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GEO-GEO Radiance Inter-Calibration of INSAT-3D with MSG-SEVIRI and Total Ozone Retrieval using Machine Learning

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Abstract

Atmospheric ozone has a unique vertical distribution among various trace gases and plays different roles at different altitudes. The useful stratosphere ozone absorbs harmful UV radiations, while tropospheric ozone, a powerful greenhouse gas, adversely affects living beings and vegetation. The continuous monitoring of the total ozone column (TOC) is necessary to understand the various large-scale dynamics, recovery of total ozone over different regions, and accurately estimate the incoming UV flux to the earth's surface. Nowadays, ozone monitoring via satellite-based remote sensing has gained wide importance. The Indian geostationary satellite INSAT-3D is accomplishing this need for India's tropical region. The poor understanding of dominant circulations and limited ground-based observations over tropical regions, like India, ozone recovery, and trend studies remain complex and uncertain, where INSAT-3D has enormous capabilities. However, INSAT-3D has underestimated the total ozone column by more than 22 DU, compared with ozonesonde and OMI. The large TOC bias could be attributed to lower reliability of retrieval and INSAT-3D radiance biases. To mitigate these differences, the radiance biases in INSAT-3D observations are calibrated using the GEO-GEO methodology with MSG-SEVIRI for collocated pixels. It shows biases in INSAT-3D by more than 5 K. These biases of INSAT-3D are corrected to better retrieve the total ozone over the Indian region from INSAT-3D. A well-trained machine learning (ML) model is then used for TOC retrieval, which retrieved TOC effectively and matches well with SEVIRI.

1. Introduction

Among the trace gases, atmospheric ozone holds a certain fascination in atmospheric science [1]. It is ubiquitous in the atmosphere, essential in the stratosphere, central to tropospheric oxidation chemistry, and harmful to human and ecosystem health near the surface [2, 3, 4]. In the stratosphere, ozone forms due to natural photochemical reactions, while tropospheric ozone has two sources: photochemical production and downward transport from the stratosphere. The downward ozone transport poses a larger uncertainty in the tropospheric ozone budget estimation, and its flux is expected to increase by 53 % in the near future [5]. Additionally, tropospheric ozone is a short-lived climate pollutant with a global mean radiative forcing of 0.40 ± 0.20 W m^{-2} [6] and sufficiently long-lived (∼22 days globally averaged) in the free troposphere. Hence regional ozone pollution may also influence air quality and climate on a hemispheric scale [7].

After reducing ozone-depleting substances (ODS) under the Montreal Protocol, the ozone layer displays clear signs of recovery over the polar-regions [8]. However, the detection of ozone healing outside the polar-regions, particularly in the tropics has not been seen and is yet to clearly emerge in the coming years [9]. In addition, ozone recovery and trend studies remain complex and uncertain in the tropical regions.

To minimize the uncertainties of ozone recovery, analyze the influences of anthropogenic activities on the tropospheric ozone, and estimate reliable radiative budgets, observations from satellite sensors (i.e., microwave limb, Ultra-violet, and infrared sounding) have become an increasingly robust tool in the recent decades owing to their global and higher temporal resolutions [10]. The quality-controlled and long-term global observation of ozone from the space-borne sensors can be utilized greatly to study the influences of natural and anthropogenic activities on ozone, including its trend over regions. The Indian satellite INSAT-3D, in the geostationary orbit, provides hourly and higher spatial resolution ozone and meteorological observations over the Indian tropical region. However, the high-quality retrieved information of such satellite observations is ensured by pre-flight and onboard radiance calibration of the sensor.

2. Data and Methodology

2.1 INSAT-3D

INSAT-3D is the first Indian advance meteorological satellite in the geostationary orbit, located at 82° E in a celestial equator of radius 36000 km. INSAT-3D carries two payloads, an imager and a sounder, apart from other satellite maintenance equipment. The INSAT-3D imager has six channels in the visible and near IR region. In contrast, the sounder has 18 IR channels in the longwave and shortwave IR region (3.8 – 15 µm), with a visible channel. It is the first atmospheric-sounding instrument to provide the vertical profiles of temperature, humidity, and total column ozone over the Indian subcontinent with hourly temporal resolution.

2.2 MSG-SEVIRI

MSG-SEVIRI is an infrared (IR) instrument onboard the geostationary satellite Meteosat-8, operated by the European Organization for the Exploitation of Meteorological Satellites. It is located at 41.5° E while operating and covers the Indian Ocean and much of the Indian region. It is a line-by-line scanning radiometer with a 50 cm diameter aperture. SEVIRI has four visible and near IR channels and eight IR channels in mid and long-wave. The typical spatial resolution of SEVIRI is 3 km at the sub-satellite point, which images an entire disk in about a 15 min temporal gap. In this present analysis, ozone-infrared channels (9.7 µm) and corresponding total ozone product are used.

2.3 Artificial Neural Network for TOC retrieval

In recent years, machine learning (ML) has achieved remarkable success in finding complex and non-linear relationships in large multivariate and inhomogeneous datasets. Atmospheric ozone is largely controlled by non-linear photochemistry, complex circulations, and varying meteorological conditions. Various studies have utilized ML models to retrieve total ozone and other satellite products owing to their easy and fast computation. In the present analysis, we have utilized the feed-forwarded artificial neural networks (ANN) ML model to retrieve the TOC from INSAT-3D observations. ANN often outperforms traditional machine learning models due to their potential to understand non-linearity between inputs and outputs, variable interactions, and weighted customization. We started with a basic NN architecture in Keras and the hyper-parameters are optimized with the grid search approach (Figure 1). The utilized inputs are also shown in top Figure 1, which are 5000 set of diverse atmospheric profiles provided by ECMWF. Furthermore, the Mean absolute error (MSE) and R^2 score are used to confirm the performance of the ANN model for training and validation data samples. The successful retrieval confidence is present in Figure 2 when the optimized ANN is able to produce the total ozone column effectively. In addition to the ANN model, a regression model, Ordinary Least-Squares (OLS), is also utilized in the present study.

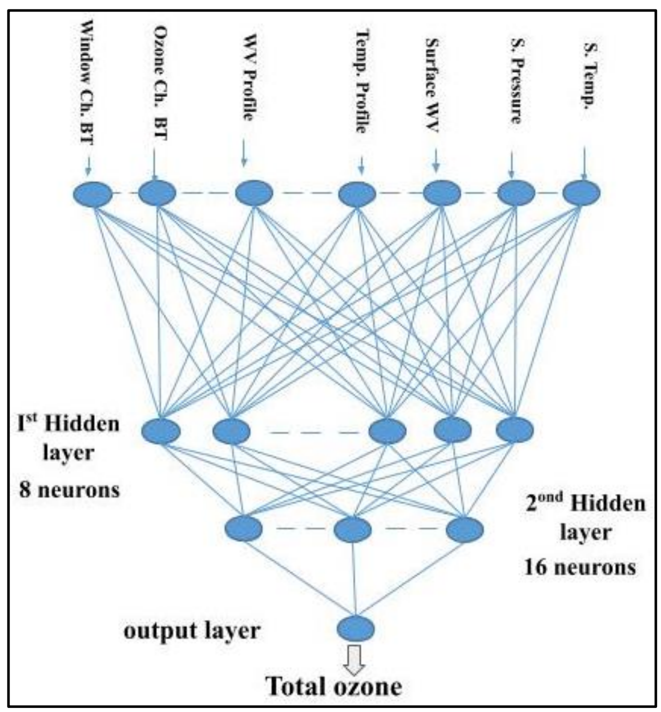

Figure 1. Optimized ANN architecture. The input parameters are also listed on the top.

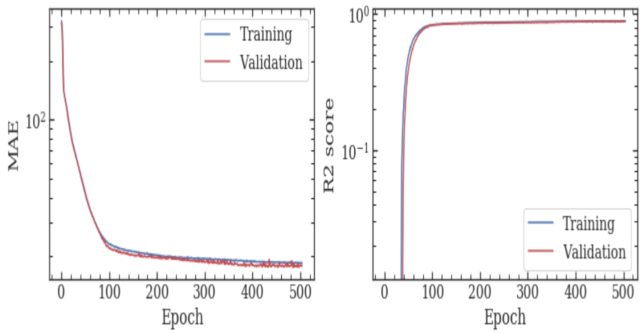

Figure 2. The learning curve for the ANN model for training (80%) and validation (20%) data samples as a function of epochs. Mean absolute error (MSE) and R^2 score are shown in the left and right panels, respectively.

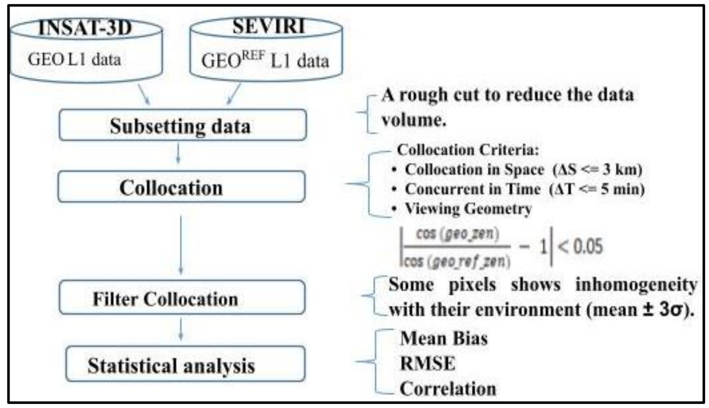

Figure 3. GEO - GEO GSICS calibration process used in the present analysis for ozone channel.

2.4. Inter-calibration of INSAT-3D ozone channel radiance with MSG-SEVIRI

Earth Observing (EO) satellites have been widely used for continuous monitoring of the atmosphere, ocean, and land areas in recent decades. The high quality of information from satellite observations are ensured by pre-flight and onboard radiance calibration of the respective sensors. In general, once the satellite is placed in orbit, its data quality degrades due to different sensing environments and degradation of the photosensitive elements of sensors. The degradation is estimated and corrected with a reference instrument installed on another satellite, with more accurate and stable radiometric characteristics defined by the Global Space-based Inter-Calibration System (GSICS). Mostly the GEO-LEO calibration is followed [11, 12], whereas, recently, the GEO-GEO calibration [13] is also utilized to minimize the radiance biases.

Additionally, corrections after the inter-calibration of different satellite instruments ensure consistent data among the diverse range of satellites, hence globally homogeneous retrieved products. In the radiance inter-calibration, first, a region is selected (the Indian region in the present case), and the collocated data is filtered based on the inhomogeneity of INSAT-3D pixels with their environments. The final information is then used to estimate the statistical analysis, as shown in Figure 3. A pixel is inhomogeneous with respect to its nearby environments (3 x 3 pixels) if it is not inside the mean ± 3σ of environments.

3. Results and Discussion

3.1 ozone channel radiance biases between INSAT-3D and MSG-SEVIRI

Generally, the radiance inter-calibration between two satellite instruments is performed when both make identical measurements. Additionally, they must cover the same target area simultaneously, with nearly the same spatial and spectral responses, under the same viewing geometry. Since these idealized conditions never occur in reality, a series of thresholds are applied for spatial, temporal, and viewing collocation (Figure 3).

Figure 4 shows the correlation of simulated ozone radiance between INSAT-3D and SEVIRI. In a simulated identical condition, the two sensor shows one to one performance with a coefficient of determination of more than 0.99 and negligible biases. It shows that these two instruments are designed to work identically for similar atmospheric conditions. However, if we see the actual ozone radiance observation (Figure 5) from these sensors, more-or-less similar atmospheric features are observed, with certain positive biases in the INSAT-3D measurements.

Figure 6 shows the mean biases, RMSE, and R^2 score of ozone channel radiance for 6 GMT observations in Jan 2020. A persistent radiance bias of more than 5 K with a higher correlation is observed in INSAT-3D with respect to SEVIRI. We have incorporated such radiance bias information into the new retrieval algorithms.

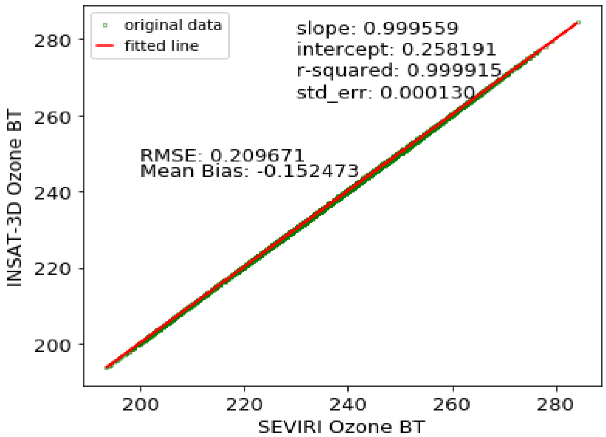

Figure 4. Correlation between INSAT-3D and SEVIRI simulated (RTTOV) ozone channel brightness temperature (BT), a measure of radiance in kelvins (K).

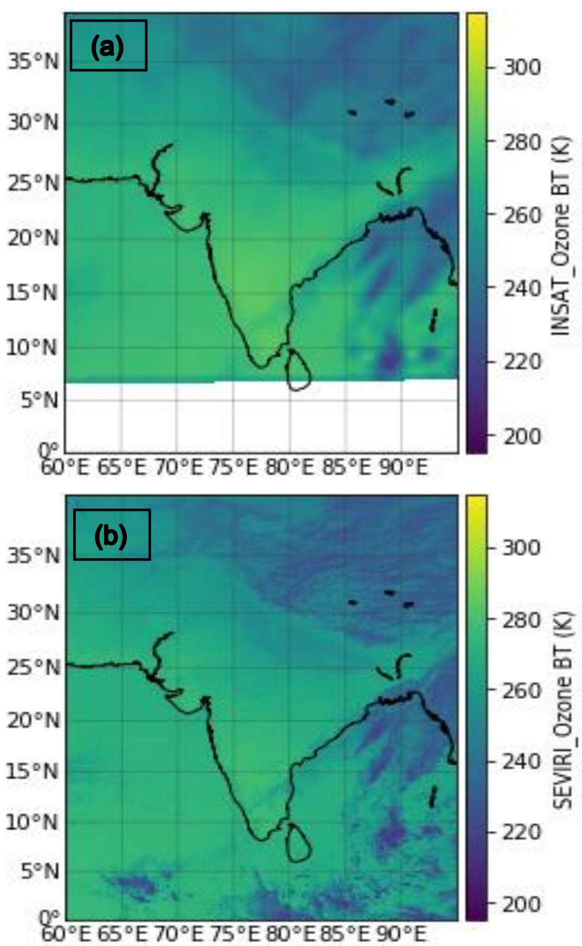

Figure 5. Observation of INSAT-3D (a) and SEVIRI (b) ozone channel brightness temperature (measure of radiance) on 01 January 2020. The lower ozone BT corresponds to the cloudy regions, which is captured well by both the sensors.

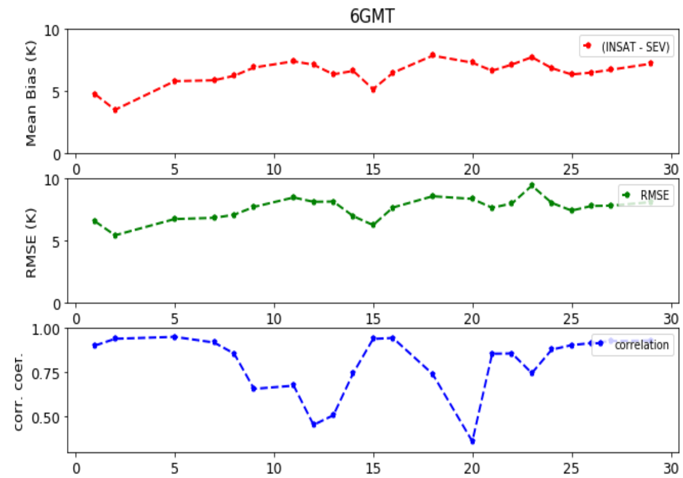

Figure 6. Time series of statistical analysis (Mean bias, RMSE, R^2) of ozone channel radiance between INSAT-3D and SEVIRI for 6 GMT observations in January 2020. The correlation is lower when there are frequent cloudy condition.

3.2 Total ozone column from INSAT-3D and its comparisons

Figure 7 shows the bias-corrected total ozone column retrieval from INSAT-3D (Old, OLS, and ANN) and SEVIRI observation. The SEVIRI is able to produce higher ozone over the higher latitude bands, which seem to be missing in the INSAT-3D old retrieval (Figure 7 top right) with a mostly constant around 270 DU. Previously TOC from INSAT-3D old retrieval is also compared with OMI and ozonesonde observation and also shows underestimation up to 22 DU [14].

In contrast, the new retrieval algorithm, i.e., OLS (Figure 7 button left) and ANN, effectively captures the latitudinal variation of TOC as observed by SEVIRI. Further, the OLS retrieval is underestimating the TOC over the Western Ghats, whose possible reason could be frequent cloudy conditions and complex terrain over the region. At the same time, ANN is free of such artifacts and a better match with SEVIRI. Over the Himalayan and Tibetan plateau, SEVIRI successfully retrieved the TOC; however, in the case of INSAT-3D, only the cloud-free pixels are used. We have also studied the TOC retrieval without applying the radiance biases in the INSAT-3D ozone channel; the retrieved TOC largely underestimated TOC and poorly replicated the latitudinal variation.

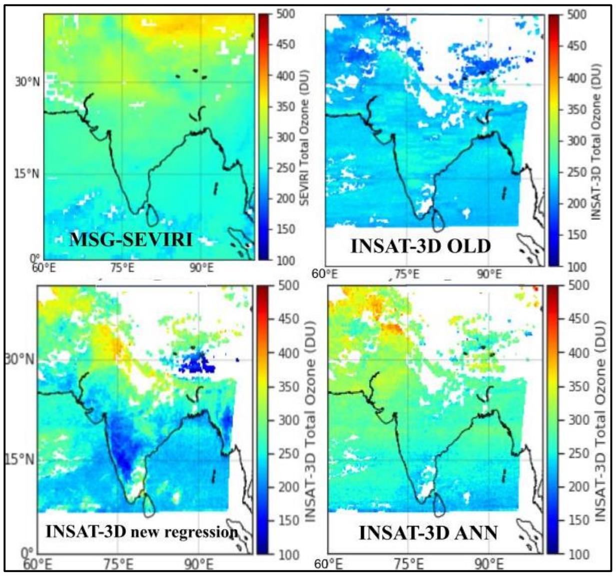

Figure 7. TOC retrieval from the INSAT-3D and SEVIRI on 18 Jan 2020. The TOC from INSAT-3D using different retrieval are shown.

5. Summary and Conclusions

In the present study, a method of inter-calibration for INSAT-3D sounder ozone channel in Geostationary Earth Orbit (GEO) is performed with MSG-SEVIRI, a European GEO satellite. A GSICS-based algorithm is developed for radiance inter-calibration of the ozone IR channel. In this GEO-GEO inter-calibration method, the calibration of INSAT-3D is performed using the SEVIRI imager onboard Meteosat-8. MSG-SEVIRI is chosen as a reference instrument due to its similar spectral channels and viewing targets. The statistical metric of mean bias, RMSE, and R^2 are used to evaluate the INSAT-3D radiances. Noticeable biases in INSAT-3D ozone channel radiance are observed, which remains persistent, about more than 5K. However, the concurrence is in reasonable agreement. The retrieved TOC product is found to be very sensitive to bias corrections. The radiance biases corrected INSAT-3D TOC retrieval using the ANN algorithm is in better agreement with SEVIRI TOC. The present study is the first attempt to study the radiance biases of Indian satellite INSAT-3D using GEO-GEO calibration and the possible utilization of ML techniques to retrieve total ozone.

6. Acknowledgements

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7. References

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