

Reply of comments

We are thankful for the valuable suggestions /comments of the learned referee for the paper Review of Inter-comparison of retrievals of Integrated Precipitable Water Vapour (IPWV) made by INSAT-3DR satellite-borne Infrared Radiometer Sounding and CAMS reanalysis data with ground-based Indian GNSS data. Ramashray Yadav et al.

Point wise reply is given below:

General observations:

This paper entitled 'Inter-comparison of retrievals of Integrated Precipitable Water vapor (IPW) made by INSAT-3DR' satellite-borne Infrared Radiometer Sounding and CAMS reanalysis data with ground-based Indian GNSS data' deals with the validation of INSAT-3DR and CAMS water vapor products using as reference GPS retrievals in India. To date there plenty of papers dealing with the validation of satellite and global reanalysis models IPW. But this paper is of interest to scientific community because INSAT-3DR is a geostationary satellite that allows continuous monitoring of IPW in Indian sub-continent. Also, the results presented here serve to validate CAMS reanalysis model. Having both INSAT-3DR and CAMS high precision data is of great importance for numerical weather predictions (NWP). Thus, I consider that the study is of interest and publishable in Atmospheric Measurement Techniques. However, I consider that the manuscript needs to be further improved before its final publication.

MAJOR REVISIONS:

RC#1. The authors remark in the introduction (Lines 73-76) and in the results sections the importance of evaluating INSAT-3DR and CAMS over Oceans. Obviously, they do not have GPS measurements in remote oceanic regions. However, Maritime Aerosol Network offers a publicly free database of IPWV over oceans that are unique for the validations of satellites and global models IPVW products. Including such data in your validations will provide a unique value to the manuscript. See the references Smirnov et al., (2004, 2011) and Perez-Ramirez et al., (2019).

Response:1. We agree with the learned referee concern of Maritime Aerosol Network data. Recently we have modified our INSAT-3DR scan strategy over oceanic region and definitely we will incorporate this data in our future strategy with our New INSAT-3DR data sets. We have added the reference suitably in the manuscripts and definitely incorporate in future studies.

RC# 2. The database used for the validation is short. Why not using more years? Or why not using AERONET data? Another possibility is to estimate IPWV from ground-based temperature and relative humidity in remote areas (see Falaiye et al., 2018).

Response: We fully agree with the referee suggestion. The Indian GNSS network is recently established and that is why the validation time is short. But we will definitely incorporate other possibilities as suggested of IPWV estimate in our future studies. The study carried out by Falaiye et al., 2018 is very important for considering the conventional data from long term observing stations of Indian domain along with the available model to establish the similar empirical relationship of getting the Precipitable water vapour. This will also support to generate improved climatological mean especially over the remote regions.

RC#3. There is a systematic lack of appropriate references in all the text. Appropriate references are needed to fulfill quality standard in Atmospheric Measurement Techniques publication. Some of the most important are:

Response: We agree with the referee's suggestions and a brief discussion along with references regarding Satellite, Mosel and Ground based IPWV measurements have been added in the manuscript.

- a. **RC#** No discussion of other satellites that provide IPWV in the introduction (e.g. MODIS, SCIAMACHY, GOME-2, AIRS)

Response: In Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption Spectrometer for Atmospheric CHartography (SCIAMACHY), both used the principle of differential optical absorption spectroscopy in red spectral range of IPWV retrieval (Beirle et al, 2018). Atmospheric Infrared sounder is a hyper spectral instrument which collects radiances in 2378 IR channels with wavelength ranging from 3.7 to 15.4 μm . Cloud cleared radiances of AIRS were utilized in the retrieval of column integrated water vapour which is contributed by a number of channels having different sensitivity towards water vapour. (Aumann et al., 2003).

Moderate Resolution Imaging Spectroradiometer (MODIS) utilized infrared algorithm employs ratios of water vapor absorbing channels at 0.905, 0.936, and 0.940 μm with atmospheric window channels at 0.865 and 1.24 μm in estimated the precipitable water vapour (Kaufman and Gao, 1992).

The uncertainties in the retrieval of precipitable water vapor from satellites (like errors of calibration of channels, viewing geometry, radiative transfer in the forward models) are already addressed by previous studies (Ichoku et al., 2005 for MODIS. Noel et al., 2008 for GOME-2 and SCIAMACHY, Susskind et al., 2003, 2006 for AIRS). Wagner et al., 2006 studied GOME data for the period of 1996-2002 and reported

globally and yearly averaged $2.8 \pm 0.8\%$ increase of total column precipitable water (excluding the ENSO period).

b. **RC#** No discussion of other global reanalysis models (e.g. MERRA-2, CFSR)

Response: The retrievals from reanalysis data sets Modern-Era Retrospective analysis for Research and applications-2 (MERRA-2) Gelaro et al., 2017, Climate Forecast System Reanalysis (CFSR)(Saha et al., 2010) Data Archive at <https://rda.ucar.edu/pub/cfsr.html> utilized 3d-var data assimilation techniques and well captured the interannual variations of precipitable water vapour in the south of the Central Asia (Jiang et al., 2019). The study carried out by Berrisford et al., 2011, found ERA interim data set is superior in quality than ERA 40 during the period 1989-2008.

c. **RC#** No discussion of other ground-based techniques used for validation of IPWV (e.g. radiosondes, AERONET sun-photometry and microwave radiometry).

Response: Ramashray et al., 2020 carried out the validation of Indian GNSS IPWV with GPS Sonde data for the period of June 2017 to May 2018 over Indian region and found reasonably well in agreement with in situ observations. In situ Radiosonde observations generally suffer spatiotemporal inhomogeneity errors and differences in relative humidity measured by different sensors. In this study he brought out positive bias less than 4.0 mm for 7 stations, correlation coefficient greater than 0.85 and RMSE less than 5.0 mm for all 09 collocated GPS sonde stations. In this direction the work carried out by Turner et al., 2003, 5 % dry bias with Microwave Radiometer and Vaisala RS80-H will be very useful while dealing with such Radiosonde observations. Miloshevich et al 2009, found a similar limitation of Relative Humidity measurement with Vaisala RS92 Radio sonde and derived an empirical correction to remove the mean bias error, yielding bias uncertainty is independent of height.

The work done in the past by Smirnov et al., 2004, 2011, in retrieving the precipitable water vapour from aerosol network data especially for marine areas is very helpful to carry out further studies in future with INSAT-3DR satellite observations over oceanic areas.

Validation with other ground based techniques Referee decision is well taken and will be carried out in future with longer duration and more number of GNSS stations.

d. **RC#** No references to INSAT-3DR neither for instrument specifications nor for retrieval algorithm.

Are data publicly available?

Response (d): ATBD of INSAT reference is added.

e. **RC#** No references for GNSS network and/or data. Are data publicly available?

Response: Data supply Portal of INSAT as well as GNSS data is under final phase of its development and will be available for public soon. The data will be downloaded as per the data policy.

f. **RC#** No references for CAMS model. The link where data were obtained is necessary.

Response: CAMS model reference is added.

g. **RC#** No comparisons of the results with other obtained in previous studies.

Response: We respect the encouragement and suggestions made by the referee in exploring the scope of the study. The reference of comparison study of GNSS with Radiosone data has been added.

MINOR REVISIONS

RC# Introduction section needs to be further improved and appropriately referenced.

Response: Modified as per suggestions.

RC# Line 37: Currently, remote sensing instrument cost has been reduced. Please rearrange.

Response: modified as per suggestion.

RC# Line 38: Give an appropriate discussion of remote sensing techniques with appropriate references.

Response: modified as per suggestion.

RC# Line 43: IPWV was already defined.

Response: modified as per suggestion.

RC# Lines 43-44: What do you mean ‘surface radiation is completely absorbed by atmospheric water vapor in its way to the satellite’? Not all energy is absorbed. It depends on wavelength and water vapor content.

Response: Agreed with the referee suggestion and the same is modified in the manuscript

RC# Lines 50-52: What are the advantages/disadvantages of geo-stationary satellites versus polar orbiting satellites? You need to discuss previous achievements by polar orbiting satellites.

Response: Geo satellites have higher temporal resolution and continuous coverage and are important for monitoring the extreme weather events. Polar satellites have higher advantage higher spatial resolution and can operate both cloudy and non-cloudy conditions more effectively as compared to Geo satellites. Courcoux and Schroder et al., 2013, worked out the accuracies of Satellite Application Facility on Climate Monitoring (CMSAF) satellite Advanced Television and Infrared Observation Satellite Operational Vertical Sounder (ATOVS) precipitable water vapour of about 2-4 mm with respect to radiosonde and Atmospheric Infrared Sounder (AIRS) data both over land and ocean with resolution 0.5 x 0.5.

RC# Line 66: What do you mean ‘much improved biases’?

Response: Statement is corrected.

RC# Line 67: there is a typo in the references.

Response: Modified as suggested.

RC# Lines 73-76: Discussion about water vapor in oceanic areas need to be further improved. See Perez-Ramirez et al., (2019).

Response: The study Perez-Ramirez et al., (2019) clearly brought out the importance of Maritime Aerosol **RC#** Network (MAN) in retrieving the precipitable water vapour over remote oceanic areas. The reanalysis model estimates have very good agreement with MAN with mean differences of ~ 5 % and standard deviation of ~15 % under clear sky conditions.

Response: we agree with the referee suggestion and reference of the same is added suitably.

RC# Methodology section is not well structured:

- Start with instrument and models (GNSS network, INSAT-3DR and CAMS). IPWV mathematical definition (Line 143) must be in the first instrument you talk about (e.g. in the GNSS network description).
- later continue with the description of statistic parameters.
- Finish the section with the matchups.

Response: Modified as per suggestions.

RC# Lines 94-95: It is unnecessary the information about the software you used for statistics.

Response:Software information has been removed from the manuscript.

RC# Line 123: NWP acronym has not been defined.

Response:NWP acronym has been mentioned in text.

RC# Section 2.3 Scan strategy of INSAT-3DR sounder: There are no references, so it seems that is the first time that is presented. Is there any literature about that? If so the section is unnecessary, just provide appropriate references.

Response:Reference (ATBD of INSAT) is added in the text.

RC# Lines 176-177: I do not understand the limitation of 5°.

Response:If we reduce the cut off angle from 5° multipath effect will occur and introduce inaccuracy in the IPWV estimation. Higher cut off angle (> 5°) may introduce dry bias in the IPWV estimation and notable 0.8 mm error in IPWV (Emardson et al., 1998).

RC# Section 2.6: It is not clear how you do make the matchups between GNSS and CAMS. Also, in section 3.3 you perform an inter-comparison of CAMS with INSAT-3DR. How do you make these matchups?

Response:The CAMS reanalysis IPWV retrievals are interpolated to different geographical locations of 19 GNSS observations. We use nearest neighbor interpolation techniques to interpolate CAMS reanalysis

with GNSS data. In this method we evaluate each station to determine the number of neighboring grid cells in $0.75^\circ \times 0.75^\circ$ box that surround the GNSS station and contain at least one valid CAMS reanalysis data. INSAT-3DR Data set has horizontal resolution at $30 \times 30\text{km}$ (3×3 pixels) for each cloud free pixel. Collocation match up has been created at $0.75^\circ \times 0.75^\circ$ (about 80 km) spatial resolution for comparison and performance of INSAT-3DR data with CAMS reanalysis data using bilinear interpolation technique.

RC# Table 1: There is typo in the units of central wavelengths.

Response: The units of central wavelengths added in the text (μm).

RC# Table 5 and Table 6. Please add to the legends that they are statistical analyses of the intercomparisons.

Response: Table 5 and Table 6 legends added that they are statistical analyses of the intercomparisons

RC# Figure 4: Which data are you using in the Figure?

Response: INSAT-3DR and GNSS IPWV data are using in Figure 4.

RC# Lines 278-283: I do not understand the paragraphs. To me there is nothing related with the intercomparisons of IPWV?

Response: Paragraph has been removed from the manuscript.

RC# Lines 289-292: To me the influence of GPS error in the differences between GPS and satellites is negligible. Please quantify the error and improve the discussion. Differences in IPWV must associated with the differences in the sampling area and with limitations in satellite retrievals.

Response: Yes, we also agree with this point and similar findings was observed in the study of Puviarasan et al., 2020. But actual quantification of such type of errors we have not done, especially when the convective development is on other side of line of sight.

RC# Lines 293-296: Could satellite data be cloud-affected data?

Response: Satellite estimates are in cloud free regions.

RC# Lines 297-300: There is a miss of any proposal to improve data retrieval or data quality.

Response: The data quality of INSAT-3DR IPWV may be improved due to proper bias correction coefficient applied before physical retrievals of IPWV during clear sky pixels.

RC# Lines 348-351: Give references.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray,

C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet [https://doi.org/10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6).

Response:

RC# Lines 352-356: Give references

Response: Same as above.

RC# Section 3.3 Inter-comparison of CAMS reanalysis and INSAT-3DR IPWV: I suggest a plot with the differences to quickly visualize the inter-comparison.

Response: Plot of Seasonal bias (figure 7) may kindly be seen.

RC# Lines 389-391: Paragraph need to rearrange, I could not catch the main message

Response: The differences in the magnitude and sign of CC of INSAT-3DR with respect to CAMS reanalysis IPWV due to lack of assimilation of quality controlled data over Indian domain. This may be due to limitations of the design of the instrument /sensor on board on INSAT-3DR or retrieval algorithm of IPWV. Therefore, it will affect the overall collocations in matchup data sets.

RC# There are lacks of discussions of Figure 7 and Figure 8 in the text.

Response: We agree with the comments.

Seasonal Analysis: During winter season, positive biases ranges (0.0 to 5.0 mm) observed between CAMS reanalysis and INSAT-3DR IPWV which are indicating overestimation of CAMS IPWV over land and oceanic region except east and west coast of India including Arabian Sea (12° N to 28° N), some pockets of South East Bay of Bengal (BOB) and Himalayan region ranges (-2.5 mm to -5.0 mm) which indicates underestimation of CAMS IPWV respectively (Figure 7).

During pre-monsoon season, positive biases ranges (0.0 to 10.0 mm) observed between CAMS reanalysis and INSAT-3DR IPWV which indicates overestimation of CAMS IPWV over land and oceanic region except some parts of North West of Arabian Sea and Himalayan region ranges (-0.0 mm to -3.0 mm) which indicates underestimation of CAMS IPWV respectively (Figure 7).

During monsoon season, positive biases ranges (2.5 to 10.0 mm) observed between CAMS reanalysis and INSAT-3DR IPWV which indicates overestimation of CAMS IPWV over land and oceanic region except Himalayan region ranges (-2.5 mm to -5.0 mm) which indicates underestimation of CAMS IPWV respectively (Figure 7).

During post monsoon season, positive biases ranges (0.0 to 6.0 mm) observed between CAMS reanalysis and INSAT-3DR IPWV which indicates overestimation of CAMS IPWV over land and oceanic region

except Arabian Sea (19° N to 29° N) and Himalayan region ranges (-2.5 mm to -6.0 mm) which indicates underestimation of CAMS IPWV respectively (Figure 7).

The IPWV retrieved from CAMS reanalysis overestimated with respect to INSAT-3DR IPWV over land and oceanic region for all the seasons except Himalayan region and some parts of Arabian Sea and BoB. This occurred because the infrared and microwave radiometer observations of land and oceans had been assimilated into the model, which has the higher systematic humidity when it was compared with Radiosonde data (Andersson et al., 2007). Underestimation of CAMS IPWV compared with INSAT-3DR over Himalayan region may be due to presence of rugged terrain/orographic features in the retrieval of IPWV.

RMSE values during winter season ranges (7.5 mm to 13.0 mm) over land region (20° N to 35° N) and the entire Arabian Sea. Above 35° N latitude including Himalayan region, RMSE values are less than 7.5 mm. RMSE values ranges (13 mm to 20 mm) observed over the Southern peninsula of India and BoB region respectively (Figure 8).

RMSE values during pre-monsoon season ranges (2.5 mm to 13.0 mm) over land region (18° N to 40° N), Arabian Sea and Himalayan region observed. RMSE values ranges (13 mm to 20 mm) are over the Southern peninsula of India, Indo Gangetic Plains (IGP) and BoB region respectively (Figure 8).

RMSE values during monsoon season ranges (14. mm to 20.0 mm) over land region (20° N to 35° N) including North West of Arabian Sea and North East of BoB. Above 35° N latitude, South West & South East of Arabian Sea including South East of BoB and Himalayan region RMSE values are less than 8.0 mm respectively (Figure 8).

RMSE values during post-monsoon season less than 7.5 mm observed over land region including both Arabian Sea as well as BoB region except Indo Gangetic Plains (IGP) and north East of BoB ranges (13 mm to 17 mm) respectively (Figure 8).

RC# Section 3.4 need to be further improved, particularly about oceanic areas. Also, Figure 9 shows seasonal analyses not annual mean values.

Response: Over the oceanic region, seasonal mean IPWV of INSAT-3DR and CAMS ranges from 25-40 mm (with standard deviation 6-15 mm) and 20-45 mm (SD 6-16 mm) and less than 25 mm with SD of less than 6 mm for both INSAT-3DR and CAMS IPWV over land region during winter season respectively (Figure 10).

Over the oceanic region, seasonal mean IPWV of INSAT-3DR and CAMS ranges from 30-45 mm (with standard deviation 7-12 mm) and 35-55 mm (SD 10-16 mm). Over land region, seasonal mean IPWV of INSAT-3DR and CAMS data ranges from 15-38 mm with SD of 2-10 and 20-40 mm with SD of 5-12mm during pre-monsoon season respectively (Figure 10).

Seasonal mean IPWV of INSAT-3DR ranges from 30 mm to more than 60 mm with SD of 2-14 mm and from 50 mm to more than 60 mm with SD of 4-16 mm of CAMS IPWV observed for both land and oceans region during monsoon season respectively (Figure 10).

Over the oceanic region, seasonal mean IPWV of INSAT-3DR and CAMS ranges from 35-55 mm (with standard deviation 6-10 mm) and 38-55 mm (SD 6-14 mm) and over land region mean IPWV of INSAT-3DR and CAMS data ranges from 15-35 mm with SD of 5-12 and 20-40 mm with SD of 10-16 mm during post-monsoon season respectively (Figure 10).

RC# Conclusion section must be improved. Point number four is not demonstrated from the analyses and discussions in the manuscript. Point number five need to be revised because it cannot be understood.

Response: Point number four has been removed and Point number five has been modified in the manuscript.

RC# Finally, I recommend that a native English speaker revise the manuscript.

Response: Manuscript has been revised as per suggestion by referee.

We once again thank the reviewer for his/her constructive comments/suggestions which made us to improve the manuscript content significantly.