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15.	**Abstract:** Ozone is found in two regions of the Earth's atmosphere at ground level (up to 18km) and in the stratospheric region (18-50 km) of the upper atmosphere. The stratospheric columnar ozone (SCO) is generally referred as good ozone and protects the life from the Sun's harmful ultraviolet rays reaching the ground level by absorbing. The depletion of strtospheric ozone is studied and it is due to colling of stratospheric temperature (Sujatha P et. al 2014: RSL). The tropospheric columnar ozone (TO) or the ground level ozone is also referred as bad ozone and not generated in the air directly, but created by photo chemical and chemical reactions between oxides of nitrogen (NO_x) and Volatile Organic Compounds (VOCs). The tropospheric ozone is generated by human activities largely due to incomplete combustion of fossil fuels, transportation and industrial emissions, etc. This is often referred to as a greenhouse gas formed with NOx, Carbon Monoxide (CO) and VOCs. These are also called Ozone Precursors. The TO is derived from Ozone Monitoring Instrument and Microwave Limb Sounder (MLS) based on Tropospheric Ozone Residual Techinque (TOR) **Key Words:** Total Columnar Ozone (TCO), Stratospheric Columnar Ozone (SCO), Tropospheric Columnar Ozone (TO), Ozone Precursors			

Table of Contents

Abstract

Ozone is found in two regions of the Earth's atmosphere at ground level (up to 18km) and in the stratospheric region (18-50 km) of the upper atmosphere. The stratospheric columnar ozone (SCO) is generally referred as good ozone and protects the life from the Sun's harmful ultraviolet rays reaching the ground level by absorbing. The depletion of strtospheric ozone is studied and it is due to colling of stratospheric temperature (Sujatha P et. al 2014: RSL). The tropospheric columnar ozone (TO) or the ground level ozone is also referred as bad ozone and not generated in the air directly, but created by photo chemical and chemical reactions between oxides of nitrogen (NO_x) and Volatile Organic Compounds (VOCs). The tropospheric ozone is generated by human activities largely due to incomplete combustion of fossil fuels, transportation and industrial emissions, etc. This is often referred to as a greenhouse gas formed with NOx, Carbon Monoxide (CO) and VOCs. These are also called Ozone Precursors, The TO is derived from Ozone Monitoring Instrument and Microwave Limb Sounder (MLS) based on Tropospheric Ozone Residual Techinque (TOR).

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The authors thank Dr. V.K. Dadhwal, Director NRSC for his encouragement to carry out this report The authors also would like to thank NASA's Giovanni and mirodor web portal for providing the data of Aura/OMI and MLS satellite. We also thank team SHADOWZ for archived Ozonesonde data.

List of Figures and Tables

1. Introduction

Most of the Ozone in the atmosphere is in the stratosphere of the atmosphere, with about 10% in the lower troposphere. Ozone is formed due to photo chemical and chemical reactions involved in presence of Sun's UV radiation. In the study of recent decades, investigation of transport of Ozone and its precursors in the upper troposphere has accelerated due to the progression in satellite estimations and model activities. Upper troposphere is the area where radiative driving, long-range contamination transport, and the transport of air into/from the stratosphere play important role (Mahlman 1997). Midy et al 2012 showed variation of TCO in the recent past, after and during landfall of tropical cyclone when it passes through an additional tropical district. During tropical cyclones, there is a change in TCO mixing ratios budget. Numerous researches completed on tropical cyclones and their effect in transporting contamination, such as Ozone and CO (Fadnavis et al., 2010, Midya et al., 2012). The mechanism for lifting gases out of the Planetary Boundary Layer (PBL) into the free troposphere is important in understanding the local and global air pollution problems and climate issues (Dickerson et al.2007). Fadnavis et al., 2010 showed the role of cyclone in transporting pollutants into the upper troposphere from lower troposphere. This study also reported vertical exchange of Ozone from lower stratosphere to upper troposphere.

The estimation of total columnar atmospheric ozone concentration using satellite sensors from Ozone monitoring instrument (OMI), Microwave Limb Sounder (MLS) and Total Ozone Monitoring Spectrometer (TOMS) were used to estimate tropospheric (TO), Stratospheric columnar Ozone (SCO) concentrations. Using multiple satellite sources from 2007-2013 over a period of 7 years on a daily basis atmospheric columnar ozone concentrations were used to derive TO and SCO over the Indian region.

2. Data and Methodology

- TCO (0.25°*0.25°): Ozone Monitoring Instrument (OMI) is a nadir-scanning instrument that detects back-scattered solar radiance to measure column ozone. OMI pixels have a nadir resolution of 13 km *24 km (Levelt et al., 2006). The OMI is one of the four Aura satellite sensors gives daily global estimations of four imperative U.S Environmental Protection Agency's criteria pollutants, for example Ozone, Nitrogen-dioxide, Sulfur-dioxide and Aerosols from biomass burning and industrial emissions.
- Vertical Profiles of Ozone: The Aura Microwave Limb Sounder (MLS) instrument measures vertical profiles of mesospheric, stratospheric, and upper tropospheric

temperature, ozone and other constituents from limb scans. In this study, we utilized the MLS standard product for ozone derived from radiances measured by the 240 GHz radiometer (Froidevaux et al., 2008; Jiang et al., 2007; Livesey et al., 2008).

Table 1 Data resource information

Mission	Period	Parameter	Resolution	Source
Aura/OMI	2007-2013	TCO	25km spatial	Giovanni
Aura/MLS	2007-2013	Temperature,O_3 profiles	3km vertical	Mirodor
COSMIC1-DVAR	2007-2013	Temperature	0.1km vertical	CDAAC
Ozonesonde	2007-2012	O_3 profiles	~7.5m vertical	SHADOZ

Tropospheric Ozone Residual (TOR) technique to derive TO

(Ziemke et al., 2006 and Schoeberl et al., 2007)

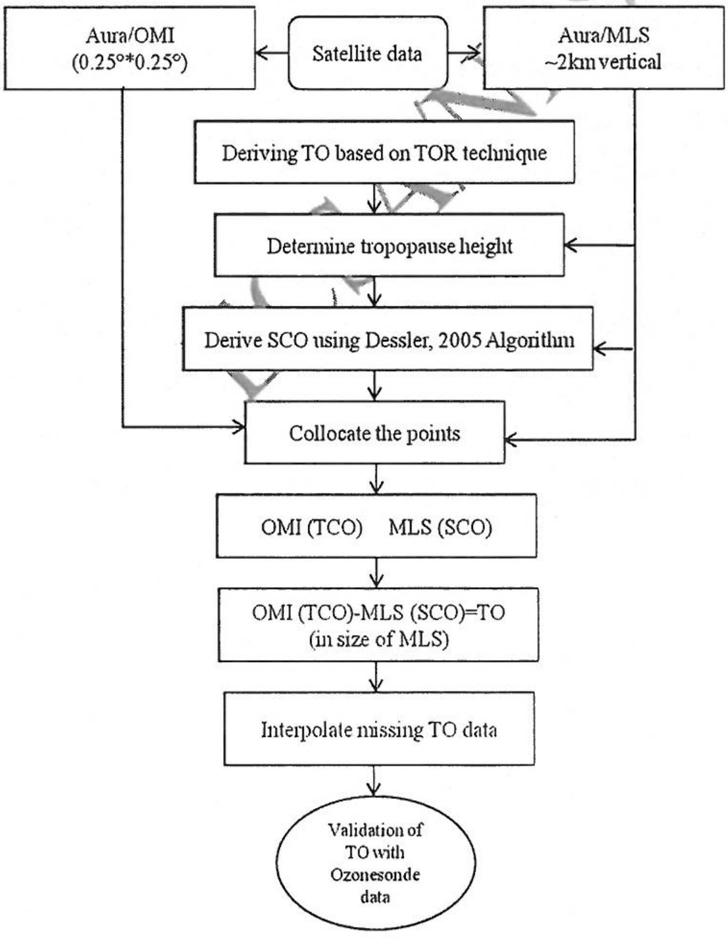


Figure 1 Methodology for deriving TO from Aura/OMI & MLS satellite data

TO is derived using tropospheric ozone residual (TOR) method introduced by Ziemke et al. 2006 and Schoeberl et al. 2007 shown in figure 1. The TOR is residual of total columnar ozone and stratospheric columnar ozone with the spatial resolution of Aura/MLS. Tropopause height is essential parameter before calculating the SCO since its behaviour is different at equator and poles. The altitude of lowest temperature in the vertical profile (i.e. Tropopause Height (TH)) is considered as a bottom level of tropopause (Jain et al. 2011; Sujatha et al. 2014). The height of the tropopause is determined using multi satellite data summarized in table 1. The tropical tropopause height has shown in figure 2 for further implementation of deriving TO over the Indian region.

Setting up tropopause height: The altitude of lowest temperature in the vertical profile (i.e. cold point tropopause (CPT)) has been taken as the level of tropopause (Jain et al., 2011). Tropopause height is required to estimate SCO using MLS data. We have ascertained the tropopause height using available ozonesonde data in the region of 6 years fortnightly146 soundings were used. The Radio Occultation data as well as microwave limb sounding of 6 years have been used to ascertain the average tropopause height in the Indian region. (Fig.2). The SCO is calculated as followed by Dessler, 2005 equation (1);

Step 1: Total Columnar Ozone direct from Aura/OMI

Step 2: Stratospheric Columnar Ozone from Aura/MLS is computed using following method

To compute SCO3, we need to know vertical profiles of Ozone from surface to mesosphere. i.e., 1000hpa to 0.01hpa. According to Algorithm and Theoretical Basis Document (ATBD) of Aura/MLS, we considered valid data fields from 215hpa to 0.01hpa and hence for tropical region of India, we used 100hpa to 1hpa covering 37 atmospheric pressure levels to derive SCO.

Ozone Vertical profiles in volume mixing ratio (vmr) to SCO in Dobson Units (DU) from Dessler algorithm (2005).

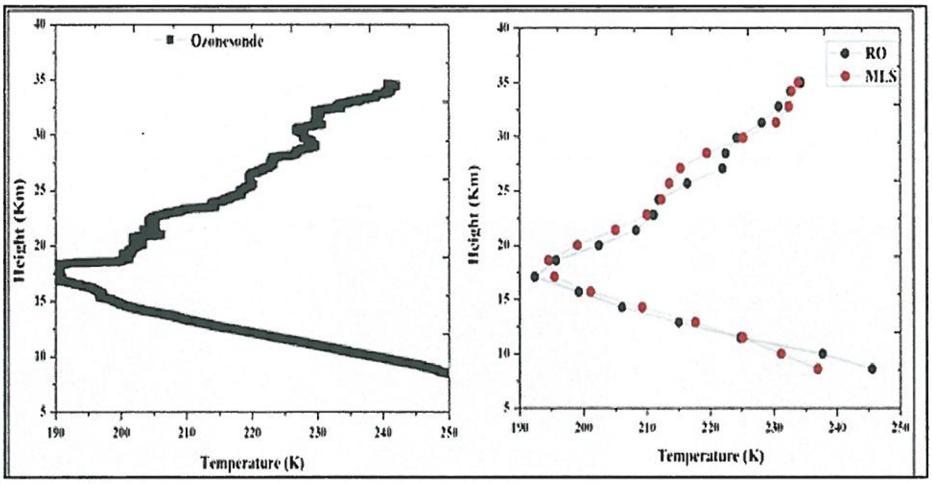


Figure 2 setting up tropopause height to derive TO

$$SCO\ (DU) = 10^7 * \left(\frac{RT_0}{g_0 p_0}\right) * \sum_{i=1}^{N-1} 0.5\left(vmr(i) + vmr(i+1)\right)(p_i + p_{i+1}) ------(1)$$

Where

P is pressure in hpa, SCO in DU and vmr is volume mixing ratio in ppm

$P_0 = 1.01325*10^5$ hpa

$R = kN_A/M_A = 287.3 JKg^{-1}K^{-1}$

k = Boltzmann constant = $1.38*10^{-23}$ JK^{-1}molecule^{-1}

N_A = Avogadro's number = $6.02*10^{23}$

M_A = mass of air = $28.94*10^{-23}$Kg

T_0 = 273.1K standard temperature

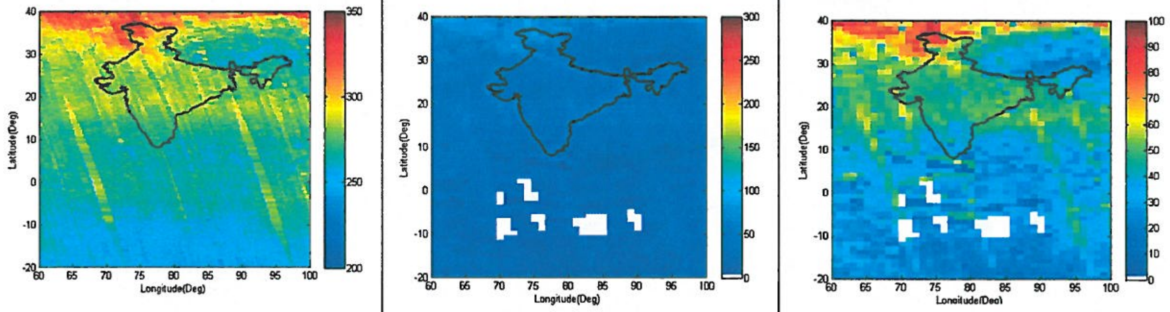
$g_0 = 9.88 ms^{-2}$

From step 1 and step2 (equation 1);

$$TO = TCO\ (OMI) - SCO(MLS) ------(2)$$

The MLS spatial observations are broad in resolution around 200-400 km. The MLS data has been uniformly distributed by interpolating to 100 km Spatial resolution. Accordingly OMI 25 km resolution has been resampled to 100 km. We followed the best possible interpolation method to get SCO observations close to OMI observations. In this method, we used nearest neighborhood to interpolate SCO data over Indian region. Mahesh et al. (2015) has discussed other interpolation techinuques to resample the TO data.

3. Results and validation



TCO (DU)
TCO is extracted from Aura/OMI for May 2013.

SCO (DU)
SCO is derived from MLS data using equation 1

TO (DU)
TO is TCO (100 Km)- SCO (100 Km)

Figure 3 SCO and TO derived from OMI & MLS satellites

Figure 3 shows total columnar ozone (TCO) extracted from Aura/OMI which has been utilized to derive tropospheric ozone (TO) and Stratospheric Columnar Ozone (SCO) based on TOR technique.

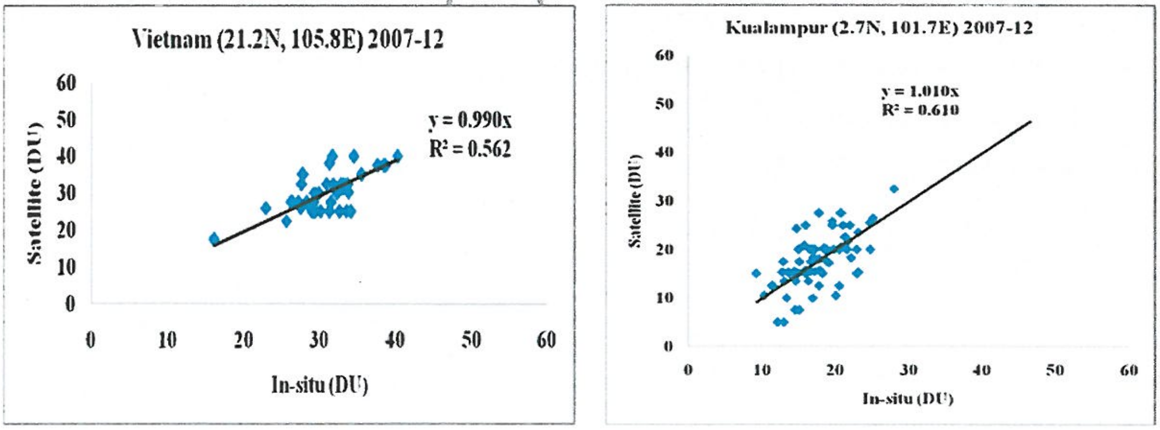


Figure 4 Scatter plot between derived TO and In-situ TO

Figure 4 shows the scatter plot between derived TO and in-situ TO for Vietnam and Kaulampur. The derived Tropospheric Columnar Ozone is compared using Ozonesonde data archived at Southern Hemisphere ADditional OZonesondes. Under the Indian Climatological zone, we considered Vietnam and Kualampur for validating derived TO from 2007 – 2012. In due course, SCO and TO will be compared using Ozonesonde data for Indian site for improving derived TO. The quality flag mean±1σ has applied for six years TO data w.r.t 6 years Ozonesonde fortnightly observations. We obtained good correlation coefficient for 2 stations shown in table 2.

Table 2 Validation of derived TO against ozonesonde

Station (2007-12)	N Satellite	N In-situ	μ±1σ (DU)	N' (flag)	R^2	Bias (DU)	RMSD	SI
Vietnam (21.2N, 105.8E)	58	60	32.8±11.1	41	0.56	0.2	4.6	0.14
Kualampur (2.7N, 101.7E)	96	109	18.96±6.8	74	0.61	0.12	4.2	0.23

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Annexure -I

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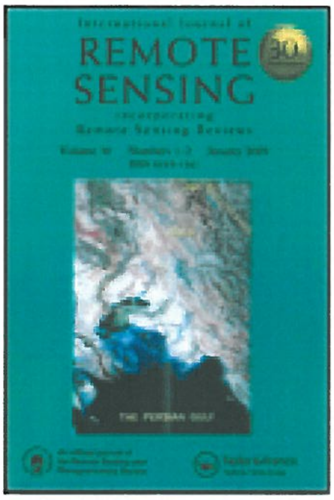

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Comparative study of the tropospheric ozone derived from satellite data using different interpolation techniques

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TECHNICAL NOTE

Comparative study of the tropospheric ozone derived from satellite data using different interpolation techniques

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Tropospheric ozone (TO) has been derived from the Aura/Ozone Monitoring Instrument (OMI) and the Aura/Microwave Limb Sounder (MLS) over the Indian sub-continent region using a tropospheric ozone residual (TOR) technique. The TO was initially retrieved at a horizontal spatial resolution following that of the Aura/MLS (300 km), which has a lower horizontal spatial resolution than that of the Aura/OMI (25 km). To overcome the limitations imposed by data at a lower spatial resolution, we have introduced a 2D rectangular interpolation (RI) algorithm for effective resampling of data to higher horizontal spatial resolutions. The performance of this algorithm has been evaluated by comparison against existing standard techniques such as nearest neighbourhood (NN) and kriging interpolation as well as comparison against *in situ* ozonesonde observations. Gridded TO estimates were subsequently generated for the region of interest at 25, 50, and 100 km horizontal spatial resolutions for further study.

1. Introduction

The short-lived greenhouse gas ozone (O_3) is an important contributor to anthropogenic forcing. The Intergovernmental Panel on Climate Change (IPCC) has reported that the total radiative forcing (RF) estimated from changes in O_3 is 0.35 W m^{-2}, with RF due to tropospheric ozone (TO) changes of 0.40 W m^{-2} and due to stratospheric ozone changes of –0.05 W m^{-2} (IPCC 2013). TO thus plays a role in global warming, leading to increases in emissions of methane (CH_4), carbon monoxide (CO), volatile organic compounds (VOCs), and nitrogen oxides (IPCC 2013). In the troposphere, O_3 forms due to photochemical reactions. Methane and CO contribute to ozone production in polluted atmosphere, particularly in the photochemical production of ozone in the free troposphere (Varotsos et al. 1994; Reid, Yap, and Bloxam 2008).

In this study, TO has been derived using the tropospheric ozone residual (TOR) technique implemented by Fishman and Larsen (1987) and Fishman et al. (1990). TO is obtained as the residual of stratospheric columnar zone (SCO) from total columnar ozone (TCO) using the TOR technique. This technique has been used by many researchers globally to generate TO (Fishman, Wozniak, and Creilson 2003; Chandra, Ziemke, and Martin 2003) using the Total Ozone Mapping Spectrometer (TOMS) for TCO and SCO retrieved from the Solar Backscatter Ultraviolet Radiometer (SBUV). Ziemke et al. (2006) used a 2D linear interpolation method to generate global SCO products before deriving TO. TO was derived recently with a combination of the Ozone Monitoring Instrument

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(OMI) for TCO and SCO from the Microwave Limb Sounder (MLS) based on the TOR technique (Levelt et al. 2006; Waters et al. 2006; Froidevaux et al. 2008). Wong, Yuan, and Perlin (2004) estimated O_3 and other pollutants using nearest neighbourhood (NN), kriging, and inverse distance weighting (IDW) interpolation methods to assess health outcomes and examine the degree to which air pollution estimates are affected using different methods.

The accuracy of an interpolated dataset depends on the techniques used to resample the data. Interpolation techniques are developed based on certain assumptions and principles of spatial autocorrelation. For instance, the NN method estimates the value that is close to the input data and its proportionate area. This method holds good for local as well as for sparse data points (Sibson 1981; Ross Hemsley 2009). The kriging method assigns weights according to a data-driven weighting function rather than an arbitrary function, and produces results similar to other techniques (Isaaks and Srivastava 1989).

In this study, we have introduced a 2D rectangular interpolation (RI) technique to fill the data gaps in our estimated TO. The veracity of this approach is assessed by comparing it with standard interpolation techniques such as NN and Kriging as well as *in situ* ozonesonde observations.

2. Data sets

TO has been retrieved using datasets from instruments on board various satellites, the details of which have been summarized in Table 1. The present study has used temperature profiles for Kuala Lumpur station sourced from the Constellation Observation System for Meteorology, Ionosphere and Climate (COSMIC) – Radio Occultation (RO) database, which is a repository of 1-DVAR wet profile data of temperature, pressure, and water vapour. Co-located vertical profiles of temperature and ozone from the Aura/MLS and COSMIC-RO have been used for inter-sensor calibration and determining the tropopause height (Reichler, Dameris, and Sausen 2003, Peethani, Sharma, and Pathakoti 2014) before deriving SCO. A comparison study was performed against *in situ* ozonesonde observations for 2013 obtained from the Southern Hemisphere Additional Ozonesondes (SHADOZ) (http://croc.gsfc.nasa.gov/shadoz/) programme.

Table 1. Data resources information.

Mission	Period	Parameter	Resolution	Source
Aura/OMI	2007–2013	TCO	25 km horizontal	Giovanni (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=omi)
Aura/MLS	2007–2013	Temperature, ozone profiles	3 km vertical & 300 km horizontal	Mirodor (http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&project=MLS)
COSMIC1-DVAR	2007–2013	Temperature	0.1 km vertical	CDAAC (http://cdaac-www.cosmic.ucar.edu/cdaac/index.html)
Ozonesonde	2007–2013	Ozone profiles	About 7.5 m vertical	SHADOZ (http://croc.gsfc.nasa.gov/shadoz)

3. Methodology

TO has been derived in this study using the TOR method introduced by Ziemke et al. (2006) and Schoeberl et al. (2007). The TO was retrieved using the TOR technique (Figure 1) as the residual of TCO and SCO at a spatial resolution equivalent to that of the lowest resolution dataset used, in this case, that of the Aura/MLS (Figure 1). Tropopause height is an essential parameter for calculating the SCO as a latitudinal variation in the tropospheric depth is observed between the poles and the equator. The height of the tropopause (TH) may be estimated from the altitude of the lowest layer of the tropopause and is determined from the altitude of the minima in the vertical profile of temperature (Jain et al. 2011; Peethani, Sharma, and Pathakoti 2014). Determination of TH using multi-satellite data has been summarized in Table 1. The TH over the Indian sub-continent has been indicated by the altitude of the minimum in the vertical temperature profiles shown in Figure 2. The TCO and SCO estimates required to compute TO have been obtained from the Aura/OMI and Aura/MLS missions of National Aeronautics and Space Administration (NASA). Global estimates of TCO were obtained from the Aura/OMI at about 25 km horizontal resolution, while

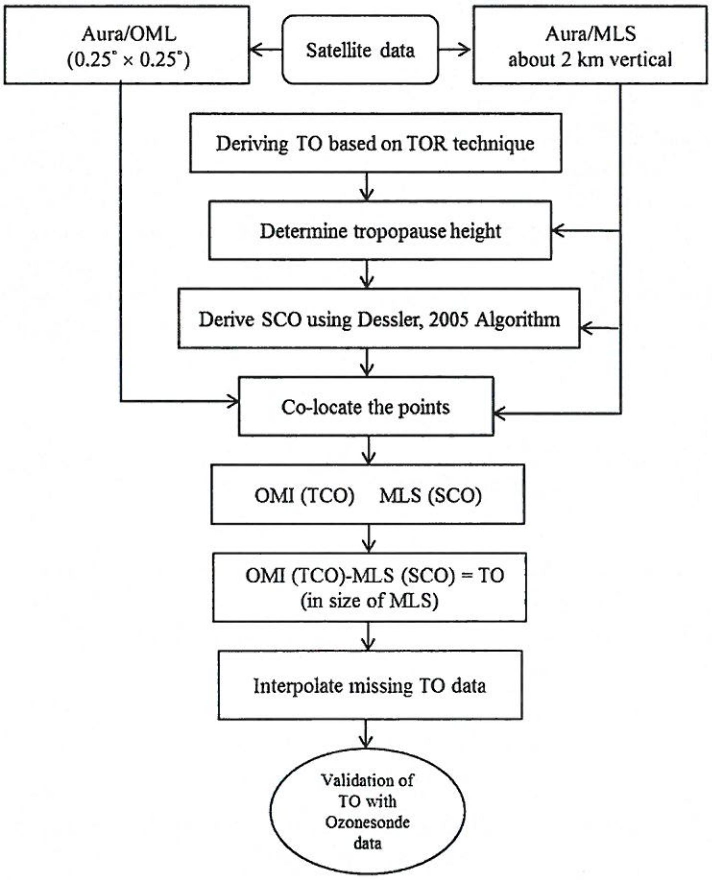

Figure 1. Methodology for deriving TO from the Aura/OMI and MLS satellite data.

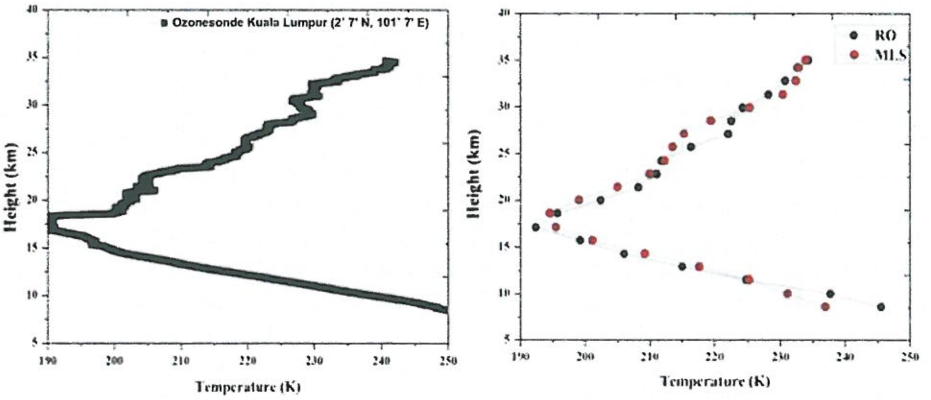

Figure 2. Setting up tropopause height to derive TO (the labels RO and MLS on the right panel indicate COSMIC-RO and Aura/MLS temperature data).

vertical profiles of ozone were obtained from the MLS at 2–6 km vertical resolution between 1000 hectopascal (hPa) and 0.01 hPa.

3.1. Computation of SCO

The computation of SCO requires a priori information on the vertical profile of ozone in the atmospheric column, i.e. 1000 hPa to 0.01 hPa. Ozone profiles from the Aura/MLS are valid only between 215 hPa and 0.01 hPa, according to the MLS Algorithm and Theoretical Basis Document (ATBD) document. Hence, for the tropical region of the Indian sub-continent, the vertical profiles of ozone for 37 atmospheric pressure levels between 100 hPa and 1 hPa have been used. The SCO may be computed in Dobson Units (DU) from the vertical profile of the volume mixing ratio (vmr) of ozone, following the method of Dessler (2005) as given.

$$\mathrm{SCO(DU)} = 10^7 \times \left(\frac{\mathrm{RT}_0}{g_0 P_0}\right) \times \sum_{i=1}^{N-1} 0.5(\mathrm{vmr}(i) + \mathrm{vmr}(i+1))(P_i - P_{i+1}), \qquad (1)$$

where P is pressure in hPa, SCO in DU, and vmr in ppm, $P_0 = 1.01325 \times 10^5$ hPa, $R = kN_A/M_A = 287.3$ J kg^{-1}K^{-1}, k = Boltzmann constant = 1.38×10^{-23} JK^{-1}molecule^{-1}, N_A = Avogadro's number = 6.02×10^{23}, M_A = mass of air = 28.94×10^{-23} kg, $T_0 = 273.1$ K standard temperature, and $g_0 = 9.88$ m s^{-2}.

$$\mathrm{TO} = \mathrm{TCO(OMI)} - \mathrm{SCO(MLS)}. \qquad (2)$$

The TO is computed at a horizontal spatial resolution equivalent to that of the coarsest resolution of the datasets used, i.e. that of the Aura/MLS.

3.2. *Rectangle Interpolation (RI) algorithm*

The TO derived using the TOR technique has relatively low spatial resolution, and thus it needs to be up-scaled to enhance its applicability. The RI technique has been used successfully for up-scaling the TO product. Figure 3 summarizes the various steps involved in deriving the TO using the TOR technique.

The steps involved in up-scaling the TO data are as follows.

- Create a database of spatially and temporally co-located observations from both Aura/OMI and Aura/MLS.
- Extract only the valid data points from both datasets to create a data matrix of co-located observations.
- The initial TO dataset, also referred to as a TOR matrix, is obtained as the residual of TCO and SCO.
- [TOR] = TCO (OMI) – SCO (MLS).
- The TOR matrix is observed to have large data gaps and thus it needs to be processed further using a suitable interpolation technique for filling the gap.

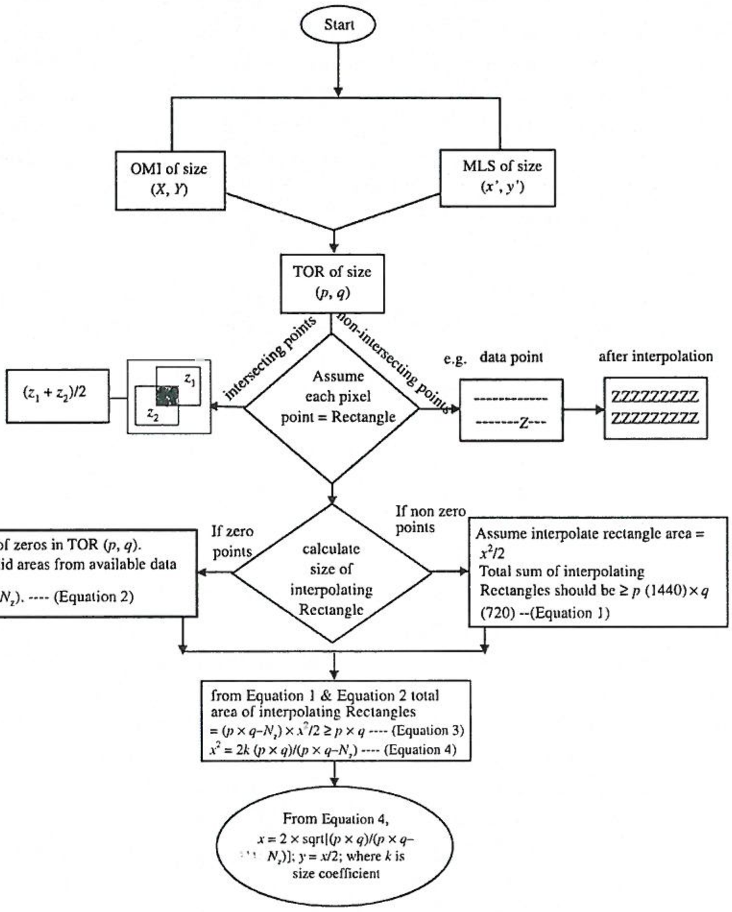

Figure 3. Implementation of the Rectangle Interpolation algorithm.

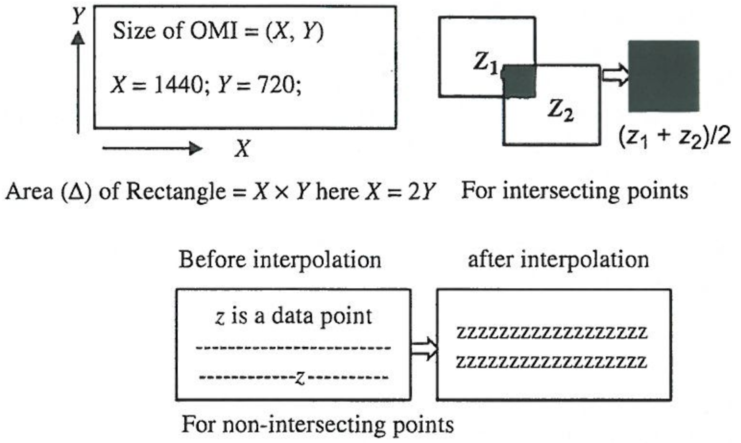

Figure 4. Schematic representations of rectangle size selection and interpolating the rectangle data point.

Ziemke et al. (2011) showed latitudinal and longitudinal TO variations. Therefore, using the RI technique may give good results. Interpolation was thus performed at each point of the dataset using a hypothetical rectangle of size (x, y). As there are usually only a few valid data points within any given rectangle, filling the gap in the data was done by assuming that each data point within the rectangle has a value equivalent to that of the mean value of all valid data points within the rectangle. A detailed representation of the Rectangle Interpolation algorithm has been given in Figures 3 and 4.

The size of the rectangle (x, y) may be derived as follows.

$$x^2 = 2k\left(\frac{pq}{pq - N_z}\right) \gg x = \mathrm{sqrt}2k\left(\frac{pq}{pq - N_z}\right);\; y = \mathrm{sqrt}\left(\frac{pq}{pq - N_z}\right), \tag{3}$$

where k is size coefficient of rectangle (here $k = 2$), (p, q) represents the size of TOR matrix, and N_z is number of non-zeros in TOR.

4. Results and discussions

TO retrieved using the RI technique was evaluated by comparing its performance against the standard NN and Kriging interpolation techniques as well as with *in situ* ozonesonde observations from the station at Kuala Lumpur (2.7° N, 101.7° E) for the 2013. TO retrieved for 1 January 2013 using different interpolation techniques are shown in Figures 5(*a*)–(*c*)). The different interpolation techniques showed similar spatial variability with less variability in the RI-derived product. The spatial variability due to the RI technique can be improved by changing the size of the interpolating rectangle. More accurate results may be obtained by clustering the data based on its density distribution and choosing a variable rectangular size for each cluster. Table 2 shows the comparative performance of different interpolation techniques against *in situ* ozonesonde observations, which gives a better insight of their performances. The RI technique returned poor estimates of TO for 10 January 2013 and 17 June 2013, which may be attributed to the sensitivity of the RI technique to sparse distribution of data points. Root mean square deviation (RMSD) and

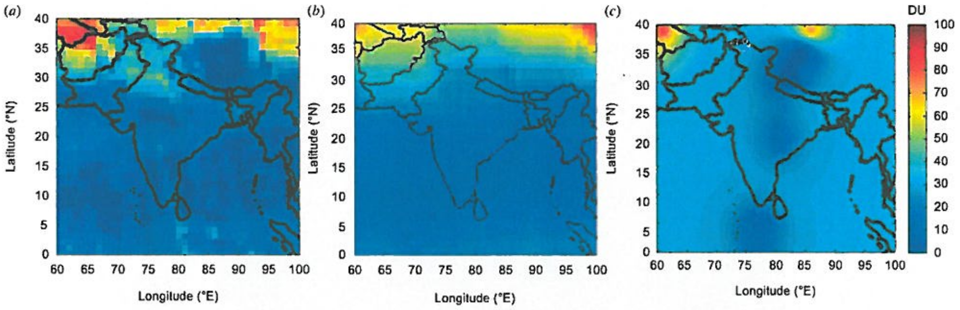

Figure 5. (*a*) Nearest neighbourhood on 1 January 2013; (*b*) rectangular interpolated tropospheric ozone on 1 January 2013; c) kriging interpolated tropospheric ozone on 1 January 2013.

Table 2. Comparison study of TO with different interpolation techniques against ozonesonde observations at Kuala Lumpur station.

Date	TO_Sonde (DU)	TO_NN (DU)	TO_RI (DU)	TO_Kriging (DU)
10 January 2013	17.95	19.62	29.02	38.30
14 March 2013	33.80	37.28	36.14	33.24
18 April 2013	21.87	26.15	26.26	50.85
2 May 2013	30.22	29.89	34.73	46.20
16 May 2013	25.74	28.42	31.52	27.09
3 June 2013	20.48	16.76	24.32	26.64
17 June 2013	16.04	18.32	26.09	16.95
16 August 2013	18.87	17.54	16.97	27.49
3 October 2013	19.09	19.02	14.01	16.05
18 October 2013	22.47	22.67	22.43	33.86
1 November 2013	22.89	21.10	31.33	23.86
18 November 2013	18.28	21.07	28.0	31.47
17 December 2013	16.67	22.37	29.97	13.43
Statistics	RMSD	2.84	5.28	12.24
	SI	0.13	0.24	0.56

scatter index (SI) are good statistical parameters for evaluating the accuracy of the TO estimated using different techniques, with lower values of SI indicative of a better estimate of TO. The RMSD of the NN, RI, and kriging interpolation techniques were found to be 2.84, 5.28, and 12.24, respectively, while the SI values were 0.13, 0.24, and 0.56, respectively. These statistics indicate that the performance of the RI technique is similar to that of the other techniques and better than that of kriging for the period of study, proving the applicability of this method for future studies. Figure 6 shows the monthly mean variations (January 2013) of TO retrieved using the RI technique over the Indian region. Analysis shows higher TO values were observed over the northern than over the southern part of India. Ziemke et al. (2011) and David and Nair (2013) also reported similar observations for January.

Table 3 shows the validation of RI-derived TO against *in situ* ozonesonde over two stations, namely Vietnam (21.2° N, 105.8° E) and Kuala Lumpur (2.7° N, 101.7° E) during 2007–2012, which are statistically summarized. The quality of the derived data

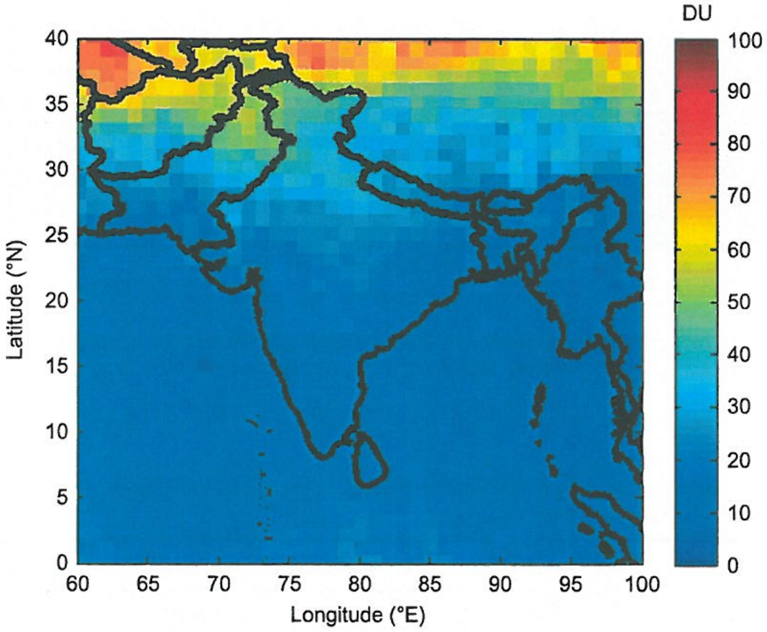

Figure 6. Monthly mean variation of TO (DU) during January 2013.

Table 3. TO (DU) over Vietnam and Kuala Lumpur derived from RI technique against ozonesonde during 2007–2012.

Station (2007–2012)	N Satellite	N *In situ*	$\mu \pm 1\sigma$ (DU)	N' (flag)	R^2	Bias (DU)	RMSD	SI
Vietnam (21.2° N, 105.8° E)	58	60	32.8 ± 11.1	41	0.56	0.2	4.6	0.14
Kuala Lumpur (2.7° N, 101.7° E)	96	109	18.96 ± 6.8	74	0.61	0.12	4.2	0.23

points (N') are ensured by removing inconsistent points based on the observed means ($N_{\text{in situ}}$) with 1 sigma deviation ($\mu \pm 1\sigma$). The statistical significance of validation is studied by calculating coefficient of determination (R^2), bias, RMSD, and SI. The average bias on Vietnam (Kuala Lumpur) is 0.20 (0.12) DU with corresponding coefficient of determination (R^2) 0.56 (0.61). RMSD and SI in both cases also showed statistically good agreement. The formulae for the statistical analysis are given in the Appendix.

4.1. *Advantages and disadvantages of RI, NN, and kriging*

Most of the interpolation techniques depend on the spatial pattern, including clustering of data and data gaps prevalent in the input data. One of the main advantages of the RI method is that it works well for data clusters. By clustering the data based on density and applying the RI technique, it may be possible to obtain better estimates as compared to the standard NN and kriging interpolation techniques. However, this method has to be further improved for cases where data points are sparsely distributed. The NN technique fills data gaps based on a weighted average of the nearest data points. The main disadvantage of the NN method is that in the case of remotely located points also, it considers only the nearest neighbouring data points, which may result in poor estimation compared to actual values. Kriging interpolation assigns weights based on a data-derived weighting function, rather than an arbitrary function, thus helping to compensate for the effect of data clustering. However, kriging interpolation is computationally intensive as compared to the RI and NN techniques.

5. Conclusions

TO retrievals using the interpolation techniques were found to be very sensitive to the spatial resolution up-scaled to as well as the method of interpolation used. In the present study, we have introduced a 2D RI technique, which showed good performance in up-scaling TO retrievals, comparable to that of the NN and kriging techniques for the period of study. The performance of the RI, NN, and Kriging methods against the *in situ* ozonesonde observations at Kuala Lumpur station was analysed for the year 2013, revealing poor correlation with respect to *in situ* observations for all three methods, which may be attributed to the spatial distribution of data over the study region. Good statistical performance was observed between RI-derived TO and *in situ* observations for two stations (Vietnam and Kuala Lumpur) during 2007–2012. The performance of RI can be further improved by selecting different data clusters based on density and choosing variable rectangle size, respectively, to enhance the accuracy of the retrieved TO product. An improvement of the RI algorithm for further increasing the accuracy for up-scaling to fine horizontal resolution is currently under implementation.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix

The formulae for statistical parameters of RMSD, SI, R^2, and bias are as follows (Steel and Torrie 1960).

$$\Delta = \sum_{i=1}^{n} (O_i - E_i)^2 \tag{A1}$$

$$R_{\in} = \sqrt{\frac{\Delta}{n}} \tag{A2}$$

$$S_I = \frac{R_{\in}}{(O_i/n)} \tag{A3}$$

$$B = \frac{1}{n}\sum_{i=1}^{n}(O_i - E_i) \tag{A4}$$

$$O = \frac{1}{n}\sum_{i=1}^{n} O_i \tag{A5}$$

$$S_t = \sum_{i=1}^{n} (O_i - O)^2 \tag{A6}$$

$$S_r = \sum_{i=1}^{n} (O_i - E_i)^2 \tag{A7}$$

$$R^2 = 1 - \frac{S_r}{S_t} \tag{A8}$$

where n is the number of observations, O_i and E_i are the observed and estimated values, Δ is the sum of squares of the O_i and E_i differences, $R_\in$ (RMSD) is the square root of mean of Δ, S_I (SI) is the ratio of $R_\in$ and mean of observed values, B (bias) is the mean of sum of the differences, O is the mean of observed values, S_t is the sum, over all observations of the squared differences of each observation from the overall mean, S_r is the sum of squares of residuals.