MAUSAM, **75**, 4 (October 2024), 1085-1094

MAUSAM

DOI : https://doi.org/10.54302/mausam.v75i4.6163
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551.509.32:551.515.4(540)

Inter-comparison of GNSS- IPWV with ERA-5 IPWV and monitoring of convective events over the Indian region

C. S. Tomar, Rajiv Bhatla*, Nand Lal Singh**, V. K. Soni and R. K. Giri

India Meteorological Department, Lodi Road, New Delhi – 110 003, India

**Department of Geophysics, Banaras Hindu University, Varanasi – 221 005, India*

***Department of Chemistry, Banaras Hindu University, Varanasi – 221 005,*

(*Received 3 February 2023, Accepted 31 March 2023*)

e mail :cstomar2002@gmail.com

सार – यह अध्ययन (*i*) यूरोपियन सेंटर फॉर मीडियम रेंज वेदर फोरकास्ट (ERA-5) के 5वीं पीढ़ी के वैश्विक जलवायु पुनर्विश्लेषण डेटा के साथ ग्राउंड बेस्ड ग्लोबल नेविगेशन सैटेलाइट सिस्टम (GNSS) व्युत्पन्न इंटीग्रेटेड प्रीसिपिटेबल वाटर वेपर (IPWV) का एक अंतर-तुलनात्मक अध्ययन (*ii*) GNSS डेटा के IPWV थ्रेशहोल्ड (*iii*) IPWV विश्लेषण के केस स्टडीज से संबंधित है।

यह पाया गया है कि दोनों डेटासेट (GNSS और ERA-5) दृढ़ता से सहसंबंधित हैं और सहसंबंध गुणांक 0.97 और 0.99 के बीच है। IPWV (MTI) की मासिक थ्रेसहोल्ड भारतीय GNSS स्टेशन से 2017-2020 के डेटा सेट के साथ तैयार की गई है, जिसमें निरंतर डेटा है और जनता को जारी किए जाने वाले दिन-प्रतिदिन के पूर्वानुमान में संवहन के निर्माण/क्षय की संभावना जानने के लिए मूल्यवर्धन के रूप में बहुत उपयोगी इनपुट पाया गया है। केस स्टडीज से पता चलता है कि GNSS स्टेशन के आसपास संवहनीय घटना होने से 3 से 4 घंटे पहले IPWV में वृद्धि हुई है और इसे तात्कालिक पूर्वानुमान के लिए बहुत उपयोगी पाया गया है।

इसलिए, IPWV (मॉडल और GNSS आधारित) का उपयोग संवहनीय गतिविधि और इसके पूर्वानुमान के बारे में बेहतर समझ के लिए उपयोगी पाया गया है। अन्य विश्लेषण उत्पादों (मॉडल, सतह, ऊपरी हवा, उपग्रह या रेडार आदि) के साथ यह पूरक जानकारी पूर्वानुमानकर्ताओं, निर्णय निर्माताओं और समाज के अंतिम उपयोगकर्ताओं को उचित निर्णय लेने में आगे सहायता कर सकती है।

ABSTRACT. The present study deals with (*i*) An Inter-comparison study of ground based Global Navigation Satellite System (GNSS) derived Integrated Precipitable Water Vapour (IPWV) with 5th generation global climate reanalysis data of European Centre for Medium Range Weather Forecast (ERA-5) (*ii*) IPWV thresholds of GNSS data (*iii*) case studies of IPWV analysis.

It is found that both the datasets (GNSS and ERA-5) are strongly correlated & the correlation coefficient ranging between 0.97 and 0.99. Monthly Thresholds of IPWV (MTI) are generated with 2017-2020 data sets from Indian GNSS station having continuous data and found very useful input as value addition to know the possibility of building up /decaying of convection in day to day daily forecast issued to the public. Case studies shows an increase of IPWV, 3 to 4 hour prior to the occurrence of convective event around the GNSS station and found very useful for nowcasting.

Therefore, utilization of IPWV (model as wells GNSS based) have found useful for better understanding about the convective activity and its forecasting. This supplement information along with other analysis products (model, surface, upper air, satellite or radar *etc.*) can support further in appropriate decision making to the forecasters, decision makers and the end users of the society.

Key words– GNSS, IPWV, ERA-5 and Convection.

1. Introduction

India Meteorological department (IMD) is the nodal Government Agency and has mandate to provide current and forecast meteorological information for optimum operation of weather-sensitive activities like agriculture, irrigation, shipping, aviation, *etc*. To generate meaningful forecast data is integrated by many conventional (in-situ and remote sensing) and advanced observations.

The water vapour concentration in the atmosphere varied both space and time and inhomogeneous in nature. These variations are different throughout the year in each season and play an important role especially in tropical region. Integrated water vapour in the atmosphere traditionally measured by radiosonde and microwave radiometer but it is expensive as well as have low spatiotemporal resolution. In the same time the accuracy of the radiosonde-derived Integrated Precipitable Water Vapour (IPWV) is lower at high altitudes and major disadvantage of using radiosondes for trend estimation is the systematic errors caused by either calibration uncertainties or sensor changes. This limits its application in the field of climate research, Ross and Elliot (1996), Wang and Zhang (2005). The continuous observation of IPWV along with pressure, temperature and humidity data is a useful tool for nowcasting, monsoon studies, thunderstorms observation, dust storms and climate research. India Meteorological Department (IMD) is the nodal agency to issue the almost all type (nowcast, short range, extended range and seasonal forecast) of forecast throughout the year. To meet this requirement, the Department is constantly implementing and upgrading the observational technology and inducting new technology to the maximum possible extent as and when required. IMD augmented a network of 25 ground based GNSS (Global Navigational Satellite system) receivers collocated with Vaisala Meteorological sensor for continuous monitoring of troposphere IPWV (Fig. 4). World Meteorological Organization (WMO) has identified the atmospheric water vapour as 44th Essential Climate Variable (ECV) and an integral part of Global Climate Observing System (GCOS). GNSS derived IPWV initially proposed by Bevis *et al*., 1992 is very useful in monitoring the convective weather events especially extreme or heavy rainfall events which have great impacts on all aspects of living and property. In the past, several studies (Puviarasan *et al.*, 2014, Jade *et al.*, 2005, Barindelli *et al.*, 2018, Misra, 2019, Vaquero-Martínez *et al.*, 2020, Cao *et al.*, 2016) have been done to analyze the potential of GNSS-derived IPWV in the improvement of forecasting of weather events. Huang *et al.* (2021, 2022) studied the GNSS data over and spatial variability over Tibetan plateau and found that the performance of ERA5 data sets is better than MEERA 2.

Inter-comparison of GNSS- IPWV with INSAT-3D IPWV data for the period of June 2017 to May 2018 over the Indian region found the Root Mean Square Error (RMSE) at different stations ranged from 5.41 to 7.14 mm. The bias between GNSS and INSAT-3D sounder values of PWV was less than 1 mm except for New Delhi (1.92 mm) and Jalpaiguri (2.14 mm), Yadav *et al.*, 2020. In the recent past, validation of GNSS estimated IPWV with in situ GPS Sonde data for the period of June 2017 to May 2018 over the Indian region has been carried out for establishing the errors and biases of GNSS IPWV estimates for 9 stations (4 inland and 5 coastal) having continuous observations. The study found reasonably good agreement with a positive bias with radiosonde data of less than 4.0 mm for, a correlation coefficient greater than 0.85 and RMSE less than 5.0 mm for all 09 GPS sonde stations (Yadav *et al*., 2020). The subsequent sections of the present works include data and methodology followed by results and discussions and concluding remarks.

2. Data and methodology

Authors have utilized the ground based GNSS, IPWV data of high temporal sampling (10 minute) data of Indian GNSS network is processed at satellite division of India Meteorological Department, Lodi Road, New Delhi. The data is processed daily by using the Trimble TPP software. Monthly data sets have been generated to calculate the IPWV threshold of each month from 2017 - 2019 IPWV data for 7 GNSS stations to examine the rainfall occurrences. Tome series of three years of GNSS data is prepared to generate the diurnal variation of IPWV.

An elevation angle of greater than 10º is set for all stations to avoid the satellite geometry change and multipath effects. This is an optimum setting as a higher cut off angle (> 10°) may introduce dry bias in the PWV estimation and notable 0.8 mm error in IPWV (Emardson *et al*., 1998). Fifth generation of global climate reanalysis data published by the European Centre for Medium-Range Weather Forecasts (ERA-5) was also utilized or inter-comparison of ground based GNSS data of the year 2017 to 2019 using nearest neighbour techniques.

Global Positioning System (GPS) is also known as Global Navigation Satellite System (GNSS) and now widely used to estimate the integrated precipitable water vapur (IPWV) by using ground-based receivers by using tropospheric induced delay measurements. The magnitude of this delay is related to the integral of the refractivity index of the air as a function of temperature, pressure and water vapour on the optical path followed by the GPS signal. The GPS or GNSS signal get delayed from both dry gases and water vapour (wet part) present in the atmosphere. The dry component is easily modelled with the help of station level pressure, temperature supplied through the met sensor attached with the GNSS station but wet components varies more both spatially and temporally and very difficult to modelled. The delay caused from ionosphere is removed by using the dual frequency receivers by subtracting the contribution of both frequencies and rest part is treated as electrically neutral and non-dispersive to the frequencies used in GNSS measurements. Therefore, the dry and wet component of troposphere together if measured in zenith direction known as are zenith tropospheric delay (ZTD). The Zenith Hydrostatic Delay (ZHD) is also known as dry delay estimated by a model based on accurate pressure measurements at the GNSS station (Bussinger *et al.*, 1996).

$ZTD = ZHD + ZWD$; where,

$ZHD = 0.002277Ps/(1 - 0.0026cos2\phi - 0.00000028Hs)$

In which Ps is the surface pressure, Hs is the receiver height and   is the latitude of the receiver.

$IPWV = C*ZWD$

$C = 10^6 / \rho_w R_v (_3T_m + K_2 - Mw/MdK_1)$ [M. Bevis, 1994)

where ρ_w stands for the density of liquid water, Rv for the specific gas constant of water vapour, Tm is the weighted mean temperature of the troposphere. Mw and Md are the molar masses of water vapour and dry air respectively. The constants, K_1, K_2 and K_3 are the constants for refractivity (Bevis, 1994).

The contributions from slant directions can also be mapped in the Zenith direction by using the mapping functions define by Niell (1996).

$$\Delta L = m_h(\theta)\Delta L_h^Z + m_w(\theta)\Delta L_w^z$$

where, θ is the elevation angle seen from the ground antenna to the satellite.

The water-vapour weighted mean temperature of the atmosphere is defined and approximated as (Wang *et al.*, 2005)

$$Tm \equiv \frac{\int \frac{Pv}{T} dz}{\int \frac{Pv}{T^2} dz}$$

Or

Tm = 55.8 + 0.77TS

Here, T_s is the surface temperature at the location of the receiver and is given in Kelvin. It varies place to place and time.

Sen Jaiswal and Lakshmi, 2022 estimated GNSS IPWV at few locations of India using Indian Regional Navigation Satellite System (IRNSS) data. They suggested that total solar irradiance (TSI) in spite of surface temperature (ST), surface pressure (SP), relative humidity (RH) in the estimation of IPWV. The results obtained by this alternative approach was in good agreement with radiosonde data.

3. Results and discussions

IPWV is one of the apparent weather response indicators at various locations of the Indian GNSS networks. Traditional water vapor detection technologies by satellite, radar, microwave radiometer and solar photometer have low spatial and temporal resolutions, and uneven accuracy. In the same time traditional data have limited spatial sampling and calibration issues with changing instruments and methods. Therefore, an attempt of Inter-comparison of GNSS- IPWV with ERA-5 IPWV has been made by the authors over Indian domain.

3.1. *Inter-comparison of GNSS- IPWV with ERA-5 IPWV*

Atmospheric reanalysis has been widely used as the data source of IPWV retrieval for the last several decades as these provide benefits of regional coverage, consistent spatial and temporal resolution and the availability of many other related meteorological variables. Compared to the ground-based point data, the reanalysis data, which are gridded data over an area have been widely used in IPWV research (Ssenyunzi, 2020; Kumar *et al.*, 2013). Various studies have shown that GNSS derived remote-sensed data and the fifth generation of global climate reanalysis data published by the European Centre for Medium-Range Weather Forecasts (ERA-5) can give sufficient variation characteristics of IPWV, temperature and specific humidity (Isioye *et al.*, 2017; Jiang *et al.*, 2019; Zhang *et al.*, 2019) The ERA5 (Hersbach *et al.*, 2020) has assimilated more satellite and in-situ datasets compared to its predecessor ERA-Interim. It also has more advanced data assimilation and modeling systems to estimate IPWV. The Radiosonde observations provides a long record of observations, but long-term radiosonde humidity measurements are very sensitive to changes in instrumentation and measuring practices (McCarthy *et al.*, 2009, Dai *et al.*, 2002). As a result, assessments of the reanalysis water vapor products are essential for the accurate understanding and interpretations of weather and climate processes over Indian region. A reliable

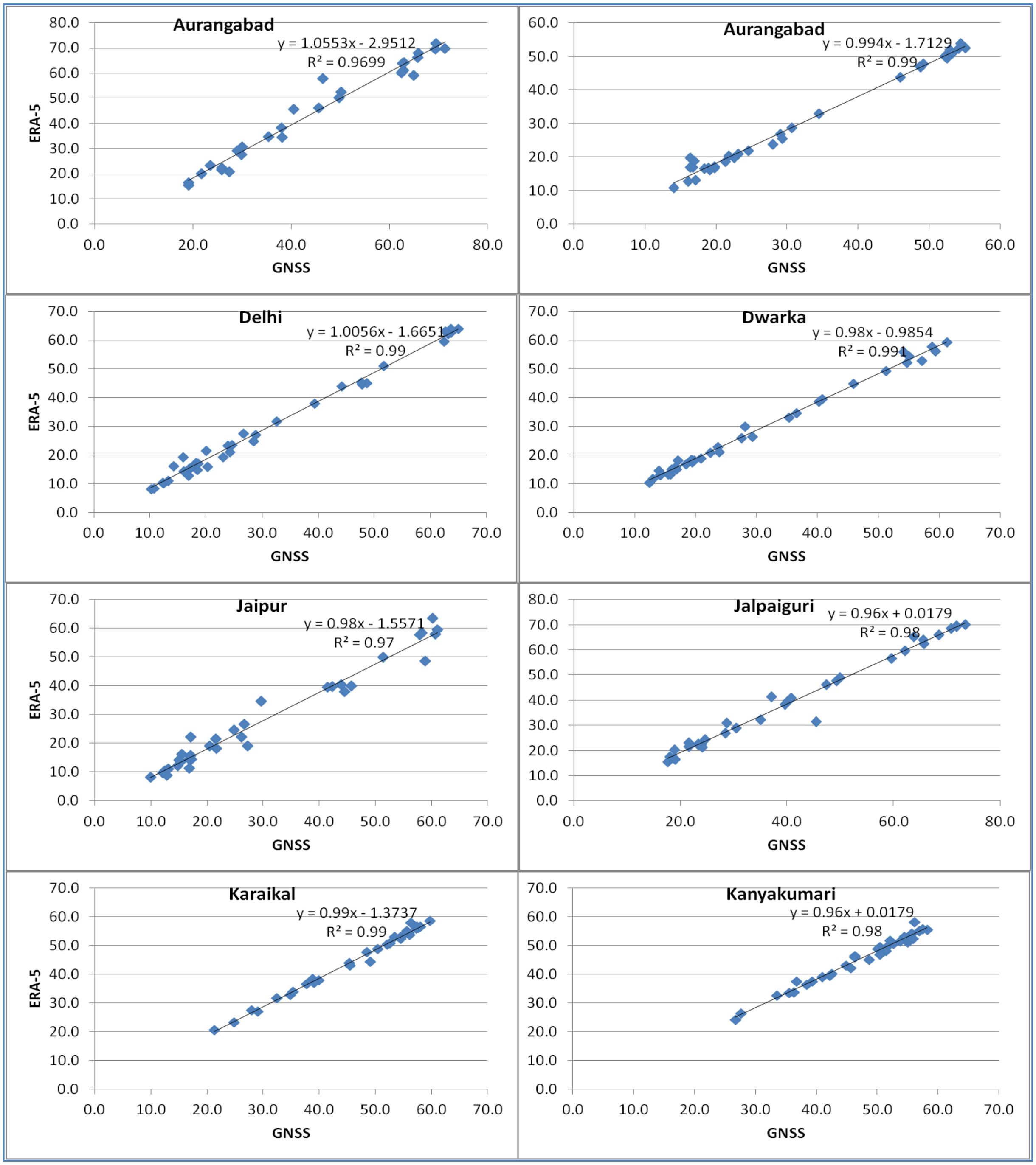

Fig. 1. Scatter plot of monthly ERA-5 IPWV and GNSS-IPWV.

assessment of reanalysis by using homogeneously reprocessed long-term time series of GNSS-IPWV as reference in India is still lacking. In addition, very few studies have focused on the performance of the latest ERA5 in reproducing the temporal features of IPWV over India so far. Monthly mean IPWV data from ERA5 is compared with GNSS-IPWV at different stations, to represent the distribution of the GNSS sites over the Indian region. Fig. 1 shows the scatter plots and statistics of the two datasets. High correlation exists between the datasets as demonstrated in figures with correlation coefficients ranging between 0.97 and 0.99.

From Fig. 2, the average values, display an increase in IPWV from minimum values in January up to maximum values in July at all the stations after which the values decrease to minimum values in December. The two datasets exhibit a single peak in IPWV during Monsoon

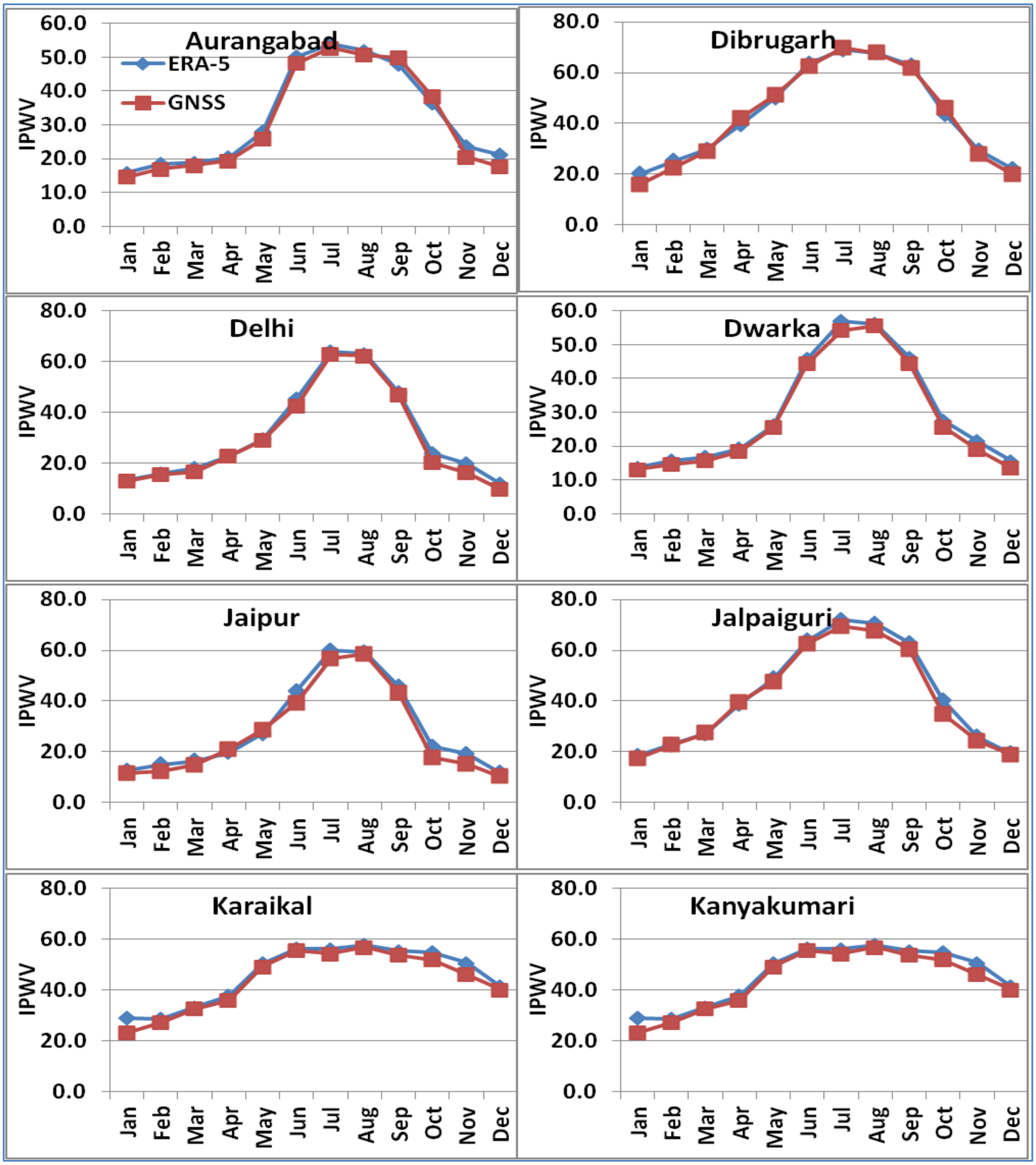

Fig. 2. The seasonal PWV cycle as captured by ERA5 and GNSS stations.

season as there is a strong correlation between precipitation and IPWV. The rainfall is associated to water vapour content in the atmosphere however, the presence of high quantities of water vapour does not mean that there will always be rainfall. The seasonal cycle is also strongly created by north-south movement of the intertropical convergence zone (ITCZ) across the region.

3.2. *Role of Multi-threshold of IPWV (MTI)*

Forecasting of convective weather is really a challenging task in tropical region. Any single piece if information is very important to decide instant solution of the vulnerability of weather event occurred in a very short time. If the temporal domain is shorter and convective

TABLE 1

Month wise IPWV threshold Generated from 2017 to 2019, Indian GNSS data

Stations Name	Month wise IPWV Threshold in mm											
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Jaipur	9.82	12.68	14.71	20.86	26.80	39.35	59.85	58.73	43.28	17.35	16.27	10.31
Thiruvananthapuram	31.57	35.14	42.00	46.57	53.58	55.31	51.64	53.60	51.49	55.29	51.67	42.68
Jalpaiguri	17.09	22.68	27.47	39.40	47.69	61.90	69.30	67.29	60.17	35.98	24.56	18.56
Delhi	12.61	15.39	16.63	22.85	28.92	49.86	62.82	62.37	47.01	21.40	16.80	9.66
Nagpur	15.80	18.00	21.00	21.03	32.18	53.57	60.22	61.62	53.88	43.96	23.97	18.20
Panjim	26.98	24.66	31.20	39.92	48.39	60.81	56.94	48.34	52.99	55.69	40.47	37.39
Aurangabad	14.49	6.90	18.02	19.40	26.36	48.26	52.26	50.78	50.28	36.58	20.93	17.76

weather affecting our agriculture zone, then MTI plays an important role in decision making. Based on the monthly or seasonal thresholds we can issue advisories with appropriate inputs based on other relevant value addition inputs. MTI inputs further also help to build up the trend analysis of water vapour availability around the station area, whether it is increasing or decreasing with time. If it shows persistence negative departure for a long time then this information can be passed to state or central government for further preventive action /measures.

3.3. *Monthly IPWV thresholds of GNSS data (2017 to 2019)*

In general, satellite remote sensing techniques especially Infrared measurements are more accurate over oceans than over land, but hold a limitation being incapable to estimate PWV in presence of cloud cover. Radio sonde measurements (twice daily) have poor spatial and temporal resolution in spite of high operational and maintenance costs. The measurements from water vapour radiometer have site specific calibration issues and expensive operating costs. On the other hand, GNSS derived IPWV have high temporal, spatial resolution, low cost and all weather availability. The Temporal variability of GNSS IPWV observations can be used to forecast precipitation events. Keeping the above facts in mind monthly thresholds of GNSS IPWV from two years (2017 to 2019) GNSS data of 7 stations (Table 1) has been generated to monitor the convection around GNSS station area. The coastal stations show high and evenly distributed IPWV values and diurnal variation over the year. These stations are greatly influenced by moisture advection from the sea areas and sometimes cause of the continuously increment of PWV even after the air temperature decreased (Ortiz de Galisteo *et al*., 2011).

4. Case studies

4.1. *Rainfall on 22nd June-2020 (0100 to 0200 IST) at Lodi Road, New Delhi*

The convective activity forecast especially pre-monsoon season is a major challenge to forecasters due to its short lived, spatially inhomogeneous and variable nature. On 21st June-2020, mid night the IPWV values reaches its maximum thresholds (49.86 mm) for Delhi and the rainfall was observed in early morning hours on 22nd June 2020 (Fig. 3a). This convective building up above its monthly threshold was established 4 to 5 hours prior to the actual occurrence of the rainfall activity. This can be varying place to place and season to season.

The rainfall occurrence at or around the stations can also be depend on the synchronization or favorability of other thermo-dynamical meteorological parameters and instability indices. These variations of IPWV are quite different during pre-monsoon, monsoon, post-monsoon and winter seasons. IPWV analysis during the precipitation period reconfirms that the rainfall pattern is not necessary to follow the IPWV time series due to interlinked atmospheric processes. However, high spatial and temporal IPWV analysis may complement towards a better understanding of the tropospheric dynamics, their effects and the future refinements in weather forecasting and numerical weather prediction regional models over the Indian region.

The rainfall occurrence at or around the stations can also be depend on the synchronization or favorability of other thermo-dynamical meteorological parameters and instability indices. These variations of IPWV are quite different during pre-monsoon, monsoon, post-monsoon

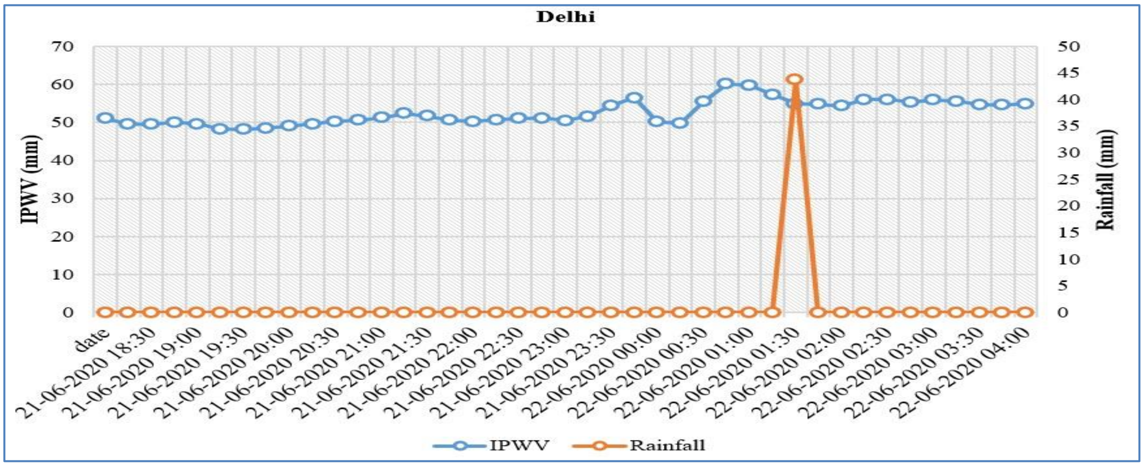

Fig. 3a. IPWV and Rainfall occurrence at Delhi on 22nd June -2020.

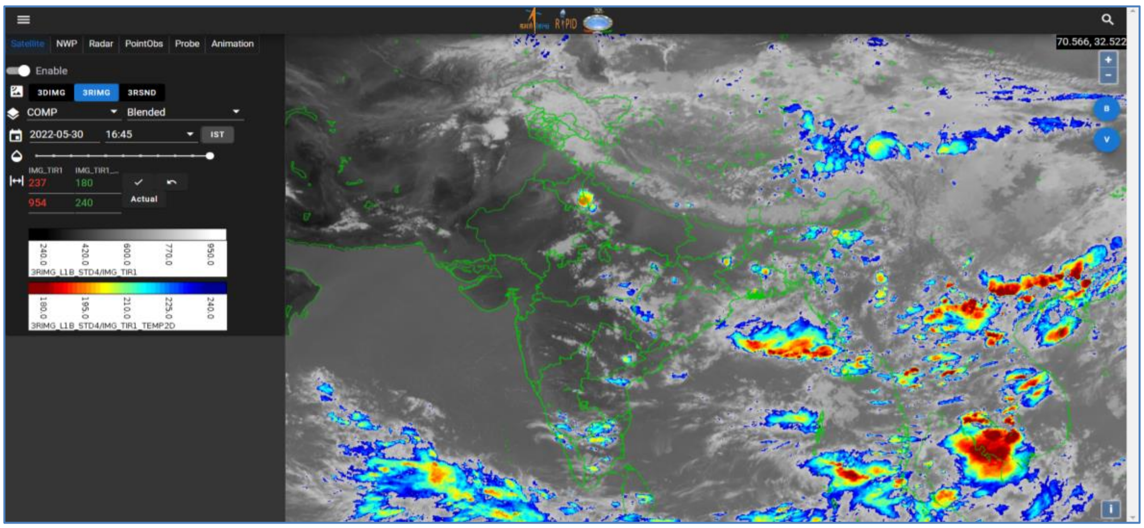

Fig. 3b. Blended Image (Infrared and Visible) of INSAT-3DR at 16:45 IST (Thunderstorm noticed at NCR): Intense convection seen around NCR.

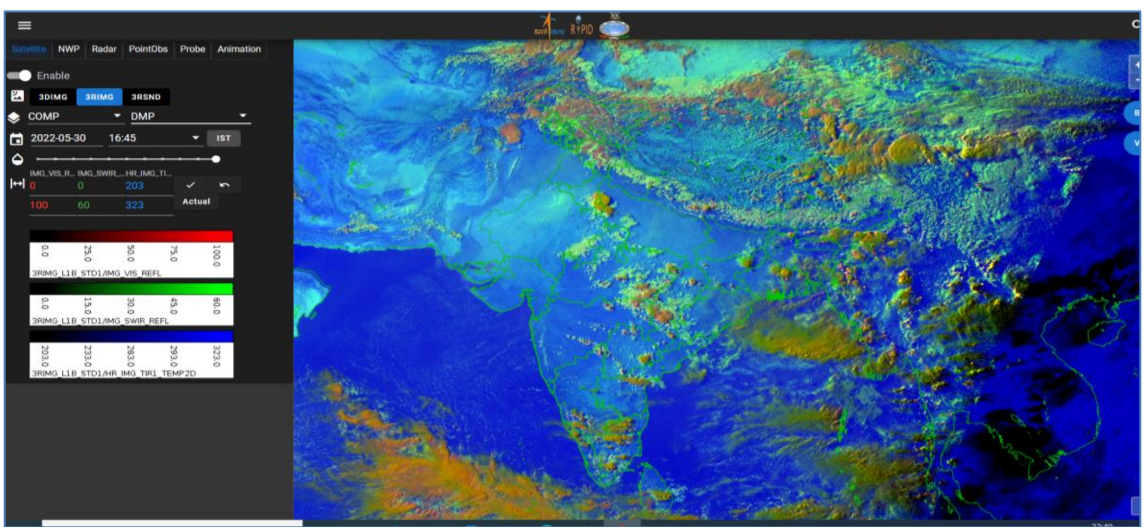

Fig. 3c. Day Microphysics (DMP) of INSAT-3DR (Visible +Shortwave Infrared + Thermal Infrared-1) at 16:45 IST (Thunderstorm noticed at NCR)/

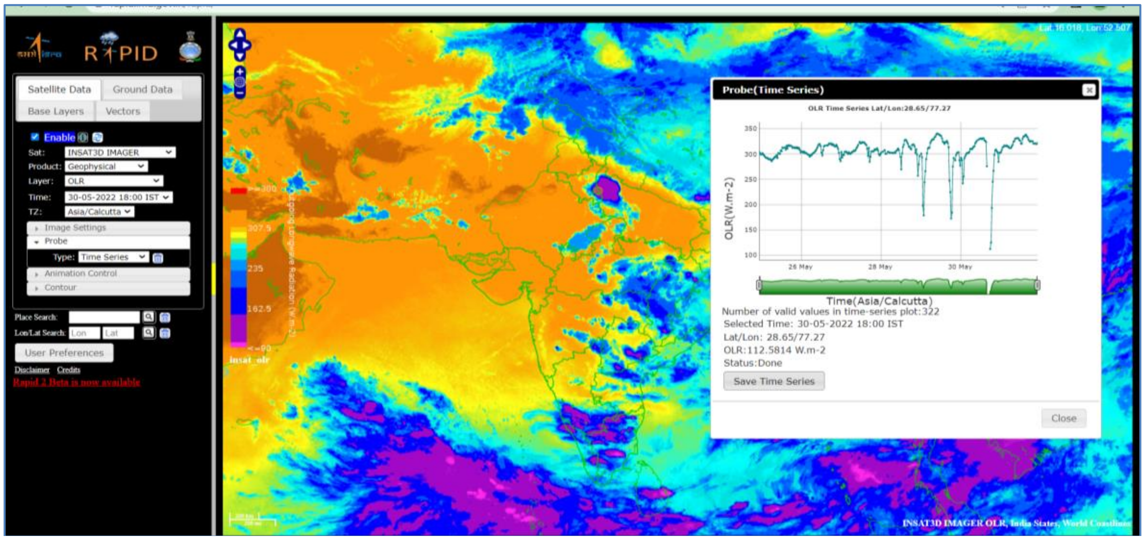

Fig. 3d. Outgoing Long Wave Radiation (OLR) in watt /m^2 noticed very intense convection (112 watt /m^2 at 1730 IST (Thunderstorm noticed at 1700 IST in NCR).

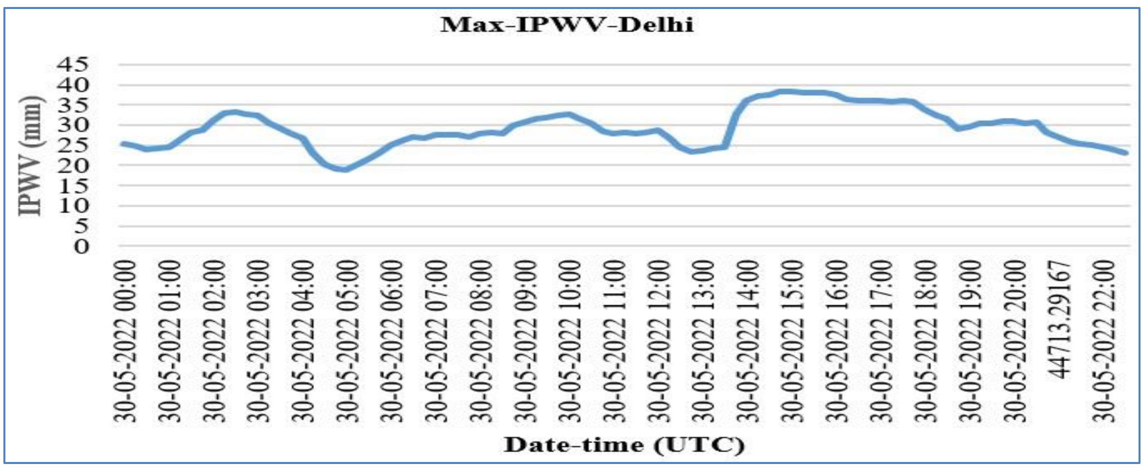

Fig. 3(e). GNSSS derived IPWV in mm of Delhi from IMD, GNSS Network on 30st May-2022.

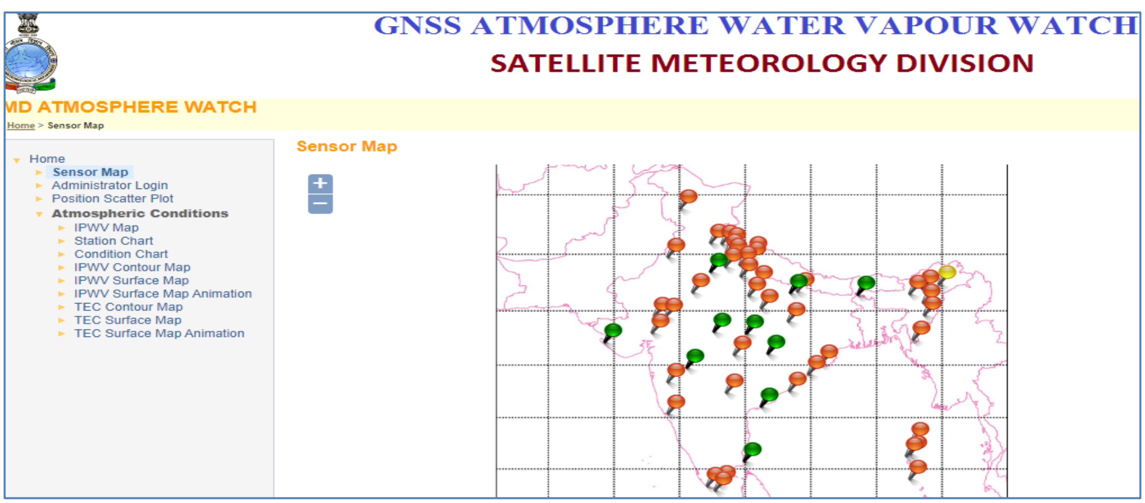

Fig. 4. GNSS setup of IMD Satellite Division, Lodi Road, New Delhi.

and winter seasons. IPWV analysis during the precipitation period reconfirms that the rainfall pattern is not necessary to follow the IPWV time series due to interlinked atmospheric processes. However, high spatial and temporal IPWV analysis may complement towards a better understanding of the tropospheric dynamics, their effects and the future refinements in weather forecasting and numerical weather prediction regional models over the Indian region.

4.2. *Intense thunder squall activity on 30-05-2022 in NCR region*

Increase of GNSS, IPWV 3 to 4 hours prior is an indicator of convection development. It will be rain or not it depends on the atmospheric instabilities and other associated mechanisms and it is really a complex process. Therefore, IPWV increase was not always associated with the rain occurrences. But it gives an idea of convective development quite well in advance (Kishtawal, 2019, Yadav *et al*., 2022, 2020, 2021, Puviarasan, *et al*., 2014, 2020). The IPWV increase can help to monitor not only thunderstorm events but also useful during onset, active and withdrawal phases of monsoons, heavy rainfall events and post landfall studies of the cyclonic disturbances. The behavior of the IPWV is different over land, desert and coastal region in each season (Yadav *et al*., 2021). In Figs. 3(b, c & d) the convection development around Delhi NCR region is clearly seen in blended, day time microphysics (DMP) images and outgoing long wave radiation (OLR) derived products of INSAT-3D satellite images. These images show intense to very intense convection around NCR region of Delhi, OLR (<112 watt /m^2). Fig. 3(e) represents the sharp increase of IPWV values at least 1 hour prior to the rainfall occurrence can be very useful value addition for the nowcast.

The study reveals that satellite derived information play an important role in weather forecasting. Both INSAT-3D/3DR and Global Navigation Satellite System (GNSS) derived products are operationally available at 15 minutes' intervals from INSAT-3D/3DR Imager and GNSS. GNSS derived Integrated Precipitable Water Vapour (IPWV) with the supports of INSAT products will be supportive prior to its occurrence and suitable inputs were supplied to the decision support system of forecasting in IMD.

5. Future scope and limitations

GNSS is an emerging tool for weather forecasting, navigation as well as seismic applications. Advancements of latest state of art receivers and computing capabilities the system is capable of handling the data with other constellations like global navigation satellite system (GLONASS), Galileo (European GNSS system), Beidou (China GNSS system) along with IRNSS (Indian GNSS system). The present receivers have better ambiguity resolution algorithms and the information can be further utilized in many seismic activities and crustal deformation studies. Multiple constellations and signals can help better to the global community from disastrous weather with sufficient lead time. The cost and maintenance of the high accuracy receivers is still an issue and with better technology and design this cost can be reduced further.

6. Concluding Remarks

The main salient points of the above study are given below:

(*i*) Both the datasets (GNSS and ERA-5) are strongly correlated and the monthly correlation coefficient ranging between 0.97 and 0.99 for the 8 GNSS stations.

(*ii*) Monthly thresholds of GNSS IPWV generated from 2017 to 2019 data sets and tested for 2020 weather events over Delhi and found fairly reasonable and accurate, however the rainfall occurrence is very complex phenomena.

(*iii*) This study is very useful in monitoring significant convective weather events and various other applications of disaster risk reduction (DRR) activities and have great potential of nowcasting

(*iv*) This analysis also useful for forecasters as value addition in early warnings in respect of severe weather events and therefore it can help to improve quality of forecast globally.

(*v*) IPWV thresholds are higher in pre monsoon and monsoon seasons as compared to winter and post monsoon seasons.

(*vi*) The thresholds of IPWV differ in every month for individual stations and rainfall occurrence is found to be sensitive with the rate of change of IPWV. To refine the input for day to day forecasting a long term IPWV data and more number of rainfall occurrences and its assimilation in NWP models are required as a future study.

Acknowledgements

Authors are grateful to the DGM, IMD for data as well as motivational support. Thanks for the entire team of ERA-5 data sets for providing the data as well as scientific support. Authors are really grateful for the anonymous reviewers for their valuable comments and suggestions.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belongs to.

References

Barindelli, S., Realini, E., Venuti, Fermi, A. and Gatti, A., 2018, "Detection of water vapor time variations associated with heavy rain in northern Italy by geodetic and low-cost GNSS receivers", *Earth Planets Space,* **70,** 28. doi : https://doi.org/10.1186/s40623-018-0795-7.

Bevis, M., Businger, S., Chiswell, S., Herring, T., Anthes, R., Rocken, C. and Ware, R., 1994, "GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water", *Journal of Applied Meteorology*. **33**. 379-386.

Cao, Y. J., Guo, H., Liao, R. W. and Uradzinski, M. 2016, "Analysis of water vapor characteristics of regional rainfall around Poyang Lake using ground-based GPS observations", *Acta Geod Geophys*. **51**, 467-479.

Dai, A., Wang, J., Ware, R. H. and Van Hove, T., 2002, "Diurnal variation in water vapor over North America and its implications for sampling errors in radiosonde humidity", *Journal of Geophysical Research: Atmospheres*, **107**, ACL-11.

Emardson, T. R., Elgered G. and Johansson, J. M., 1998, "Three months of continuous monitoring of atmospheric water vapor with a network of global positioning system receivers", *J. Geophys Res.* **103**, D2, 1807. doi : https://doi.org/10.1029/97JD03015.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R. and Schepers, D., 2020, "The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society", **146**, 1999-2049.

Huang, Liangke, Fang Xiaoyang , Zhang Tengxu , Wang Haoyu , CuiLei Liu and Lilong. 2022, "Evaluation of surface temperature and pressure derived from MERRA-2 and ERA5 reanalysis datasets and their applications in hourly GNSS precipitable water vapor retrieval over China", *Geodesy and Geodynamics*, doi : https://doi.org/10.1016/j.geog.2022.08.006.

Huang, Liangke, Mo, Zhixiang, Liu, Lilong, Zhaoliang, Zeng, Chen, Jun, Si, Xiongand He, Hongchang, 2021, "Evaluation of Hourly PWV Products Derived from ERA5 and MERRA-2 over the Tibetan Plateau Using Ground-Based GNSS Observations by Two Enhanced Models", *Earth and Space Science*. **8**. doi :10.1029/2020EA001516**.**

Isioye, O. A., Combrinck, L. and Botai, J. O., 2017, "Retrieval and analysis of precipitable water vapour based on GNSS, AIRS, and reanalysis models over Nigeria", *Int. J. Remote Sens*. **38**, 5710-5735.

Jade, Sridevi, Vijayan, M. Sithartha Muthu, Gaur, Vinod, Prabhu, Tushar and Sahu, S. C. 2005, "Estimates of precipitable water vapour from GPS data over the Indian subcontinent". *Journal of Atmospheric and Solar-Terrestrial Physics*. **67**. 623-635. doi :10.1016/j.jastp.2004.12.010.

Jiang, J., Zhou, T., Zhang, W., 2019, "Evaluation of Satellite and Reanalysis Precipitable Water Vapor Data Sets Against Radiosonde Observations in Central Asia", *Earth Space Sci*. **6**, 1129-1148.

Kishtawal, C. M.: Use of satellite observations for weather prediction, 2019. *Mausam*, **70**, 709-724.

Kumar, S., Singh, A. K., Prasad, A. K., Singh, R. P., 2013, "Variability of GPS derived PWV and comparison with MODIS data over the Indo-Gangetic plains", Phys. Chem. Earth Parts A/B/C **2013**, 55-57, 11-18.

McCarthy, M. P., Thorne, P. and Titchner, H. A., 2009, "An analysis of tropospheric humidity trends from radiosondes", *Journal of Climate*, **22**, 5820-5838.

Misra Anoop, 2019, "Variability of integrated precipitable water over India in a warming climate" Meteorological Applications, **27**, 1,. doi : https://doi.org/10.1002/met.1869.

Niell, A. E., 1996, "Global mapping functions for the atmosphere delay at radio wavelengths", *Jour. Geop. Res. Solid Earth*, **101**, B2.

Ortiz, deGalisteo JP, Cachorro V, Toledano C, Torres B, Laulainen N, Bennouna Y, de Frutos A., 2011, "Diurnal cycle of precipitable water vapor over Spain", *Q J Roy Meteor Soc*, **137**, 657, 948-958. doi : https://doi.org/10.1002/qj.811.

Puviarasan, N., Sharma, A. K., Ranalkar, M. and Giri, R. K., 2014, "Onset, advance and withdrawal of southwest monsoon over Indian subcontinent: A study from precipitable water measurement using ground based GPS Receivers", *J. Atmos. Sol.-Terr. Phy*., **122**, 45-57, doi : https://doi.org/10.1016/j.jastp.2014.10.010, 2014.

Puviarasan, N., Yadav, R., Giri, R. K. and Singh, V. 2020, "GPS Meteorology: Error in the estimation of precipitable water by ground based GPS system in some meso-scale thunderstorms – A case study", *Mausam*, **71**, 175-186.

Ross, R. J. and Elliott, W. P., 1996, "Tropospheric water vapor climatology and trends over north America: 1973-93", *J. Climate*, **9**, doi : 10.1175/1520-0442, 561-3,574.

Sen Jaiswal, Rajasriand K., Thirumala Lakshmi., 2022, "Predicting rainfall from IRNSS-retrieved precipitable water and surface meteorological elements", doi : 10.21203/rs.3.rs-1718983/v1.

Ssenyunzi, R. C., 2020, "Performance of ERA5 data in retrieving Precipitable Water Vapour over East African tropical region", *Adv. Space Res*., **65**, 1877-1893.

Vaquero-Martínez, Javier, Antón, Manuel, Román, Roberto, Cachorro, Victoria, Wang, Huiqun, Gonzalez Abad, Gonzalo and Ritter, Christoph, 2020, "Water vapor satellite products in the European Arctic: An inter-comparison against GNSS data. Science of The Total Environment", **741**. 140335. doi :10.1016/j.scitotenv.2020.140335.

Wang, J. H., Zhang, L. Y. and Dai, A. G., 2005, "Global estimates of water-vapor-weighted mean temperature of the atmosphere for gps applications". *J. Geophys. Res*., **110,** (D21101).

Yadav, R., Giri, R. K and Singh. Virendra., 2021, "Intercomparison review of IPWV retrieved from INSAT-3DR sounder, GNSS and CAMS reanalysis data", *Atmos. Meas. Tech*., **14**, 4857–4877, doi : https://doi.org/10.5194/amt-14-4857.

Yadav, R., Puviarasan, N., Giri, R. K., Tomar, C. S. and Singh, V., 2020, "Comparison of GNSS and INSAT-3D sounder retrieved precipitable water vapour and validation with the GPS Sonde data over Indian Subcontinent", *MAUSAM*, **71**, 1-10, doi : https://mausamjournal.imd.gov.in.

Yadav. Ramashray., Giri, R. K., Puviarasan, N and Bhan, S. C., 2022, "Meteorological Applications of Indian GNSS derived IPWV Spatial distribution of IPWV (mm)", *Meteorological Monograph*, MoES/IMD/SAT. MET./GNSS/01(2022)/11.

Zhang, Y., Cai, C., Chen, B. and Dai, W., 2019, "Consistency Evaluation of Precipitable Water Vapor Derived From ERA5", ERA-Interim, GNSS, and Radiosondes Over China. Radio Sci. **54**, 561-571.