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Evaluation of MERRA-2 Total columnar ozone from ground based and AIRS satellite product

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Abstract

In the present study, a first systematic evaluation and analysis of long-term (2009-2020) gridded datasets (0.5° × 0.625) of total columnar ozone (TCO) from Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2TCO) is carried out over the Indian subcontinent. The MERRA-2_{TCO} is first validated with observed (IMD_{TCO}) and then further compared with Atmospheric Infrared Sounder ($AIRS_{TCO}$) satellite dataset. For an in-depth comparison and statistical analysis, the dataset has been segregated into seven distinct regions, i.e. Western Himalaya (WH), Northeast (NE), North Central (NC), Northwest (NW), West Peninsula India (WPI), East Peninsula India (EPI), and South Peninsula India (SPI). Descriptive statistics (NMSE, FB, R, FA2 and d) reveals significant correlation of MERRA-2_{TCO} with IMD_{TCO} over Delhi (NMSE=0.0013, FB=-0.029) and Varanasi (NMSE=0.0008, FB=-0.014) cities. Further, a comparison of MERRA-2_{TCO} with $AIRS_{TCO}$ represents the NMSE values ranging from 0.0023-0.0047 DU and a correlation coefficient of 0.62-0.87 in different regions of India. In support of Brewer's circulation pattern, an increasing strong shift of columnar ozone from low (SPI) to high (WH) latitudinal regions in annual variation (2009-2020) is observed. Our finding indicate that the MERRA-2 ozone dataset can be effectively used for ozone air quality studies over the Indian regions and the analysis may highlight the necessity for independent, reliable, consistent, and accurate ozone observations.

Keywords: Total column ozone, MERRA-2, AIRS, Validation

1. Introduction

Ozone in the atmosphere has been extensively studied, with applications ranging from assessing the thermal structure of the atmosphere to participating in tropospheric photochemical processes (Forster and Shine, 1997). In keeping with all of the aforementioned considerations, variations in the amount of ozone, whether they occur globally or throughout the entire atmosphere, will change the atmospheric dynamics caused by radiative processes. Hence, it becomes very essential to accurately assess the spatio-temporal variation in ambient ozone concentration. Total Column Ozone is a significant parameter employed by the scientific community to measure the fluctuation in ambient ozone concentration (TCO). TCO is the total concentration of ozone (as measured at standard pressure and temperature) in a vertical air column with a base area of 1 cm2. About 90% of this total columnar ozone is constituted of stratospheric ozone which is responsible for absorbing the solar ultraviolet radiation (Forster and Shine, 1997). The aforementioned results reveal that huge variability exists in spatio-temporal as well as vertical distribution of total columnar ozone, thus this analysis may strengthen the need for independent, high quality, consistent and long-term global measurement with small uncertainties. Additionally, quantifying trends and variability of ozone will also require the same. This is particularly important over the tropical region which covers a large fraction of the world and experiences upper troposphere to lower stratosphere exchange (Monahan et al., 2007). However, the availability of long-term ozone data sets with high resolution is sparse with only a handful meeting all the prerequisites.

In this regard, useful observations can be acquired from space-borne instruments in order to achieve the required spatio-temporal coverage. For the estimation, TCO dataset can be acquired from sensors onboard polar-orbiting satellites. A few examples of such sensors are Global Ozone Monitoring Experiment (GOME), Microwave Limb Sounder (MLS), Ozone Monitoring Instrument (OMI), Total Ozone Mapping Spectrometer (TOMS), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), etc. Among this one particularly useful high-quality observation are provided by AIRS, launched in the year 2002, are being utilized for monitoring global ozone variability and trends over a decade (Monahan et al., 2007). In 2009, NASA's Global Modelling and Assimilation Office (GMAO) was the first released Modern-Era Retrospective Analysis for Research and Applications (MERRA-2), a reanalysis dataset created using the Goddard Earth Observing System (GEOS) data assimilation system (DAS) covering the time period of 1979–2015. The accent of this paper particularly falls on MERRA-2 dataset (Bosilovich et al., 2015) which trailed the aforementioned reanalysis. While majority of the reanalysis incorporates assimilated ozone fields, the wide spread utilization of these dataset in scientific investigations are still lacking, primarily due to the uncertain quality of these fields and the overall lack of validation. Instead, scientist choose to make use of ground based and satellite retrieved ozone dataset alongside assimilated climatological parameters.

Therefore, the focus of the present work is to fully analyze the TCO product from MERRA-2 regarding biases, random errors and long-term constancy with respect to ground-based TCO observations. In this context, the accuracy and long-term stability of total column ozone estimates from the MERRA-2 (Bosilovich et al., 2015), product will be examined via comparisons to already established spaceborne mission Atmospheric Infrared Sounder (AIRS) on NASA's Aqua Satellite, which have been collocated in space and time. As a result, this work verifies MERRA-2 columnar ozone with IMD observation datasets over New Delhi and Varanasi cities for a long period of time depending on the data availability. Another goal is to assess the monthly, annual, and seasonal fluctuations of TCO datasets over selected regions of India, including WH, NE, NW, NC, WPI, EPI, and SPI, using the MERRA-2 and AIRS products.

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2. Datasets used:

2.1. AIRS: In the current study, we have used Level 2, V006 AIRS retrieved datasets (AIRS/Aqua L2 Standard Physical Retrieval, (AIRS2RET006) with a spatial resolution of 50 km x 50 km. Since AIRS2RET is a newly developed product utilizes AIRS IR only. It consists of retrieved temperature profile, carbon monoxide, ozone, water vapor and methane as well as retrieval estimates of cloud and surface properties.

2.2. MERRA-2: Providing dataset from the beginning of 1980, Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) was introduced as a successor to the original MERRA dataset. The dataset is provided at a grid resolution of 0.5° × 0.625°. MERRA-2 columnar ozone is available at 1 hour, 3 hour and monthly temporal resolution. This study uses the MERRA-2 (M2T1NXCHM_5.12.4) 1-hourly columnar ozone for time period 2009-2020.

2.3. Methodology:

2.3.1 Comparison Statistics: Further, the statistical tools used to evaluate the MERRA-2_{TCO} comprises the Normalised mean square error (NMSE), Fractional bias (FB), correlation coefficient (r), Index of agreement (d) and fraction of model predictions within a factor of two of observation (FA2) are given by following equations.

$$\mathrm{NMSE} = \frac{\overline{(\mathbf{X_M}-\mathbf{X_O})^2}}{\overline{\mathbf{X}}_\mathbf{M}\overline{\mathbf{X}}_\mathbf{O}} \tag{1}$$

$$\mathrm{FB} = \frac{(\overline{\mathbf{X}}_\mathbf{M}-\overline{\mathbf{X}}_\mathbf{O})}{\mathbf{0.5}(\overline{\mathbf{X}}_\mathbf{M}+\overline{\mathbf{X}}_\mathbf{O})} \tag{2}$$

$$\mathrm{R} = \frac{\overline{(\mathbf{X_O}-\overline{\mathbf{X}}_\mathbf{O})(\mathbf{X_M}-\overline{\mathbf{X}}_\mathbf{M})}}{\sigma_{\mathbf{X_M}}\sigma_{\mathbf{X_O}}} \tag{3}$$

FA2=Fraction of data which satisfy

$$0.5 \le \frac{X_M}{X_o} \le 2.0 \tag{4}$$

$$d = 1 - \frac{\sum_{i=1}^{n}\left(\mathbf{X_{O_i}}-\mathbf{X_{M_i}}\right)^2}{\sum_{i=1}^{n}\left(\left|\mathbf{X_{M_i}}-\overline{\mathbf{X}}_\mathbf{O}\right|+\left|\mathbf{X_{O_i}}-\overline{\mathbf{X}}_\mathbf{O}\right|\right)^2} \tag{5}$$

where,

X_M : MERRA-2_{TCO}, X_O : observations/AIRS$_{TCO,}$ $\overline{X}_O$ and $\overline{X}_M$: average of the dataset, σ_{X_M} and σ_{X_O}: standard deviation of the dataset.

Results and Discussion: Comparative analysis of MERRA-2 columnar ozone with IMD observed and AIRS satellite datasets reveals that MERRA-2 is a righteous tool for temporal and spatial TCO study. In the current paper, the MERRA-2 columnar ozone is systematically evaluated and validated with ground based and AIRS satellite datasets over India for a period of ten (2009-2018) and twelve year (2009-2020) respectively. Long-term examination of the MERRA-2 product using ground-based datasets over the cities of Delhi and Varanasi reveals good agreement with low NMSE, FB high correlation coefficient, and agreement index (d). MERRA-2 and AIRS comparison analyses on a daily, monthly, annual, and seasonal basis have been done for all the studied regions(WH, NE, NW, NC, EPI, WPI, and SPI). In all regions of India, with the exception of WH, the seasonal variation in TCO shows that the peak TCO concentration (305-315 DU) occurs in the spring months of March, April, and May. In both the datasets (MERRA-2 and AIRS), the spatial variation of annual average TCO shows a nearly identical pattern of distribution, ranging from 270-284 DU throughout the northern portion of India (WH, NE, NW, and NC) to between 260-274 DU toward the southern region (WPI, EPI, and SPI). The TCO distribution appears to vary significantly with the seasons and topography. High TCO concentration is seen in the summer season (MAM), which is correlated with high temperatures and long days of sunshine. While low TCO is seen in the winter (DJF) because less photochemical synthesis occurs then. Additionally, MERRA-2_{TCO} and AIRS$_{TCO}$ fluctuate slightly depending on the season. While MERRA-2_{TCO} appears to be significantly under- or over-estimated during the monsoon and post-monsoon seasons, especially across WPI and EPI regions, in the winter and pre-monsoon season (by +1 to +8 DU) virtually everywhere in the region.

Moreover, MERRA-2 and AIRS exhibit similar patterns over a twelve-year period (2009–2020) with high data differences in the WH region and modest differences in the EPI and SPI regions. The final comparison shows good agreement between the MERRA-2_{TCO} and AIRS$_{TCO}$ products at the regional level, with NMSE values ranging from 0.0023 (WPI) to 0.0047 (WH) and FB from 0.05 (WH) to -0.0075. (WPI). Both datasets show a growing shift in columnar ozone from low (SPI) to high (WH) latitudinal locations, which is consistent with Brewer's circulation pattern. Overall, MERRA-2 total columnar ozone modest biases based on the seasons and the year are realistic, exhibiting good agreement between reanalysis TCO and independent AIRS satellite and ground-based data. In terms of the spatial, temporal, and interannual investigation of total columnar ozone, the study found that MERRA-2 reanalysis is scientifically sound.

5. Figures and Tables

5.1 Figures

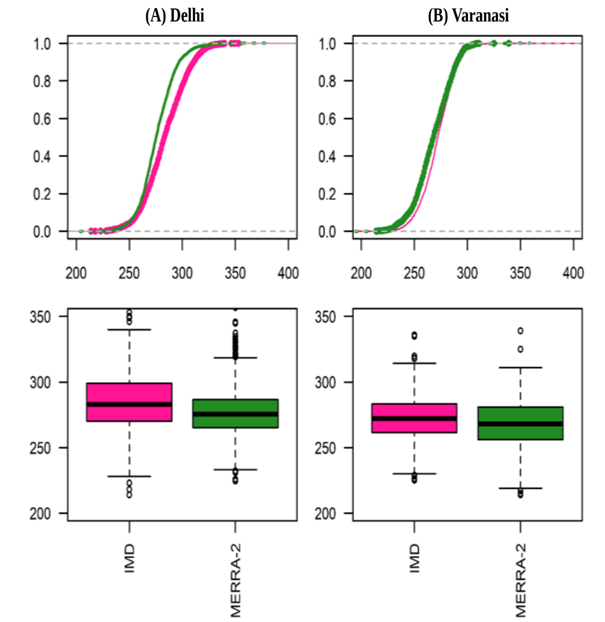


Figure1: ECDF of MERRA-2$_{TCO}$ with IMD$_{TCO}$ over Delhi and Varanasi city for time period of 2009-2018.

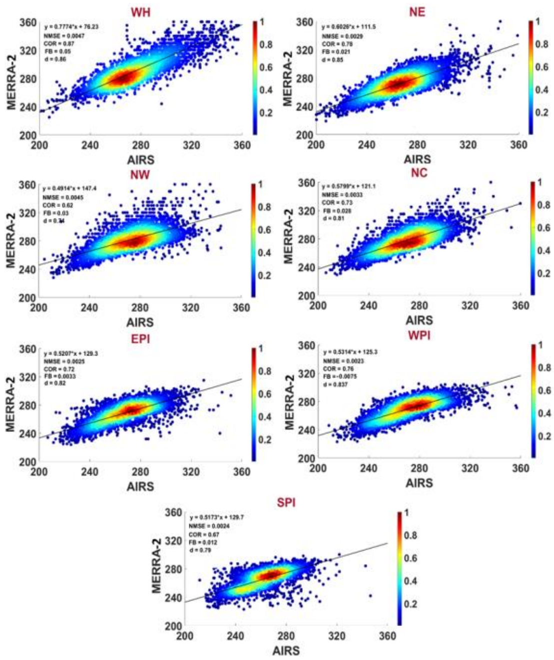


Figure4: Density scatter plot comparing MERRA-2 and AIRS TCO over different regions of India.

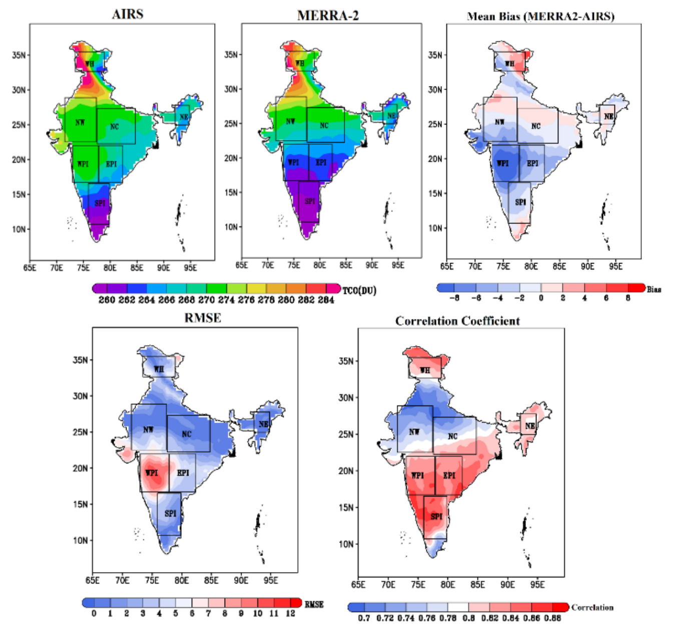
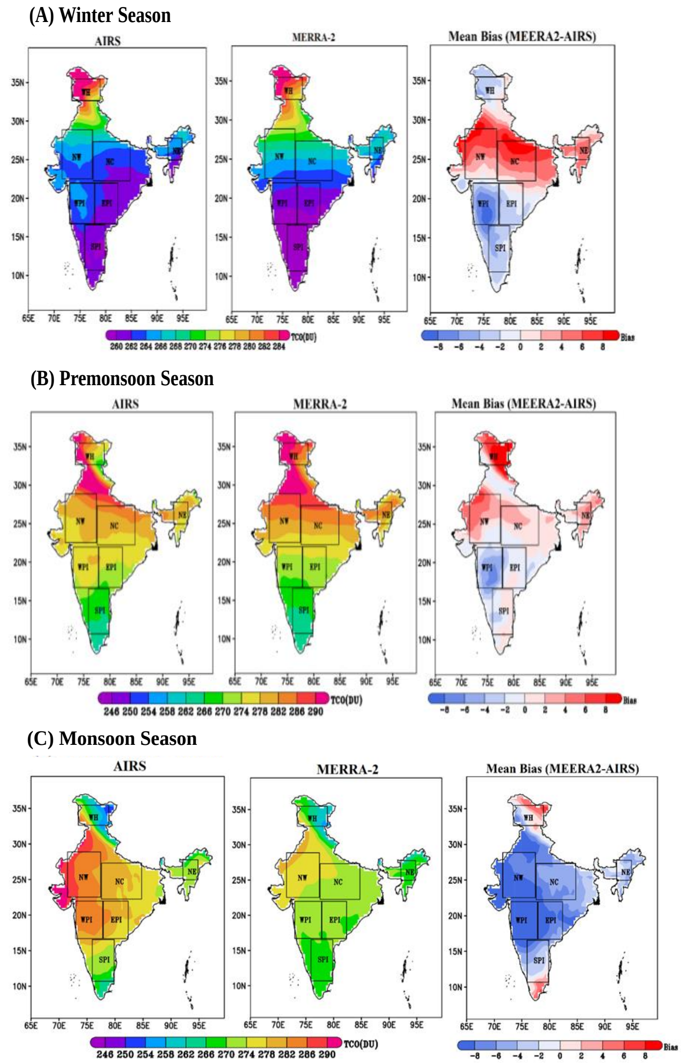


Figure2: Annual mean TCO derived from MERRA-2 and AIRS datasets from 2009-2020.



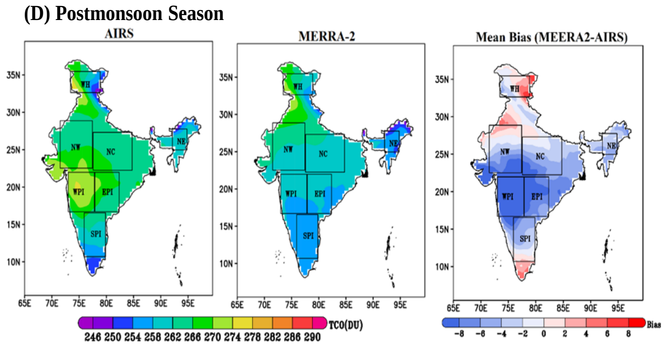


Figure3: Seasonal distributions; A) winter B) Pre-monsoon C) monsoon and D) post-monsoon season of MERRA-2 and AIRS$_{TCO}$ during 2009-2020.

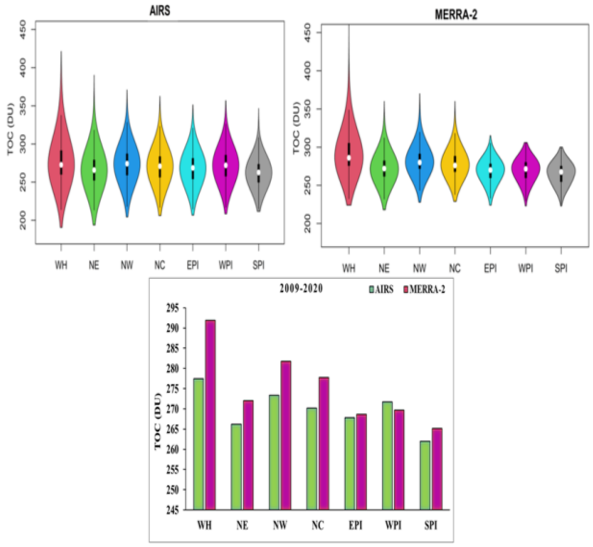


Figure 5: Twelve year (2009-2020) average TCO over different regions of India (WH, NE, NW, NC, WPI, EPI and SPI).

5.2 Tables

Table1: Descriptive Statistical; MERRA2 vs. IMD.

Statistics	MERRA-2 Vs. IMD	
	Delhi	Varanasi
NMSE	0.00134	0.00082
R	0.94	0.88
FB	-0.029	-0.0145
FA2	100	100
D	0.88	0.91

Table2: Statistical performances of MERRA-2$_{TCO}$ vs. AIRS$_{TCO}$

Regions	NMSE	FB	R	d
WH	0.0047	0.05	0.87	0.86
NE	0.0029	0.021	0.78	0.85
NW	0.0045	0.03	0.62	0.74
NC	0.0033	0.028	0.73	0.81
WPI	0.0023	-0.075	0.76	0.84
EPI	0.0025	0.0033	0.72	0.82
SPI	0.0024	0.012	0.67	0.79

6. Acknowledgements

MERRA-2 data is obtained from https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/. AIRS data were obtained from the Level-2, (https://disc.gsfc.nasa.gov/datasets/AIRS2RET_006/summary?keywords=airs%20version%207). We also acknowledge the AIRS mission scientists, Worldview and associated NASA personnel for the production of the data used in this research effort. We also acknowledge the data from the Indian Meteorological Department (IMD), India. The funding support from Ministry of Earth Sciences (MoES/16/18/2017-RDEAS), Government of India are acknowledged.

7. References

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