NATIONAL REPORT : INDIA

1. OBSERVATIONAL ACTIVITIES

India Meteorological Department (IMD) developed a total column ozone monitoring network at five stations in India namely New Delhi, Kodaikanal, Pune, Srinagar and Varanasi using Dobson spectrophotometers for the last many years. At present, two IMD Stations, i.e., New Delhi and Varanasi have functional Dobson Spectrophotometers. In India, Ozone and UV-related monitoring and research is undertaken by IMD alongwith Indian Institute of Tropical Meteorology (IITM), National Atmospheric Research Laboratory (NARL), National Physical Laboratory (NPL) and Indian Space Research Organisation (ISRO) etc. For Total Column Ozone measurements, Dobson spectrophotometer, Brewer spectrophotometer, Ozone Sunphotometer and Satellites are used in India while electrochemical ozonesondes are used for vertical profile of Ozone in the atmosphere. Ozone measurement activities are also there at two Indian stations in Antarctica. Solar UV radiation is measured at a number of sites across India.

1.1 Column measurements of ozone and other gases/variables relevant to ozone loss

The first Columnar Ozone Observations in India were made in 1928-29 at Kodaikanal as part of Dobson's worldwide Total Ozone Measurements. IMD acquired first Dobson Spectrophotometer in 1940. Regular measurements of total columnar ozone were started by IMD from 1957 onwards. Dobson Spectrophotometer No. D112, maintained by IMD, is designated as National Standard Instrument. IMD also has five Brewer Spectrophotometers at different locations for varying periods of time. A inspection of these instruments had been done by Dr. Alberto Redonas Merreo, Head, Ozone & UV Division, AEMET, Spain in the year 2019 and his efforts made four (04) Brewer Spectrophotometers operational. NARL, Gadanki (13.48ºN, 79.18ºE) is operating a Brewer MKIII spectrophotometer (#221) since September 2014. Details of the Total Columnar Ozone Measurement network in IMD are given in Table 1.

Table-1: Details of Dobson and Brewer Spectrophotometers in India

S. No.	Name of Station	Lat.	Long.	since when	Status
1	New Delhi (Dobson 36)	28°35'N	77°12'E	Jan. 1955 – till date	Working, calibrated in the year 2020
2	New Delhi (Dobson 112) National Standard	28°35'N	77°12'E	Apr, 1969 – till date	Working, calibrated in the year 2019
3	Varanasi (Dobson 55)	25°18'N	83°01'E	Dec, 1963 – May, 2019	Working, need calibration and maintenance
4	Pune (Dobson 39)	18°32'N	73°51'E	Mar, 1973 – May 2003	Not Working, Repairable
5	Kodaikanal (Dobson 45)	10°14'N	77°28'E	Jul, 1957 – Apr, 1998	Not Working, Repairable
6	Srinagar (Dobson 10)	34°05'N	74°50'E	Nov, 1955 – Aug, 1989	Not Working.
7	New Delhi (Brewer#89)	28°35'N	77°12'E	Aug, 1994 - Oct, 2002	Working, Calibrated in the year 2022
8	New Delhi (Brewer #164)	28°35'N	77°12'E	Jan, 2006 - Feb, 2011	Working, need calibration
10	Pune (Brewer #170)	18°32'N	73°51'E	Oct, 2005-Jul, 2010	Working, need calibration
11	Kodaikanal (Brewer #94)	10°14'N	77°28'E	Mar, 1994 - Nov, 2005	Calibrated in the year 2022
12	Maitri, Antarctica (Brewer #153)	70°45′S	11°43′E	Jan, 1994 - Nov, 2011	Not Working.

1.1.1 Satellite measurements

Indian National Satellite System – 3D Repeat (INSAT-3DR), a meteorological satellite, was launched on September 08, 2016 into the geostationary orbit. INSAT-3DR sounder has 18 Infrared channels distributed over long wave and shortwave bands (3.8 – 15 μm) with a visible channel for providing improved cloud detection ability during daytime. The primary objective of the sounder is to provide the vertical profiles of temperature and humidity, along with total column ozone over the Indian subcontinent with hourly temporal resolution. INSAT-3DR takes ~55 min to scan the Indian landmass from the GEO orbit. The spatial resolution is 10x10 km; however, for retrieval of the sounder data, 5x5 pixels is used to reduce the noise and effect of fractional cloud contamination.

1.2 Profile measurements of Ozone and other gases/variables relevant to Ozone loss

Vertical profile of Ozone is monitored using Ozonesonde at New Delhi and Bharati. IMD started regular measurements of vertical distribution of ozone every fortnight from 1971 onwards at New Delhi, Pune, Thiruvanathapuram and Maitri (Antarctica). Apart from this, the NARL started regular Ozonesonde launches every fortnight from October 2011 onwards. The Ozonesonde observations continued at New Delhi with Graw, Germany make Ozonesonde system since 2015.

India established Meteorological Observatory at Indian Antarctic station 'Bharati (69°24.41'S, 76°11.72' E, WMO Index Number 89776)' in eastern Antarctica during 2015. Regular Ozonesonde and surface ozone measurement were started at the station from 2015.

1.3 UV measurements

IMD have established a network of 45 Solar radiation stations having UV-A and UV-B radiometers as shown in Figure-1. UV-A sensors had been installed during 2009 -2010 at all 45 Stations. UV-B sensors have been installed during 2012-2014 at all 45 Stations. UV-A and UV-B irradiance data is being measured at an interval of every 10 minutes and archived in National data center of IMD. The hourly, daily and monthly average UV Irradiance values are calculated from 10 minutes observed data.

Figure 1 : IMD's Radiation Network

1.4 Measurements of substances controlled under the Montreal Protocol

The Indian Institute of Tropical Meteorology (IITM), Pune, started greenhouse gas (GHG) measurements at Sinhagad, a semi-background hilly site, in 2009 which is located in Maharastra state of India. The GHG observation network encompasses three scientific data measurement labs in various parts of India i.e. 1. Sinhagad lab near Pune, 2. IITM Pune, and 3. 72-meter tower observatory at IITM ART Silkheda Bhopal in central India. All these labs provide high-frequency continuous observations of atmospheric CO_2, CH_4, CO, H_2O, CO_2, CH_4 isotopes 12C, 13C, 17O, 18O. Additionally, the Carbon flux observations network was initiated in 2016 at different ecosystems in India, Kaziranga National Park (KNP) ,Tezpur, Asam; Pichavaram, Tamil Nadu; Nanital etc., under the IITM MoES Metflux project.

1.5 Calibration activities

Indian Total Column Ozone monitoring instruments are calibrated against the World Standards at regular intervals. Dobson Spectrophotometer No. D112 is maintained by Ozone Unit, India Meteorological Department, New Delhi is designated as National Standard Instrument and it had participated in the many WMO organized international inter-comparison campaigns of Dobson Spectrophotometer e.g. Boulder (USA) in 1977, Melbourne (Australia) in 1984 and Tsukuba (Japan) in 1996 and Tsukuba (Japan) in 2006. Dobson Ozone Spectrophotometer No. D112 was last calibrated in October, 2019 during the Dobson inter-comparison campaign at Irene, South Africa with an average difference of -0.3% in total ozone for ADDSGQP observations in Mu (μ) range 1.15 to 3.2 between Dobson spectrophotometer nos. D112 and D064. Dobson Spectrophotometer No. D036 has been calibrated at the Meteorological Office, Hohenpeissenberg, Germany (MOHp) in July, 2020 and the difference values were found less than 0.01 after final inter-comaprison with the European Regional Standard Dobson Spectrophotometer No. D064. Recently, in the year 2022, two Brewer Spectrophotometers (089 and 094) of India have been calibrated at International Ozone Services Inc. (IOS), Canada through the financial support from WMO. WMO's Julich Ozone Sonde Inter-comparison Experiment (JOSIE), 1996 showed that IMD's ozonesonde showed a precision of about ± (4 – 8 %) and an accuracy of ± (6 – 13) % in the lower stratosphere (GAW report No. 201, Oct, 2014). A comparison of the Indian Satellite INSAT-3DR monitored Total Column Ozone (TCO) physical product has been made with Dobson spectrophotometer's data along with data monitored by other satellites e.g. Ozone Monitoring Instrument onboard NASA's Aura satellite (OMI) and Infrared Atmospheric Sounding Interferometer (IASI), on board European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Metop-A and Metop-B. INSAT-3DR monitored TCO values are lower then TCO values, monitored by other satellites and ground-based instruments' data as shown in Figure 2. Regular calibrations of GHG instruments were performed using WMO-authorized calibration standards imported from NOAA Boulder, Colorado, USA.

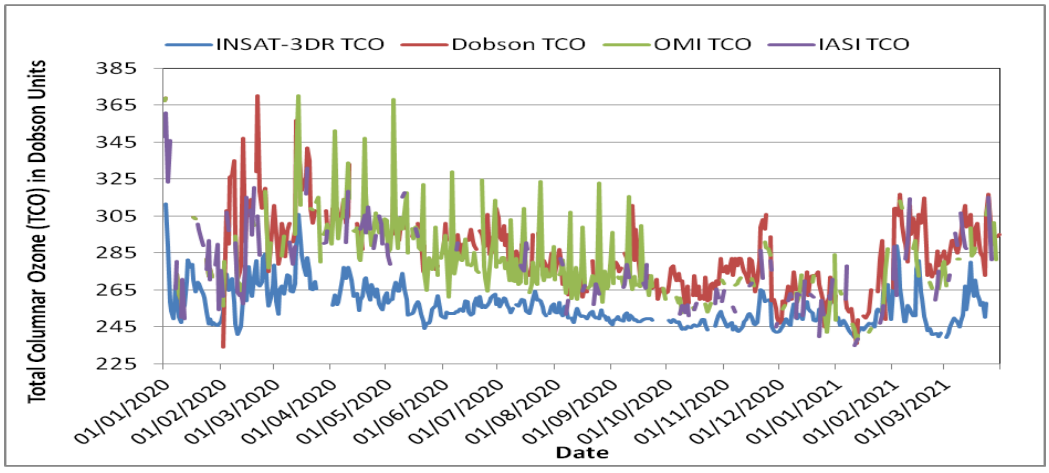

Figure 2 : Comparison of daily averaged Indian Satellite (INSAT-3DR) retrieved Total Column Ozone (TCO) data with ground-based Dobson spectrophotometer and other satellites'(OMI and IASI) data at New Delhi, India

2. RESULTS FROM OBSERVATIONS AND ANALYSIS

A positive Total columnar ozone (TCO) trend value of 0.34% and 0.41% per decade is seen in Delhi and Varanasi based on 2012 – 2023 data of Dobson spectrophotometer. Yearly averaged total ozone values over the Indian region are in the range of 240–300 DU (Dobson Unit). Yearly variations of Total Column Ozone Concentrations over two Indian stations i.e. New Delhi and Varanasi are shown in Figure 3.

MERRA-2 data shows that Total columnar Ozone concentration has been found to be increasing towards higher latitudes over India since 2005. The maximum TCO in India has been found over Leh during 2003 and the concentration has been observed as 340 DU. Leh is located at latitude 34.15 ^{0}N in Jammu & Kashmir state of India. The lowest TCO has been found 220 DU over Kanyakumari during the year 2013. Kanyakumari is located at latitude 8.08 ^{0}N in Tamilnadu province of southern India. Further, the highest ozone in a year is observed during April–June period and the lowest during winter. A significant increasing trend in tropospheric column ozone (TPO) over India has been observed for the period of 2005–2020 using satellite and ground-based data, with the highest trend in the peninsular region (0.295 ± 0.0617 DU/year) and the lowest in North West India (0.179 ± 0.048 DU/year) (Rathore et al., 2023). The climatological mean values of TCO at New Delhi, Varanasi, Pune and Kodaikanal are observed to be 276.0 ± 6.7 DU, 266.7 ± 8.0 DU, 260.8 ± 5.1 DU and 258.7 ± 6.4 DU respectively. The ozone hole phenomenon has also been observed over the Indian Antarctic station at Maitri and Bharati.

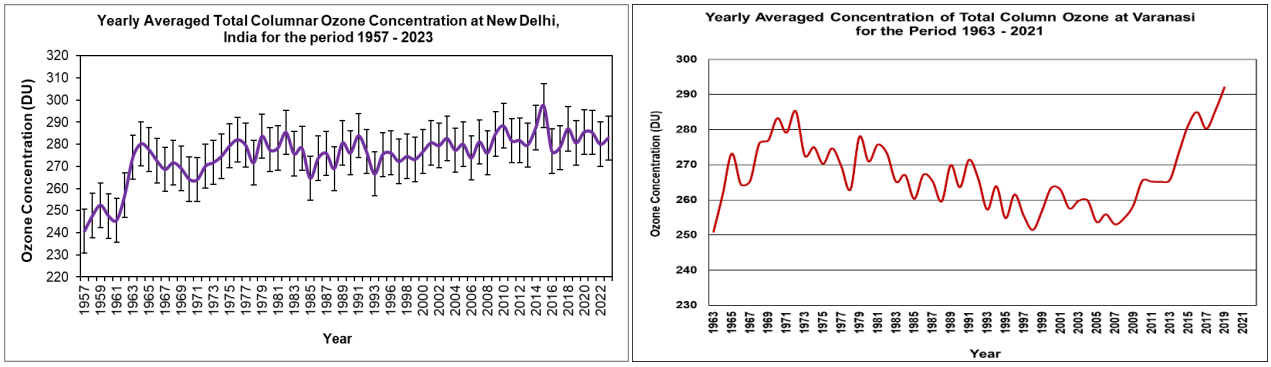

Figure 3 : Yearly Averaged total ozone concentrations, measured with the Dobson spectrophotometer, at two Indian Stations namely New Delhi and Varanasi

3. THEORY, MODELLING, AND OTHER RESEARCH

The latest version of Air Quality forecast model "System for Integrated modelling of Atmospheric composition (SILAM v5.8)" has been operationalized for Indian region. Hourly air quality forecast for 96 hours of all criteria pollutants (PM_{10}, $PM_{2.5}$, O_3, CO, NO_2, SO_2 and other species) is being generated for the domain 60-100^{o}E, 0-40^{o}N. The model is validated with air quality observations. A very high resolution city scale air quality model "ENvironmental information FUsion SERvice (ENFUSER)" has been also operationalized for Delhi. Hourly air quality forecast for 96 hours of all criteria pollutants (PM10, PM2.5, O3, CO, NO2, SO2) is generated for the domain (28.362 °N-28.86 °N, 76.901 °E-77.56 °E) at 30m spatial resolution by ENFUSER.

For GHG, the research studies are being conducted using observations in conjunction with model simulations. IITM recently studied the variability in the GHGs in connection with the changes in primary productivity in the changing climate with the help of FLUXCOM, CMIP6 GPP simulations. Multiple peer-reviewed articles have been published based on these outputs.

4. DISSEMINATION OF RESULTS

4.1 Data reporting

Total Columnar Ozone and related data are regularly submitted to the World Ozone and UV Data Centers at Toronto (WOUDC). The data are also archived at National Data Centre, India Meteorological Department, Pune. Quality checked and quality controlled GHG data is maintained at Atmospheric Research Data Centre server at IITM and shared as per required with the scientific community.

4.2 Information to the public

At present information are provided to public via several formats; e.g. website https://nwp.imd.gov.in/silam_imd.php and https://ews.tropmet.res.in/ , mobile App and Digital Display Boards. The Early Warning System for air quality provides the information on real time observations along with air quality forecasts for 46 cities. Press releases and dedicated warnings

are published by the appropriate agencies and institutes as per requirement. UV-A and UV-B radiation data from IMD network of 45 stations are also made available for study and research through the website of India Meteorological Department (www.imd.gov.in). Also, published studies on GHG are communicated in plain language to the news agencies for public awareness.

4.3 Relevant scientific papers published recently

- *Abirlal Metya, Amey Datye, Supriyo Chakraborty*, Yogesh K. Tiwari, Prabir K. Patra, Charuta Murkute, 2022, Methane sources from waste and natural gas sectors detected in Pune, India, by concentration and isotopic analysis, Science of the Total Environment, 842 (2022) 156721, 16 June 2022, http://dx.doi.org/10.1016/j.scitotenv.*2022.156721.
- *Anjumol Raju, S. Sijikumar*, Vinu Valsala, Yogesh K Tiwari, Santanu Halder, Girach I A, Chaithanya D Jain, M Venkat Ratnam, 2022, Regional estimation of methane emissions over the peninsular India using atmospheric inverse modelling, Environ Monit Assess (2022) 194:647, https://doi.org/10.1007/s10661-022-10323-1 .*
- *Das, S.S., Suneeth, K.V., Ratnam, M.V. et al., 2019, Upper tropospheric ozone transport from the sub-tropics to tropics over the Indian region during Asian summer monsoon. ClimDyn 52, 4567–4581.* https://doi.org/10.1007/s00382-018-4418-6.
- *Fadnavis S. et al., 2023, Comparison of ozonesonde measurements in the upper troposphere and lower Stratosphere in Northern India with reanalysis and chemistry-climate-model data, Scientific Reports volume 13, Article number: 7133 .*
- *Korhale Nikhil , Vrinda Anand, and Gufran Beig, 2021, Disparity in ozone trends under COVID-19 lockdown in a closely located coastal and hillocky metropolis of India, Air Qual Atmos Health. 2021; 14(4): 533–542.*
- *Pawar,V. S., Domkawale, M. A., Pawar, S. D., Salvekar, P. S., Pradeep Kumar, P., 2017, Inter annual variability of tropospheric NO2 and tropospheric ozone over Maharashtra (India): the role of lightning. Remote Sensing Letters, 8, 11, 1015-1024, DOI:* 10.1080/2150704X.2017.1346398.
- *Potdar SS. et. al., 2018, Statistical analysis of total column ozone during three recent solar cycles over India, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 181, Part A, December 2018, Pages 44-54.*
- *Rathore A., G.S. Gopikrishnan, J. Kuttippurath, 2023, Changes in tropospheric ozone over India: Variability, long-term trends and climate forcing, Atmospheric Environment, Volume 309, 15 September 2023, 119959.*
- *Rawat P. et al., 2020, Assessment of vertical ozone profiles from INSAT-3D sounder over the Central Himalaya , CURRENT SCIENCE, VOL. 119, NO. 7, 10 OCTOBER 2020 1113*
- *Santanu Halder, Yogesh K. Tiwari*, Vinu Valsala, M. G. Sreeush, S. Sijikumar, Rajesh Janardanan, Shamil Maksyutov, 2021, Quantification of Enhancement in atmospheric CO2 background due to Indian biospheric fluxes and fossil fuel emissions, JGR-Atmospheres, Vol.126, Issue 13, 16 July 2021 e2021JD034545. https://doi.org/10.1029/2021JD034545 .*
- *Smrati Gupta, Pramit Kumar Deb Burman, Yogesh K. Tiwari, Umesh Chandra Dumka, Nikul Kumari, Ankur Srivastava, Akhilesh S. Raghubanshi, 2023, Understanding carbon sequestration trends using model and satellite data under different ecosystems in India, Science of The Total Environment, Volume 897, 2023, Nov, 166381, ISSN 0048-9697,https://doi.org/10.1016/j.scitotenv.2023.166381.*
- *Siddhartha Singh et. al., 2023, Calibration of Indian Dobson Spectrophotometer Nos. D112 and D036 during WMO Dobson Intercomparison Campaigns, MAUSAM Vol. 74 No. 1.*
- *Tiwari,Y.K., Sreenivas,G., Datye, A., et al., 2022, Atmospheric CO2 and CH4 observation at an urban location in India: multi-instrument in-situ concentration and isotopes monitoring approach (Published in Poster presentation at WMO expert meeting at Geneva).*

5. PROJECTS, COLLABORATION, TWINNING AND CAPACITY BUILDING

IMD provides the hands-on training periodically to scientists / observersers on Dobson Spectrophotometer, Ozonesonde operations and data processing. Close cooperation is established with World Radiation Centre in order to assure high quality of the calibration of the

radiation instruments. Field observers from India Meteorological have been trained at WMO-GAWTEC; AEMET, Spain etc. The air quality modelling systems are developed under a collaborative project with Finnish Meteorological Institute. Further, to strengthen the forecasting services, the Air Quality Early Warning System (AQ-EWS) was developed under the aegis of Ministry of Earth Sciences, jointly collaboration of IITM, IMD and NCMRWF. For GHG concentrations, fluxes, and related modelling studies, there are several active research and data-sharing collaborations with various national and international agencies. Indian scientist has contributed to IPCC report on 2019 GHG guidelines and is a Steering Committee Member of WMO IG3IS. Regular course work classes of atmospheric chemistry and observation are also taken up for the research scholars of the institute and universities.

6. IMPLEMENTATION OF THE RECOMMENDATIONS OF THE 11th OZONE RESEARCH MANAGERS MEETING

- Two Indian Brewer Spectrophotometers (089 and 094) have been calibrated at International Ozone Services Inc. (IOS), Canada in the year 2022 through the financial support of WMO.
- IMD is submitting total column ozone data to WOUDC and maintaining existing observation capabilities for climate and ozone layer monitoring.
- Many papers have been published on Ozone, GHG and other related issues in peer reviewed journals.
- NIST Standard Reference Photometer (SRP) serial number 43 (SRP43), setup at CSIR National Physical Laboratory-India, is continue to act as the primary standard for all the national and international Ozone monitoring network for Quality assurance and apex level traceability in ground level Ozone measurements in the Country and South Asian Region.
- Indian Institute of Tropical Meteorology, Pune, India, has developed Earth System Model (IITM-ESMv2) by transforming a state-of-the-art seasonal prediction model Climate Forecast System (CFSv2) into a radiatively balanced climate modeling framework suitable for investigating long-term climate variability and change which has contributed to the CMIP6 for the IPCC-AR6.

7. FUTURE PLANS

a) India is now involved in METFLUX India project which has 3 running sites and is commencing 3 new sites in India for measurement of GHG fluxes in different ecosystems. Modeling efforts are underway to support carbon cycle research from surface to the upper atmosphere.
b) Participation in the international intercomparison campaigns of Brewer and Dobson Spectrophotometers in future is done with the support of WMO.
c) Ongoing monitoring of ozone, water vapor, UV radiation and other species will continue to improve our understanding of the chemistry–climate interactions.
d) IMD has two non-operational Dobson Spectrophotometers (D39 and D45) which will be put in operation after refurbishment and calibration with the technical support from WMO.
e) IMD is exploring possibilities for putting all the 03 old Brewer Spectrophotometers back into the operation.
f) IMD will expand UV monitoring at more stations in India.

8. NEEDS AND RECOMMENDATIONS

- To understand the methane and ozone co-variability, long-term ground observations is required. Ozone is also a sink for methane gas in the atmosphere. We lack the observational evidence to understand of its coherent variability. Therefore, it is highly recommended that the observational network be strengthened with dense and continuous observations in India.
- IMD acknowledges the support provided by WMO for calibration with repair of two Brewer Spectrophotometers (089 and 094). IMD requests further support from WMO for refurbishment and calibration of Dobson Spectrophotometer D39, D49 and D55. IMD has three Brewer Spectrophotometers which need calibration / repair and requests technical support for maintenance and calibration of these instruments.