Abstract

The latest IPCC report released has unequivocally stressed the point that all scientific evidences indicate that the climate change has inflicted the Earth with global warming and Ozone depletion. Climate change *per se* implies that increasingly the Earth’s climate regime is under stress. These changes are affecting different (vital) global natural processes, which are essential to ensure the availability of the appropriate habitat for all life forms to exist, reproduce, and evolve. The threat to the stratospheric ozone layer is one such important dimension of global natural processes among others. Enough scientific evidence is available to state with confidence that the well being of the Stratospheric Ozone layer is vital to ensure the persistence of all biotic manifestations, particularly on land. Considerable damage to the Ozone layer has already occurred from the anthropogenic activities, where the role of CFC's, NOx and OH in the presence of solar radiation in the troposphere-stratosphere region is central. The early cognizance of the damage to the Ozone layer at global level resulted in the global moratorium on the use of compounds, classified as Ozone depleting substances (ODS) after the Montreal protocol agreement was signed between large numbers of countries. The early recognition towards the damage to the stratospheric ozone layer\(^1\), world over, resulted in the global initiative to install total Ozone column (TOC) measuring equipments at many locations to collect continuous data to monitor the state of TOC as a function of latitude; the initiative proved to be valuable as the analysis reflected the state of the Ozone layer. Given the importance of stratospheric Ozone layer, and the expected location specific variations in TOC over different time spans, the analysis of TOC database collected from different instrument's global network database had been under investigation. The analysis of TOC time series data in some of these investigations, at conceptual level, included known scientific aspects about

---

the formation and dispersion of Ozone\textsuperscript{2,3}. Statistical methods, linear and non-linear regression, to estimate the long-term trends in the TOC data at a given location\textsuperscript{4,5} were also used. Though the decrease in the TOC abundance, at higher latitudes was evident, but the estimates differed between the studies. Similar estimates done in tropical regions were not conclusive; positive to negative trends in TOC were reported for locations separated by few hundred km, having similar climatic regime\textsuperscript{2,3,6}. The variability in TOC at stations located in India also reported significant variations in the trend estimates. In some cases, the analysis was simplistic at best as the TOC data was not de-seasonalized\textsuperscript{4,5,7}.

It is evident from the previous studies that there are trends of total Ozone depletion in the tropical zones, but ironically it is also this region over the tropical zone that has the least total Ozone layer thickness even though there is high incoming solar irradiance. Consequently, even a small decrease is likely to have far reaching implications on life forms in general. The tropical region accounts for more than fifty percent of global Ozone production, which is transported to mid-latitudes. The region on earth sustains more than ninety percent of global bio-diversity. In Indian context; where the region has tropical-subtropical climate, large biological diversity, inhabits a human population of 1028.7 million\textsuperscript{8}, and house two global bio-diversity hot spots, even a small decrease in the Ozone layer will have far reaching consequences. Thus, the issue of Ozone layer depletion, perhaps, is much more important for the tropical regions.

\textsuperscript{8}Census India (2001), available at: http://www.censusindia.gov.in/
Studies done so far in Indian context are at best tentative as the statistical analysis approach lacked robustness; however few investigations of Ozone column trends at Indian locations were robust\textsuperscript{2,3,9}, but these analysis are not recent. The most recent investigations on Ozone column variability on many Indian stations were reported by few groups\textsuperscript{4,5,7,10}, however the analysis used to determine the trends did not account for seasonal effects, and it was limited to trend estimates only. The seasonal and inter-annual variability’s effects on the total ozone column were not accounted for.

Keeping in view the far reaching importance of TOC over tropical region, and the available current status from the past investigations, a detailed statistical analysis of the trend and variability in TOC at 15 locations in India was undertaken; Singapore (1.3° N to 34.5° N) location was included to cover the tropical region with respect to latitudinal spread. The analysis done in the present investigation entails following objectives:

- a) Use of TOMS Overpass monthly mean TOC time-series data sets 1979-1993 (TS-I) and 1997-2005 (TS-II) for total 16 locations;
- b) De-seasonalization of each time-series data-set;
- c) Determination of seasonal variation in the ozone column at each station;
- d) Estimation of long term trend at each station with appropriate statistics of regression fits;
- e) Detection of Inter Annual Variation (IAV) in de-sesonalized and de-trended time-series of Total Ozone Column at respective stations.

In this analysis, the data set has been treated as two separate time series: (A) 1979 to 1993 (TS-I); and (B) 1997 to 2005 (TS-II). This was convenient as the first series would have the signature of decreasing TOC trend and the later time series would carry signature of revival, if any.

The time-series analysis approach used in the present study is similar to the one used to estimate the trends in the global methane concentrations in

case of the methane time-series data set\textsuperscript{11}. Stepwise de-convolution of the transformed data was done in steps to extract all relevant influences present in the time series with reference to the known processes affecting the TOC.

The TOC values in time series were expressed in equation form as:

\[ TOC = \text{trend} + \text{annual cycle} + \text{residuals} \]

\[ \text{trend} = \text{intercept} + \text{linear-trend} \times \text{time} + \text{inter-annual variations} \]

The long-term trend estimates were done on de-seasonalized data set of respective TOC time-series. The moving trends over 31-month span, season-wise and Month-wise long-term trends present in TOC were also estimated. The estimates to detect the presence of inter annual variation (IAV) present in TOC data was done on de-seasonalized monthly mean TOC time-series data from which the estimated long-term trends were subtracted. The data set was subjected to Discrete Fourier Transform (DFT) to detect the presence of harmonics in IAV having the time-period akin to the harmonic present in the multi-annual climatic cycles like Quasi Biennial Oscillations (QBO). Data set after the subtraction of IAV from the de-seasonalized and de-trended monthly mean TOC time-series was equated to White or Random Noise.

Inferences, in short from this study are concluded as:

a) The TOC data used (monthly mean TOC values) for all the stations manifest normal distributions as tested by Shapiro-Wilk's test of Normality.

b) The seasonal (annual-cyclic) variations in TOC, at all locations were evident: positive over months coinciding with summer-monsoon-early winter (April to October). The annual cycle of seasonal variations exhibited an increase in phase with increasing latitude; but notably in both the cases Srinagar was an exception.

c) Except for Singapore, the long-term trends present in TOC at all locations registered statistically significant decline in TOC: -0.66 to -3.60 percent per decade (TS-1). The estimated decline in TOC

manifested latitudinal dependence. The estimated trends in TOC for TS-II differed in comparison; overall, they were declining (-0.48 to -3.25 percent per decade). The locations below latitude 17° N [Singapore, Trivandrum, Kodaikanal, Banglore, Madras] registered more negative long-term trends for TS-II as compared to TS-I. The extent of decrease was less in TOC (TS-II) for locations above latitude 13° N; this may be the early sign of the recovery in the TOC.

d) The season-wise long-term trends in de-seasonalized monthly mean total Ozone column during December-January-February (DJF) and March-April-May (MAM) were higher for Singapore and Trivandrum. The locations away from the equator (Kodaikanal, Banglore, Madras, Hyderabad, Poona and Bombay) manifested higher TOC trends March-May (MAM). Higher trend was observed during June-August (JJA) for Nagpur, Dum Dum, Ahemdbad, Mount Abu, Benares, Varanasi, New Delhi and Srinagar. Except for Singapore, all locations registered positive trend during December-February. Similarity in the estimates was observed between TS-I and TS-II with some deviation: for TS-II of the locations [Banglore, Madras, Hyderabad, Poona, Bombay, Nagpur, Dum Dum, Ahemdbad, Mount Abu, Benares and Varanasi] manifested positive TOC trend during MAM and JJA. No systematic pattern was observed between the seasons during which the TOC trend was positive, over different locations.

e) The analysis of month-wise long-term trend in TOC (TS-II) at Singapore, during January – June, was positive; not seen in TS-I. Most of the locations manifested negative monthly trend in TOC during rest of the months.

f) The magnitude of the variations in TOC explained by Inter-Annual Variations (IAV) was around ± 30 DU for almost all the locations (TS-I and TS-II); Srinagar registered maximal IAV magnitude. The IAV strength waned as locations moved away from the equator.
g) The dominant harmonics detected in IAV (TS-I and TS-II) showed correspondence with the time-period of harmonic present in 30 hPa Equatorial Zonal Winds; a proxy used to detect Time-Period and Phase of QBO.

h) The harmonic having the QBO signature was present in the IAV signal in TOC for both time-series (TS-I and TS-II). The locations closer to the Equator (Singapore) registered maximal power density for harmonic having QBO signatures. As locations move away from the equator the number of other harmonics, in addition to the one coinciding with QBO, could be observed.

i) There was significant latitude dependent increase in the phase difference of QBO cycle present in 30 hPa Equatorial Zonal Winds and the corresponding cycle having the same period in IAV. The Coupling Factors between harmonics representing QBO effect in IAV present in TOC decreased as locations moved away from the equator (TS-I and TS-II). The QBO influence in TOC at New Delhi and Srinagar was least. The Harmonic Strength (QBO–IAV) has marked distinction between the locations near to equator and farther, where a steady decrease is detected in the Harmonic Strength of dominant cycle in IAV. The QBO effect on TOC was significant between 0 – 10° N; at higher latitude the QBO effects were modulated by other short term seasonal and annual cycles. Complete reversal in the phase difference (between QBO and IAV signal) at New Delhi and Srinagar was observed for TS-I and TS-II, indicating suppression of QBO effect.

j) Random (white) noise explained significant magnitude in TOC (±20 DU). It is likely that there may be other unknown natural reasons/phenomenon, which could explain further the extent of the random variability present in the TOC time-series.