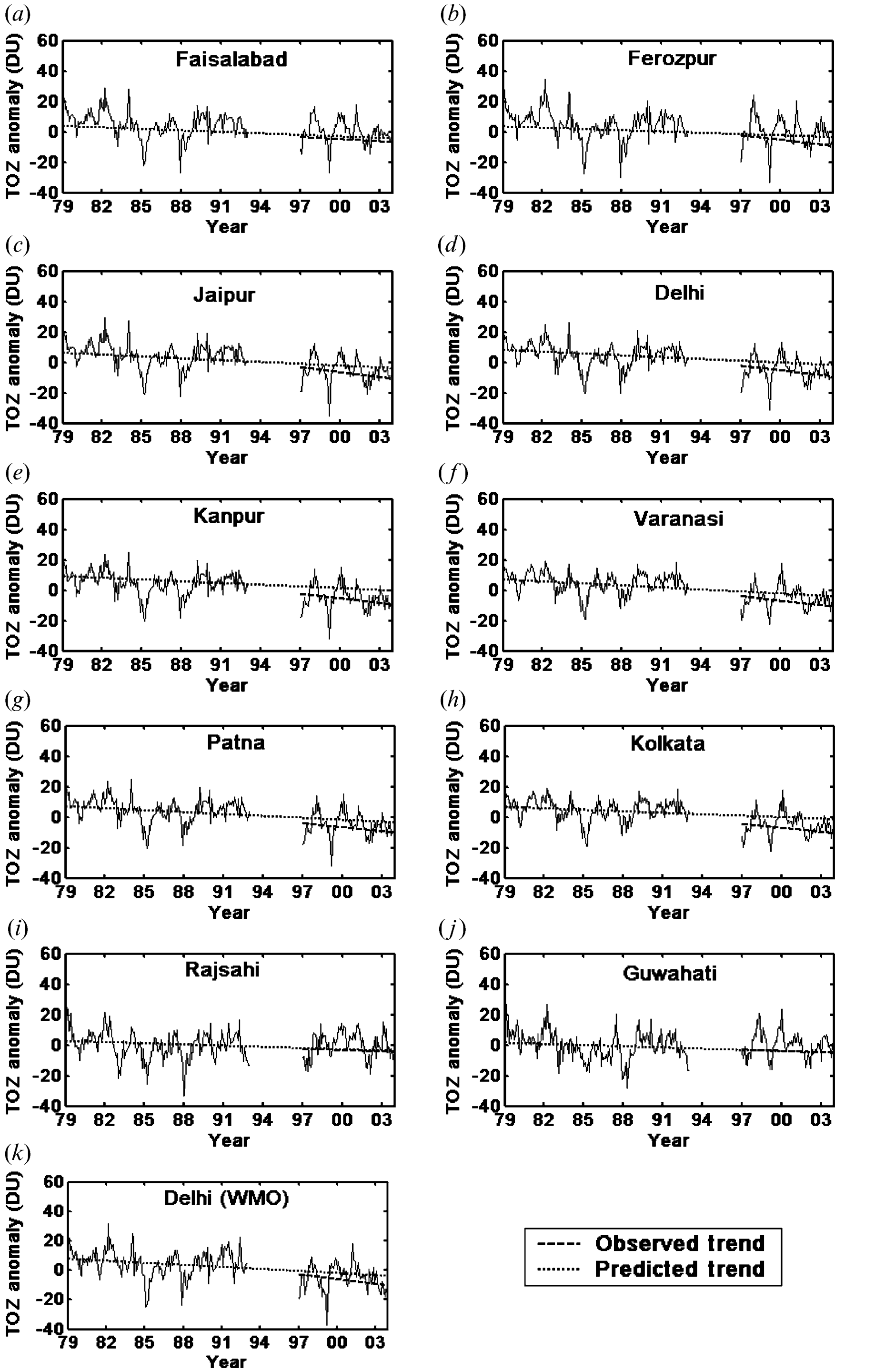

Figure 1. (*a*)–(*j*) The TOZ anomaly plots for the stations in northern India for the period 1979–2003 plotted continuously from two different instruments (data are missing for 1994–1996). The predicted trend line is the actual trend line for the data for 1979–1993 which has been extended until 2003 and the observed trend line is for the period 1997–2003. (*k*) Same as (*a*)–(*j*), but for Delhi as observed by ground-based Dobson instrument.

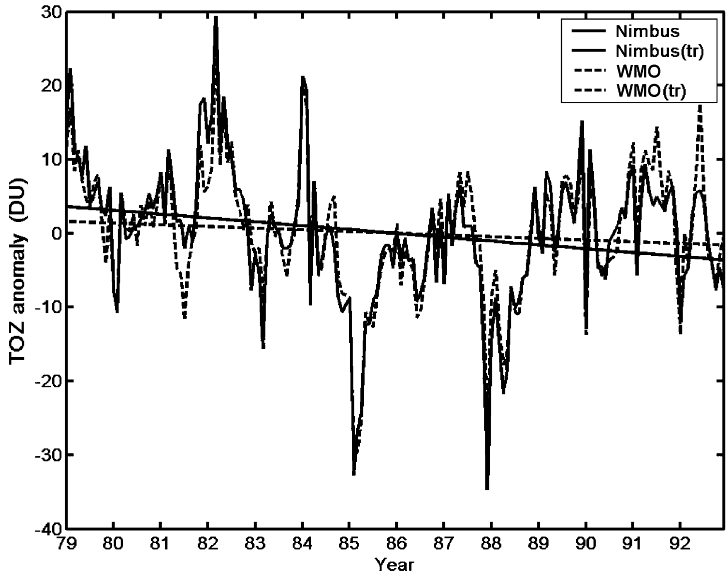

Figure 2. Nimbus and WMO TOZ anomaly plots, along with the linear trend lines for Delhi (1979–1992).

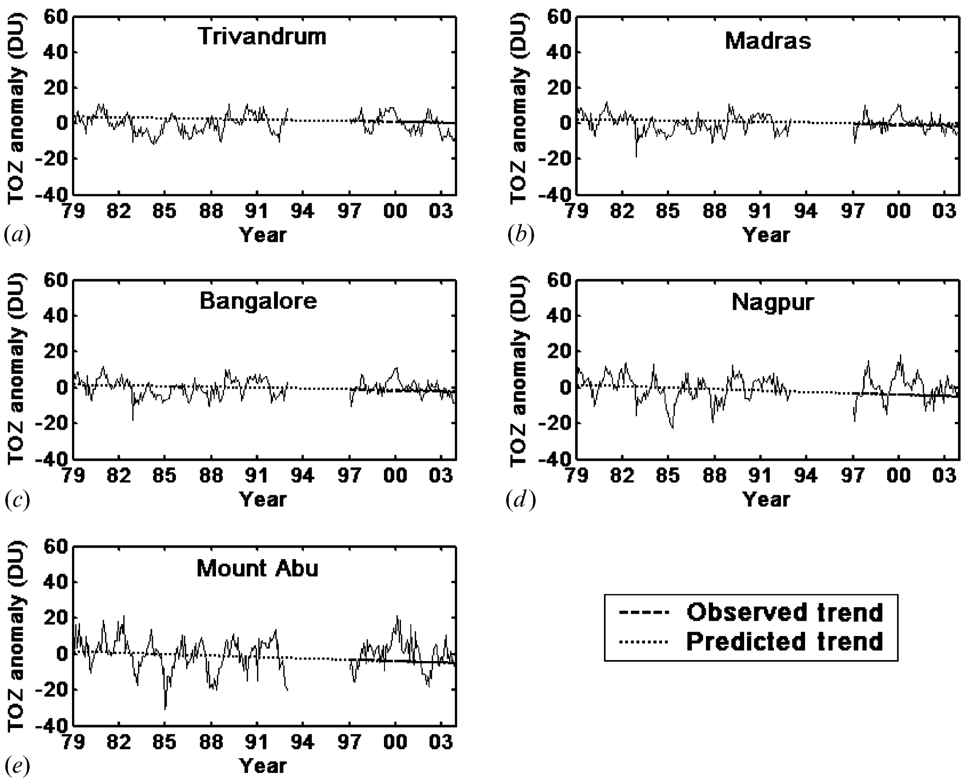

Figure 3. (*a*)–(*e*) The TOZ anomaly plots for stations in other parts of India for the period 1979–2003.

Table 3. Trend estimates in decades for observed and predicted trends over each station.

Serial number	Station	Latitude (° N)	Longitude (° E)	*p*-value	Predicted trend per decade (DU)	Observed trend per decade (DU)
A	Faisalabad	31.5	73	0.0628	−14.4	−19.9
B	Ferozpur	30.5	74.4	0.0189	−15.9	−32.4
C	Jaipur	26	75	0.0968	−16.6	−36.3
D	Delhi	28.67	77.22	0.0329	−15.0	−36.8
E	Kanpur	26.28	80.24	0.0153	−12.6	−37.3
F	Varanasi	25	83	0.0499	−11.3	−33.8
G	Patna	25.6	85.2	0.0322	−13.5	−36.2
H	Kolkata	22.65	88.45	0.0306	−10.8	−32.3
I	Rajsahi	24.4	88.6	0.0419	−9.5	−11.2
J	Guwahati	26.2	91.5	0.0846	−10.6	−12.4
K	Trivandrum	8.48	76.95	0.0425	−9.3	−12.4
L	Madras	13.08	80.17	0.0372	−8.1	−9.5
M	Bangalore	12.98	77.58	0.0265	−9.5	−9.1
N	Nagpur	21.09	79.09	0.0156	−6.0	−8.3
O	Mount Abu	24.6	72.7	0.0521	−8.2	−8.1

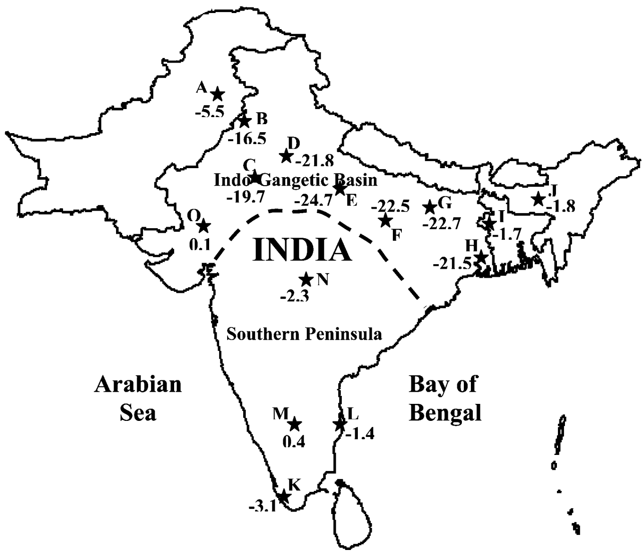

Figure 4. The difference between the observed and predicted trends (in DU per decade) is shown for all the study locations over India. The thick dotted line separates the Indo-Gangetic basin from the Southern Peninsula. See table 3 for explanation of A–O.

factors. Recently, Varotsos *et al.* (2004) have found a relationship between the declining TOZ trend and the tropopause height over Athens. Over the IG basin, the tropopause height has been computed using the pressure level National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis temperature data and following the WMO criterion of a thermal tropopause. The tropopause height shows a stable trend of about 7 hPa per decade over the IG basin during 1997–2003. No significant correlation is found between the tropopause height and TOZ content over India.

The IG basin is characterized by significant aerosol loading. Sulphate aerosols form the major constituent of such loading (Sharma *et al.* 1994, 2003), comprising about 29% (Satheesh and Ramanathan, 2000). Dust and mineral particles form a second primary source of aerosol as significant aerosol build-up takes place over the IG basin during and preceding the summer monsoon following extensive transport of dust from the Sahara. These dust and sulphate aerosols have been shown to react with atmospheric gases (Bonasoni *et al.* 2001) and are likely to play an important role in the declining trend of TOZ content in the IG basin. A multi-phase heterogeneous reaction scheme involving the aerosol particles may be responsible for the observed decline in TOZ content over the IG basin. Detailed analysis of satellite, ground and sounding data and modelling studies are required to affirm this theory and provide further validation.

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