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Initial Assessment of IPW data from SOI-CORS stations over Uttar Pradesh

MEENAKSHI SHENOY[1#], SURYAKANTI DUTTA[1$], ASHISH ROUTRAY[1]* and V.S. PRASAD[1@]

[1]*National Centre for Medium Range Weather Forecasting (NCMRWF), Ministry of Earth Sciences (MoES), A-50, Sector-62, Noida – 201309, U. P., India (*[#]*meenakshi.shenoy1994@gmail.com,* [$]*suryakanti@gmail.com,* [@]*ps.vijapurapu@nic.in)*

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***Corresponding author's email: ashish.routray@gov.in**

सार – यह अध्ययन ग्रिडपॉइंट सांख्यिकीय इंटरपोलेशन (जीएसआई) के साथ मौसम अनुसंधान और पूर्वानुमान (डब्ल्यूआरएफ) मॉडल का उपयोग करके मौसम के पूर्वानुमान में सर्वे ऑफ इंडिया (एसओआई) - निरंतर संचालित संदर्भ स्टेशनों (सीओआरएस) से एकीकृत वर्षण योग्य जल (आईपीडब्ल्यू) डेटा को आत्मसात करने के प्रभाव की पड़ताल करता है। उत्तर प्रदेश और पड़ोसी क्षेत्रों में स्थित एसओआई-सीओआरएस स्टेशनों से आईपीडब्ल्यू डेटा। अनुसंधान जून और जुलाई 2024 में किया गया था, जिसमें उच्च-रिज़ॉल्यूशन डब्ल्यूआरएफ मॉडल डोमेन (3 किमी ग्रिड स्पेसिंग) ने इस अवधि के दौरान वर्षा की घटनाओं पर ध्यान केंद्रित किया था। डेटा आत्मसात दिन में चार बार 0000, 0600, 1200 और 1800 UTC पर किया गया था, जिसमें पूर्वानुमान 72 घंटे तक बढ़ाए गए थे। रेडियोसॉन्ड के साथ तुलना करने पर 600 hPa से ऊपर के पवन घटकों के मूल माध्य वर्ग त्रुटि (RMSE) में 2% की कमी और सतही आर्द्रता (q) त्रुटि में 7% की कमी देखी गई, जो बेहतर प्रारंभिक स्थितियों का संकेत है। 200 hPa (पहले दिन 7.71%) और 850 hPa (पहले दिन 4.78%) पर पवन पूर्वानुमानों के लिए RMSE में उल्लेखनीय कमी देखी गई। 200 hPa पर तापमान पूर्वानुमानों ने सभी पूर्वानुमानित दिनों में लगातार सुधार प्रदर्शित किया, जो 3.05% से 4.70% तक था। भू-संभावित ऊँचाई पूर्वानुमानों में सबसे उल्लेखनीय सुधार देखा गया, जिसमें 200 hPa (पहले दिन) पर RMSE में 15.33% की कमी, और 850 hPa पर कई दिनों तक निरंतर सुधार (3.28%-5.47%) रहा। ये परिणाम उच्च-रिज़ॉल्यूशन IPW डेटा को मौसम मॉडलों में एकीकृत करने के सकारात्मक प्रभावों को उजागर करते हैं, विशेष रूप से ऊपरी-स्तरीय वायुमंडलीय मापदंडों की सटीकता और समग्र मॉडल प्रदर्शन में सुधार के संदर्भ में।

ABSTRACT. This study explores the impact of assimilating Integrated Precipitable Water (IPW) data from the Survey of India (SOI) – Continuously Operating Reference Stations (CORS) into weather forecasts using the Weather Research and Forecasting (WRF) model with Gridpoint Statistical Interpolation (GSI) as the assimilation scheme. IPW data from SOI-CORS stations located in Uttar Pradesh and neighboring regions. The research was conducted over June and July 2024, with a high-resolution WRF model domain (3 km grid spacing) focusing on the rainfall events during the period. Data assimilation was performed four times daily at 0000, 0600, 1200, and 1800 UTC, with forecasts extending up to 72 hours. The study found that assimilating IPW data significantly improved both the analysis and the forecasts of various meteorological parameters. Comparison with radiosonde showed a 2% reduction in Root Mean Square Error (RMSE) of wind components above 600 hPa and surface moisture (q) error reduction by 7%, indicating enhanced initial conditions. Significant RMSE reductions were observed for wind forecasts at 200 hPa (7.71% on Day 1) and 850 hPa (4.78% on Day 1). Temperature forecasts at 200 hPa exhibited consistent improvements across all forecast days, ranging from 3.05% to 4.70%. Geopotential height forecasts showed the most substantial improvements, with RMSE reductions of 15.33% at 200 hPa (Day 1), and sustained improvements at 850 hPa (3.28% - 5.47%) over multiple days. The results highlight the positive effects of integrating high-resolution IPW data into weather models, especially in terms of improving the accuracy of upper-level atmospheric parameters and overall model performance.

Key words – IPW, GNSS, Data assimilation, SOI-CORS network, Skill scores.

1. Introduction

The hydrological cycle describes the continuous movement and transformation of water between the Earth's surface and atmosphere. Water evaporates from oceans, lakes, and land surfaces, rises as water vapour, and condenses to form clouds, eventually returning as precipitation. This process not only regulates the distribution of water but also plays a crucial role in transferring heat and energy within the atmosphere. Water vapour, the gaseous phase of water, is a vital component of the atmosphere and one of the most significant greenhouse gases influencing weather and climate (Schmidt *et al*., 2010). Its presence affects cloud formation, precipitation, and radiative processes, making its accurate measurement essential for meteorological and climate studies. Precipitable water vapour (PWV) is the total column-integrated water vapour expressed as the equivalent depth of liquid water if condensed (Hu *et al*., 2020). Integrated Precipitable Water Vapor (IPWV) quantifies the amount of water vapour in an atmospheric column per unit area, represented as liquid water depth (Viswanadham, 1981).

Traditional methods for measuring PWV include radiosondes, microwave radiometers, and sun photometers, each with limitations. Radiosondes provide accurate vertical profiles but are costly and infrequent. Microwave radiometers are expensive and require frequent calibration. Sun photometers rely on solar radiation, limiting their usability in cloudy conditions. While satellite-based observations offer global coverage, they often suffer from low temporal resolution (Elgered *et al*., 1982; Liu *et al*., 2000; Hu *et al*., 2020). To overcome these limitations, GNSS (Global Navigation Satellite System) meteorology has emerged as an effective method for PWV estimation. GNSS-derived PWV utilizes signal delays caused by atmospheric water vapour to retrieve high-resolution temporal data. Bevis *et al*. (1992) pioneered the use of GPS for PWV estimation, later refining the approach with numerical weather models (Bevis *et al*., 1994). Hagemann *et al*. (2003) further improved this method by converting GNSS-based Zenith Total Delay (ZTD) into Integrated Water Vapor (IWV) using European Centre for Medium-Range Weather Forecasts (ECMWF) data. Studies in Ghana (Acheampong *et al*., 2015) and Egypt (Younes, 2016) confirmed the accuracy of GNSS-derived PWV, while Chen *et al*. (2018) validated this approach using data from 58 GNSS stations across China. These studies underscore the reliability of GNSS meteorology in atmospheric research.

In India, Jade *et al*. (2005) estimated PWV using GPS data from continuously operating stations between 2001 and 2003. Dutta *et al*. (2014) evaluated GPS-IPW data using global models run operationally at the National Centre for Medium-Range Weather Forecasting (NCMRWF) and found improvement in the model analysis and forecast after the assimilation of GPS-IPW. Yadav *et al*. (2020) validated GNSS-derived IPWV using GPS-sonde data for June 2017 to May 2018, demonstrating strong agreement with a correlation of 0.85–0.98 and biases within ± 4.7 mm with in situ observations. Further, Yadav (2022) analyzed seasonal, monthly, and diurnal variations of GNSS-derived IPWV over India from 2017 to 2020, identifying spatial patterns and IPWV thresholds useful for rainfall prediction. Long-term trends in PWV over India (1980-2020) were studied by Srivastava (2022) using satellite and reanalysis data, revealing significant spatial and temporal variability and emphasizing the need for multi-source validation.

Conventional radiosonde observations often suffer from spatial and temporal inconsistencies, as well as errors arising from sensor differences. The Continuously Operating Reference Stations (CORS) network addresses these challenges by providing high-precision positioning data through real-time kinematic (RTK) technology. Established by NOAA’s National Geodetic Survey (NGS), CORS enhances the National Spatial Reference System (NSRS) by offering precise geodetic data essential for meteorological, economic, and scientific applications. Snay (1989) demonstrated a transition from traditional line-of-sight surveying with a relative accuracy of 1:250,000 (1 mm error over 250 meters) to GPS-based 3D positioning, achieving accuracies exceeding 1:1,000,000 (1 mm error over 1 km). Dutta *et al*. 2014 examined the impact of GPS-IPW data from Indian stations and showed a positive impact by assimilating them in the NCMRWF Global Data Assimilation System. The CORS network integrates GNSS receivers operated by various governmental, academic, and private organizations. Globally, CORS networks facilitate precise meteorological and geophysical research. The NOAA CORS Network (NCN) in the U.S., Japan’s national GNSS network, and European Space Agency (ESA)-operated frameworks exemplify international collaboration. These networks support applications such as 3D positioning, space weather analysis, and atmospheric research. Since its inception in 1994, the CORS network has expanded to over 1,350 stations worldwide, driven by initiatives like Earth Scope’s Plate Boundary Observatory.

In India, state-owned CORS networks are operational in Andhra Pradesh, Telangana, and Tamil Nadu. The Survey of India (SOI), in collaboration with the Panchayati Raj Ministry, has established multiple CORS stations across the country, with plans to expand the network & integrate meteorological sensors for improved

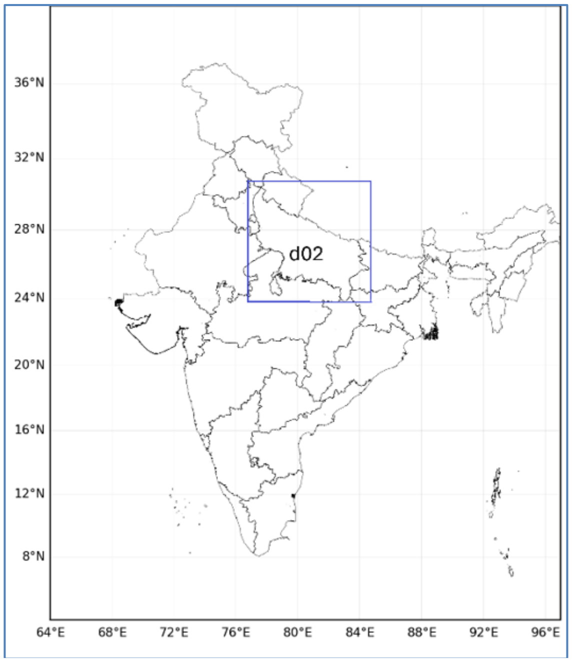


Fig. 1. Study Domains (d02 represents domain 2)

atmospheric monitoring. In the present study, the IPW from SOI-CORS stations are assimilated in a high-resolution regional model to study its impact on the state of Uttar Pradesh.

2. Data and methodology

2.1. *Experiment design*

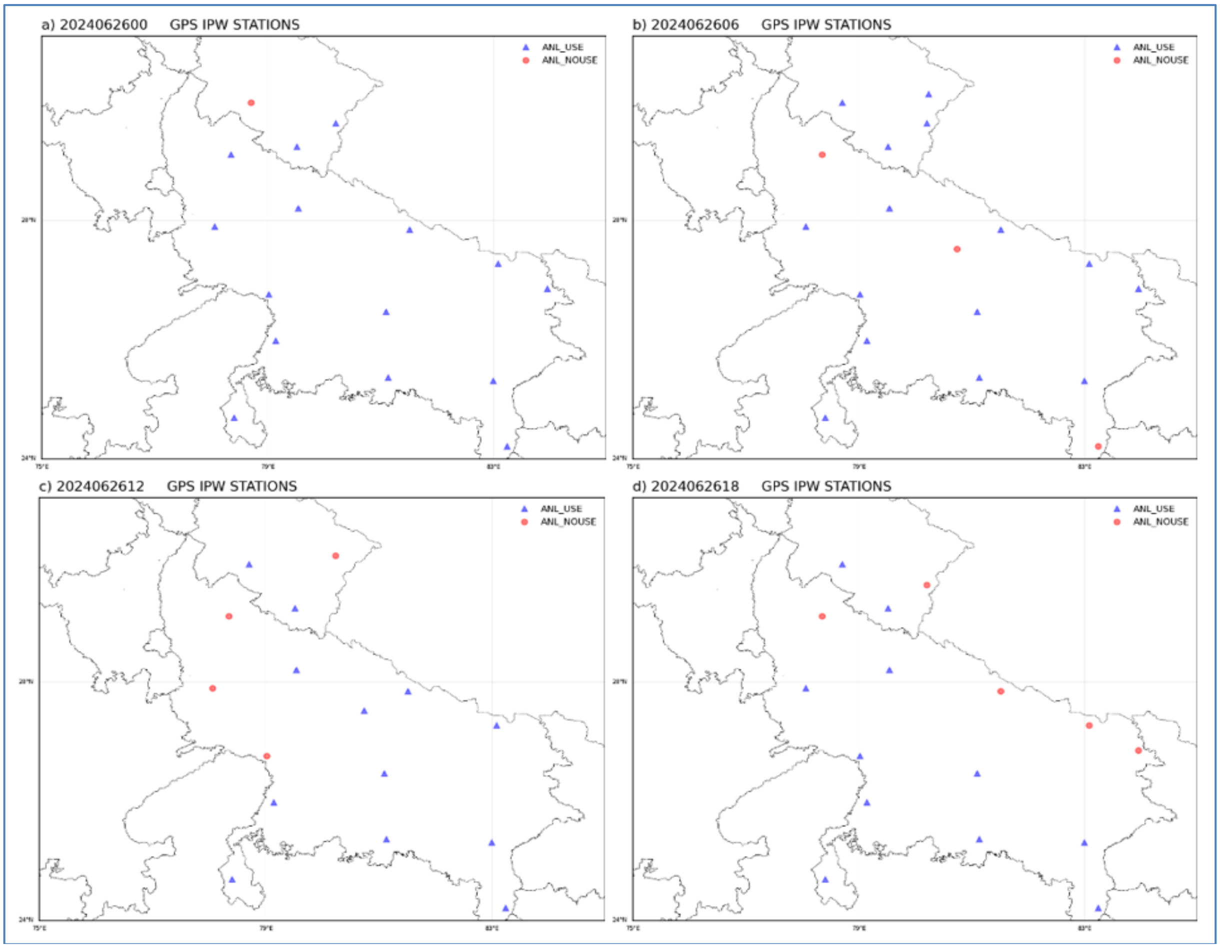
This study employs the regional Weather Research and Forecasting (WRF) model (Skamarock *et al*., 2021) with the Gridpoint Statistical Interpolation (GSI; Kleist *et al*., 2009) for data assimilation. For the present study, the WRF model operates at a resolution of 9 km and 3 km nested domain. Assimilation is conducted in 3D Var, with assimilation occurring every 6 hours. The domain of the study is shown in Fig. 1. The focus is on the state of Uttar Pradesh. The initial and boundary conditions for the model are provided by the NCMRWF Global Forecast System (GFS) data. Two runs, namely control (CNTL) and experiment (IPW) are conducted for two rainfall events in June and July 2024.

In the CNTL experiments, only conventional observations [surface, upper-air, satellite atmospheric motion vectors (AMVs), buoy], excluding integrated perceptible water (IPW), are assimilated. On the other hand, the IPW experiment incorporates precipitable water from SOI-CORS IPW in addition to the conventional observations used in the CNTL. The assimilation and forecast runs are made in two phases. Beginning on June 22, 2024, at 00 UTC, assimilation was begun in cyclic mode, with a 72-hour forecast at every 00 UTC. The runs were continued until July 10, 2023.

Validation of the analysis and forecast results from both CNTL and IPW is performed against the ECMWF Reanalysis V5 (ERA5) data. The rainfall forecasts from the model are verified against the Indian Meteorological Department (IMD) and NCMRWF merged satellite gauge (NMSG) data (Mitra *et al*., 2009). For rainfall verification Contiguous Rain Area (CRA) assessment is performed. The details of the CRA can be found in Ebert and McBride (2000) and Ebert and Gallus (2009).

2.2. *GPS-IPW methodology*

The GNSS sensors/receivers in the SOI-CORS network and other ground-based GNSS stations receive and record the signal emitted by the GNSS satellites. These GNSS signals emitted from the satellites get delayed due to various atmospheric interferences while reaching the ground-based receivers. In the troposphere, GPS signals experience delays due to atmospheric constituents. A significant portion of this delay is caused by atmospheric water vapour, commonly referred to as zenith wet delay (ZWD)**.** Additionally, dry air, hydrometeors, and other particulates contribute to signal delay, which is known as zenith hydrostatic delay (ZHD) (Niell, 1996; Solheim *et al*., 1999). A mapping function is used to convert this measured delay into Zenith Total Delay (ZTD), which is an important scientific parameter having meteorological significance and is not satellite-dependent quantity. ZTD is the sum of two components: Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). ZHD is sensitive to surface pressure and temperature and, can be computed using an empirical formula requiring meteorological data. The retrieval of PW from ZWD is detailed in Dutta *et al*., 2014. For measuring the required meteorological parameters, meteorological sensors are required at the ground-based GNSS locations. Once ZHD is computed, ZWD is obtained by subtracting ZHD from ZTD. ZWD depends exclusively on the overlying water vapour. Integrated Precipitable Water (IPW), also known as Total Precipitable Water (TPWT), defined as the amount of atmospheric water vapour (in kilogram) overlying per unit area of the earth's surface, is derived from the measured ZWD values. Its unit is kg/m^2. GPS-derived IPW measurements have demonstrated high accuracy, with root mean square errors (RMSE) varying across different regions. In North America, studies have reported RMSE values of less than 2 mm (Rocken *et al*., 1993, 1997; Duan *et al*., 1996; Fang *et al*., 1998). Similarly, GPS-based IPW estimates in Australia have shown an accuracy of approximately 1.4 mm (Tregoning *et al*., 1998). In



Figs. 2(a-d). IPW Coverage received from SOI-CORS stations at NCMRWF on a typical day of 26th June 2024

contrast, studies in Taiwan have reported RMSE values around 2.2 mm (Liou *et al*., 2001), while in Japan, the accuracy was found to be lower, with an RMSE of approximately 3.7 mm (Ohtani & Naito, 2000). These remotely sensed parameters (ZTD & IPW) are used worldwide in almost all meteorological operational centres for weather forecasting through numerical weather models. This parameter exhibits rapid spatial and temporal variations, making it a vital component in climate and weather modelling. For deriving the IPW from ZTD, meteorological sensors are essential to be installed at the GNSS stations and well-calibrated for proper accuracy. These meteorological sensors in addition to surface pressure and temperature provide other parameters useful for Nowcasting and medium-range forecasting through numerical models. GPS-derived Integrated Precipitable Water (IPW) measurements offer several advantages, including high temporal resolution (data available every few minutes), self-calibration, cost-effectiveness, & extensive spatial coverage. These benefits make GPS-based IPW a valuable tool for atmospheric studies & weather forecasting (Ware *et al*., 2000). Since the same GNSS sensors can be used for a long time, the observations recorded are also a good use for climate studies.

3. Results and analysis

3.1. *Distribution of SOI-CORS stations over the study domain*

NCMRWF receives Integrated Precipitable Water (IPW) data from ground-based GNSS networks, including the Survey of India's Continuously Operating Reference Stations (SOI-CORS). Despite ongoing expansion, station density over India remains limited. As of the study period, IMD operates 26 GNSS-IPW stations nationwide, and SOI-CORS IPW data were made available through IMD.

Fig. 2 shows the coverage of SOI-CORS stations over the study region for a typical day of 26 June 2024. There are 18 stations from which data is available for assimilation. Stations are labelled as assimilated (ANL_USE) or not assimilated (ANL_NOUSE). Out of

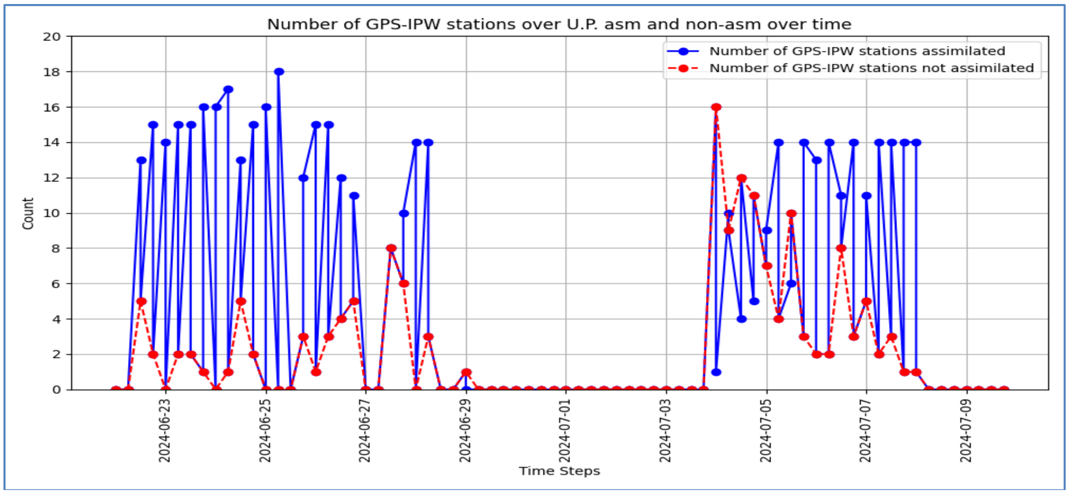
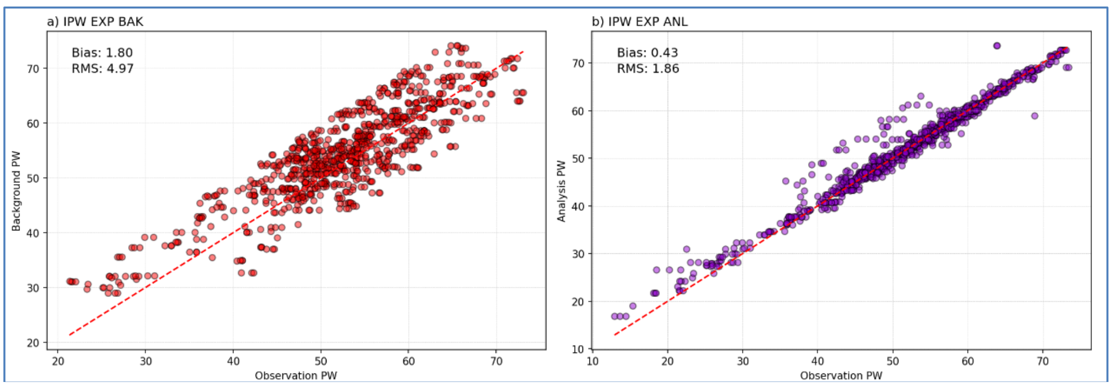


Fig. 3. Temporal variation in the number of SOI-CORS station data over the domain during the study period



Figs. 4(a&b). Scatter diagram of Observed PW v/s Model PW for the study period. a) Model background and b) Model analysis bias of 0.43 and RMS error

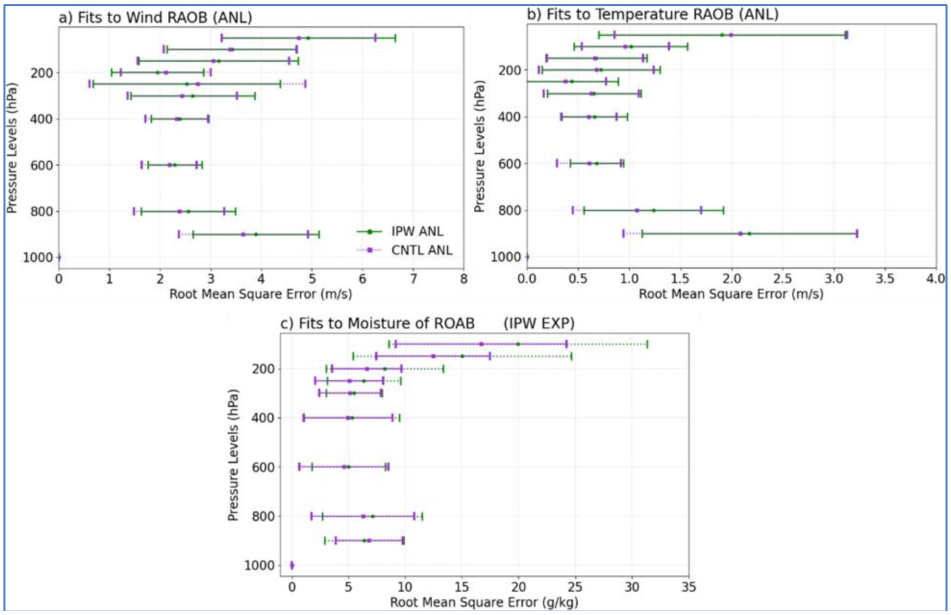
18 stations, two to four stations are not used in the data assimilation. Out of the 18 available SOI-CORS stations, data from two to four stations were not assimilated on certain days due to non-receipt or incomplete availability of IPW data. The exact reasons for these gaps are not determined here. This emphasizes the importance of consistent and reliable data availability for the effective integration of the CORS network into operational numerical weather prediction (NWP) systems.

Fig. 3 shows that, from 22 June to 10 July 2024, an average of 12 SOI-CORS stations contributed to each assimilation cycle. However, from 29 June to 3 July, no IPW data were received from any station. Such gaps highlight the importance of ensuring uninterrupted data delivery for reliable GNSS-based assimilation in regional NWP.

3.2. *PW comparison: model vs observations*

The comparison of precipitable water (PW) computed from the model background and analysis, with the observed PW from SOI-CORS stations for the study period is shown in Fig. 4. The background shows a positive bias of 1.80 and root mean square (RMS) error of 4.97, indicating systematic over-estimation and larger deviations from observations. In contrast, the analysis demonstrates significant improvement, with a reduced bias of 0.43 and an RMS error of 1.86. Reduction in the RMSE and bias for the model analysis is observed.

During June, the bias reduced to 0.38 from 1.68 and that for July reduced from 0.47 to 1.94. Similarly, the RMSE also dropped by ~63% for both months. This suggests that the observational data used in assimilation was relevant and properly weighted through the background error covariance (B) and observation error covariance matrix (R). The reduction in RMSE from the model background to the analysis indicates that the data assimilation process effectively improved the representation of the atmospheric state by incorporating observational data.



Figs. 5(a-c). Fit to radiosonde observed a) Wind, b) Temperature and c) Moisture during the study period

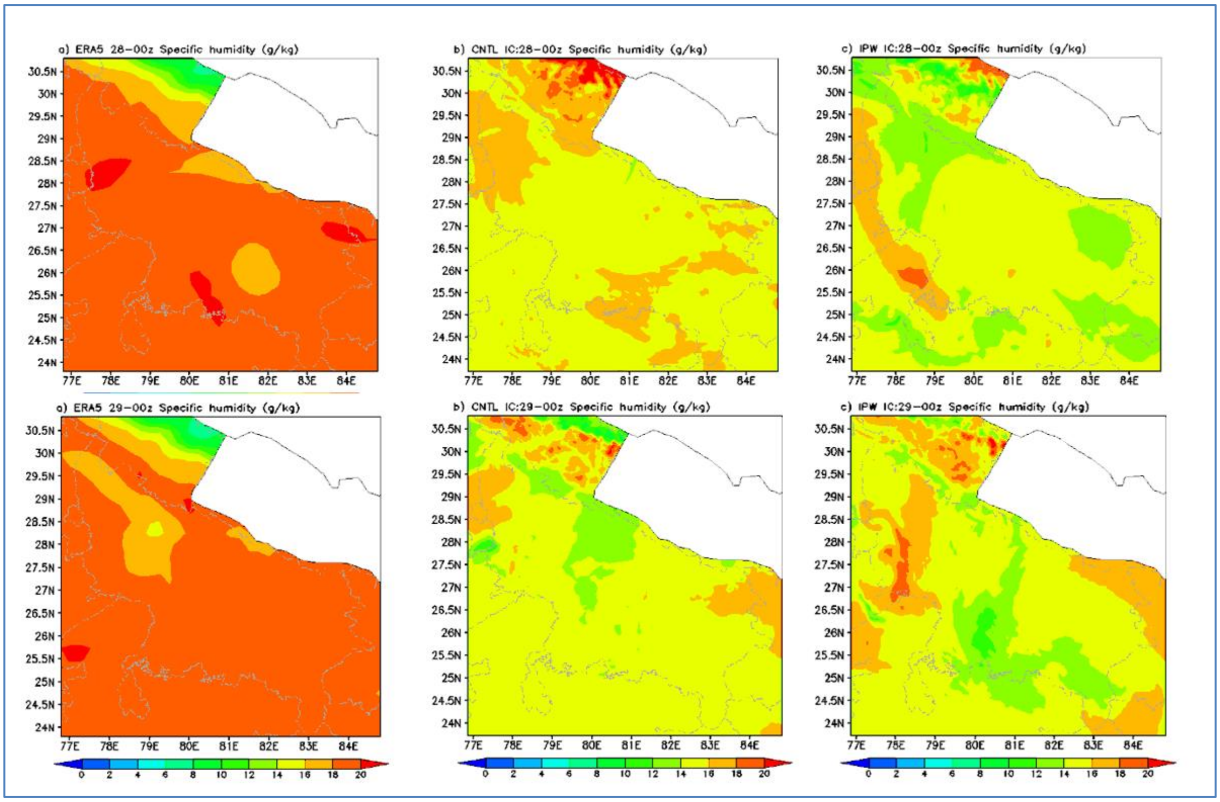
3.3. *Fit to observations*

Fig. 5 shows mean RMSE profiles for wind (zonal and meridional), temperature, and moisture fits to radiosonde observations, comparing the CNTL and IPW experiments. The IPW experiment consistently demonstrates lower RMSE values compared to CNTL at most pressure levels. From 1000 to 300 hPa the RMSE from IPW experiments range from 2-3 m/s (Fig. 5a). Notably, the largest improvements are seen in the mid-troposphere, indicating that the assimilation of SOI-CORS IPW data significantly enhances the model's ability to predict wind profiles, particularly in the region where wind patterns are often most variable and challenging to model. For temperature (Fig. 5b) while the RMSE values for both experiments are similar across most pressure levels, IPW shows small improvements, especially at higher altitudes. The relatively modest impact on temperature RMSE, compared to the stronger improvements in wind and moisture, is consistent with the physical nature of IPW observations. Since IPW provides a column-integrated measure of water vapor, it does not directly constrain the temperature field in the assimilation process. Instead, any temperature improvement results indirectly from changes in latent heating, vertical motion, and stability associated with improved moisture initialization. These effects depend on the model's internal dynamics and parameterizations, making temperature responses to IPW assimilation more diffuse and nonlinear.

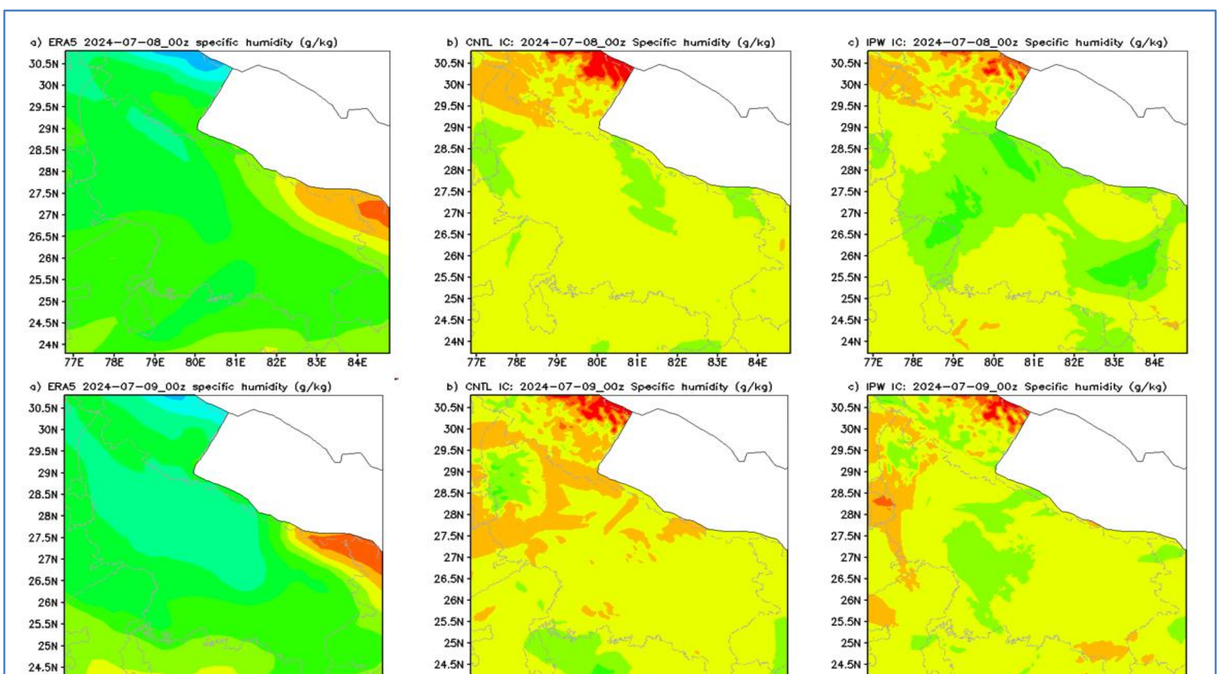
The RMSE for moisture (q) is notably lower in the lower and mid-troposphere, where moisture plays a crucial role in weather systems, particularly in precipitation forecasting. The RMSE has reduced by 7% for moisture at the surface and 2% for wind above 600hPa. Across all variables, IPW generally outperforms CNTL, with significant RMSE reductions for wind and moisture, particularly in the mid and lower troposphere, demonstrating the positive impact of assimilating SOI-CORS IPW data. These results highlight the overall benefit of IPW assimilation in enhancing the accuracy of model fields, especially for wind and moisture. These findings emphasize the importance of incorporating accurate moisture data for better model performance, especially in regions where moisture is critical for weather processes. In summary, the assimilation of SOI-CORS IPW data significantly improved the model's moisture analysis by reducing systematic bias and RMSE, confirming the high relevance and weight of this observational dataset in the analysis cycle.

3.4. *Impact on analysis*

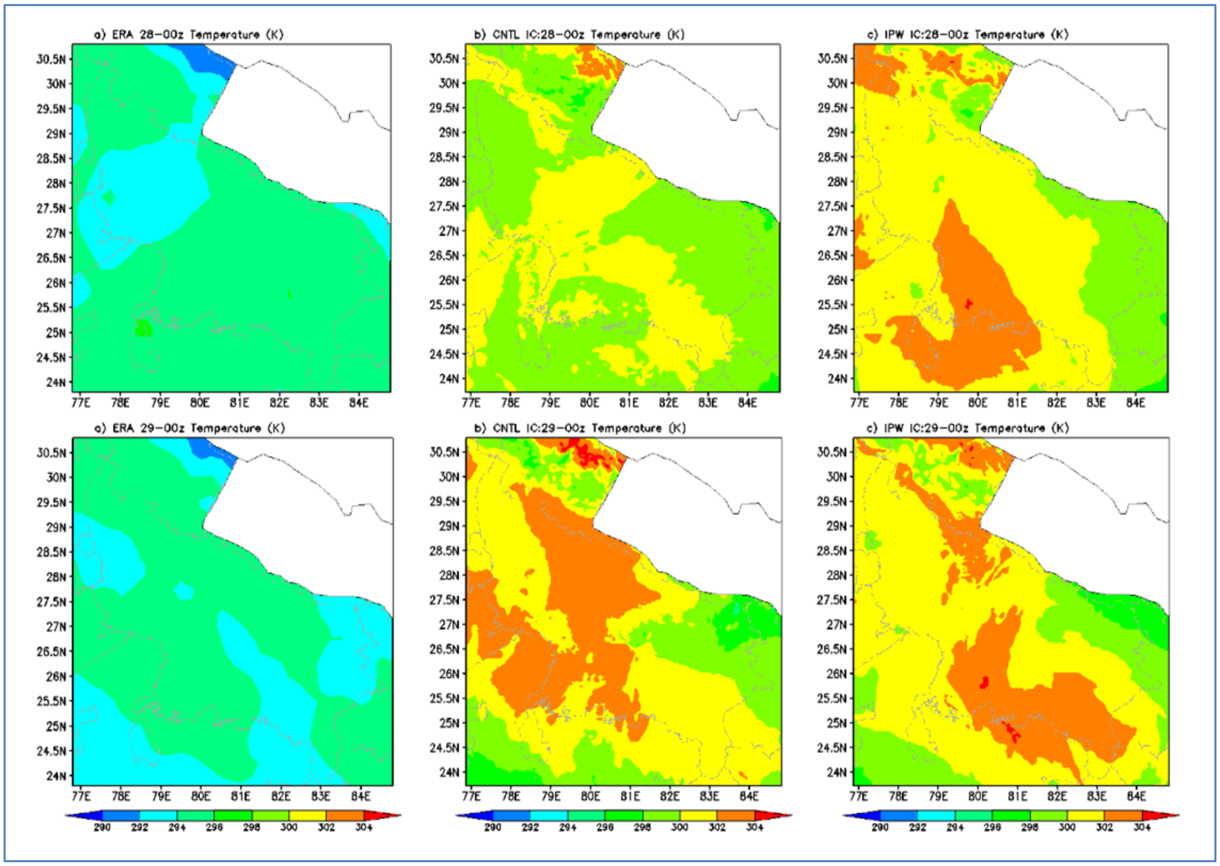
Figs. 6 to 7 compares the specific humidity fields from CNTL and IPW with ERA5 (reference dataset) for 28-29 June 0000 UTC and 8-9 July 0000 UTC. On June 28-29 (Fig. 6), spatial analysis reveals that assimilating IPW data significantly improves the model's representation of moisture. The IPW experiment exhibits closer agreement with ERA5 reanalysis in central and eastern regions, effectively correcting model biases in moisture transport and vertical motion. Notably, the eastern region shows a strong match between IPW and ERA5 in both spatial patterns and magnitudes of specific humidity.



Figs. 6(a-c). Comparison of Spatial distribution of specific humidity on 28th (top panel) and 29th June 2024 (bottom panel) from a) ERA5, b) CNTL and c) IPW experiments



Figs. 7(a-c). Comparison of Spatial distribution of specific humidity on 8th (top panel) and 9th July 2024 (bottom panel) from a) ERA5, b) CNTL and c) IPW experiments

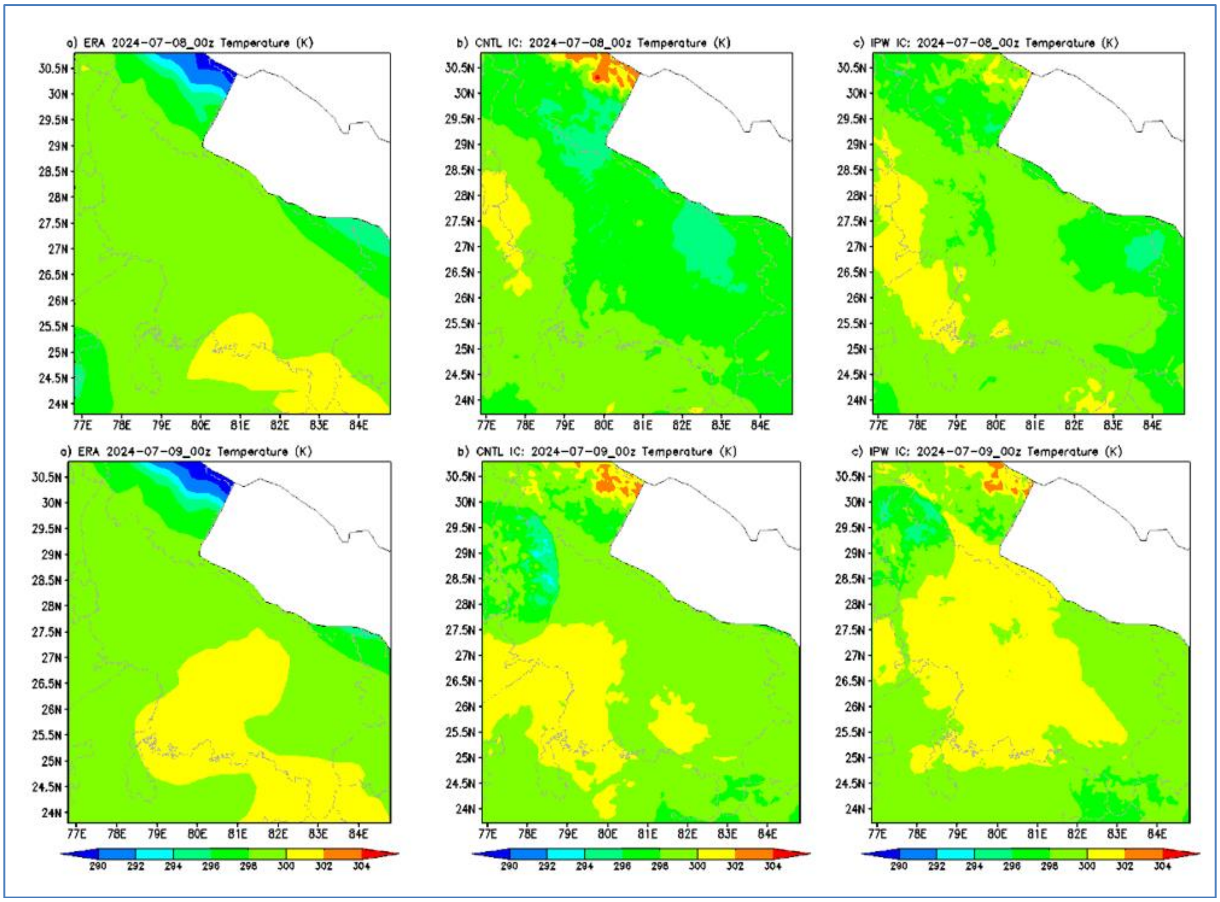


Figs. 8(a-c). Comparison of Spatial distribution of 2m temperature on 28th (top panel) and 29th June 2024 (bottom panel) from a) ERA5, b) CNTL and c) IPW experiments.

However, in some western regions, both CNTL and IPW simulations align well with ERA5, suggesting that assimilation may have a limited impact in areas where the model already performs adequately. Conversely, in some southern regions, the IPW experiment deviates more from ERA5 than CNTL, indicating that assimilation may occasionally introduce errors. This suggests that IPW assimilation effectively corrected model biases in moisture representation, particularly in these inland areas. The improved representation of temperature, coupled with better specific humidity fields, suggests a positive feedback effect on atmospheric processes like vertical motion and moisture transport.

As for the July event (Fig. 7), in the northern region, where ERA5 indicates high specific humidity, the IPW experiment aligns more closely with ERA5 than the CNTL experiment, which underestimates humidity in these areas. Similarly, areas of lower specific humidity in ERA5 are better captured in the IPW experiment compared to the CNTL run. However, in some western regions, both IPW and CNTL experiments show closer alignment with ERA5, indicating areas where the model performs relatively well even without IPW assimilation.

Figs. 8 to 9 compares the temperature fields from ERA5, CNTL, and IPW assimilation experiments for June 28-29, 2024, and July 8-9, 2024. On June 28, the IPW simulation exhibited warmer temperatures compared to the CNTL simulation in several regions. By June 29, both IPW and CNTL simulations showed higher temperatures than ERA5 in certain areas. Despite these variations, the IPW simulation consistently demonstrated a closer resemblance to ERA5 on both days, particularly in capturing temperature gradients and the spatial distribution of warmer and cooler regions. Notably, in the eastern regions, IPW assimilation led to a strong match with ERA5, whereas in some western regions, CNTL and IPW simulations were already closely aligned with ERA5 observations. The CNTL experiment overestimates temperatures in the northern and central regions, particularly in areas where ERA5 indicates cooler conditions. These biases are reduced in the IPW experiment, particularly in regions critical for rainfall dynamics. However, discrepancies remain, as temperature fields from the IPW experiment still deviate from ERA5 in some locations. Notably, in western regions, both



Figs. 9(a-c). Comparison of Spatial distribution of 2m temperature on 8th (top panel) and 9th July 2024 (bottom panel) from a) ERA5, b) CNTL and c) IPW experiments

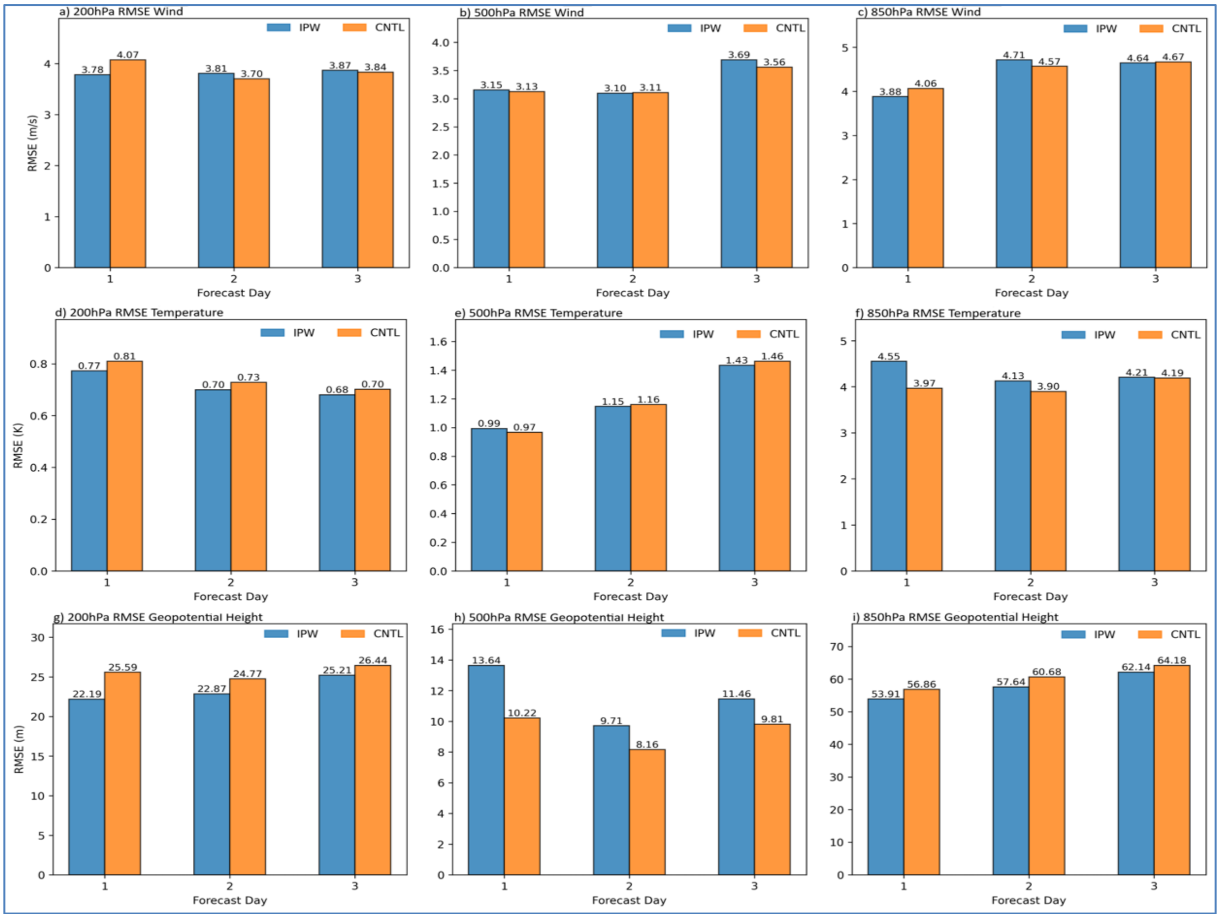
CNTL and IPW experiments show reasonable alignment with ERA5 temperature distributions, highlighting areas where the model performs well without significant assimilation impact.

A combined analysis with specific humidity fields reveals that regions with higher temperature overestimates in the CNTL experiment correspond to areas of lower specific humidity (Figs. 6-7). This aligns with atmospheric thermodynamics, where reduced moisture limits evaporative cooling, leading to higher temperatures. The assimilation of IPW data in the IPW experiment helps correct these biases by better constraining the initial moisture fields, thereby improving the temperature representation and its spatial patterns. Across both cases, the IPW assimilation's impact on temperature representation is evident, though it does not fully eliminate biases. The results highlight the potential of IPW assimilation to improve temperature fields, albeit with some limitations.

3.5. *Forecast Verification*

The impact of the IPW and CNTL experiments on model forecasts is verified against ERA5 reanalysis. To assess forecast performance, RMSE for wind vectors, temperature, and geopotential height is computed at 200, 500, and 850 hPa pressure levels. The comparison between forecasts and observations is restricted to forecasts valid up to Day 3. Figs. 10(a-i) presents the bar diagram plots for RMSE of wind vector [Figs. 10(a-c)], RMSE of temperature [Figs. 10(d-f)] and RMSE of geopotential height [Figs. 10(g-i)] respectively.

The comparison between IPW and CNTL runs revealed consistent improvements across all variables and pressure levels. For the wind vector, the IPW runs show reduction in RMSE by 7.71% at 200 hPa (Day 1) and 4.78% at 850 hPa (Day 1)**,** with smaller improvements **(**0.44%-0.48%**)** at other levels. The RMSE for temperature also showed notable improvements at 200 hPa (3.05%-4.70%) across all forecast days, while at 500

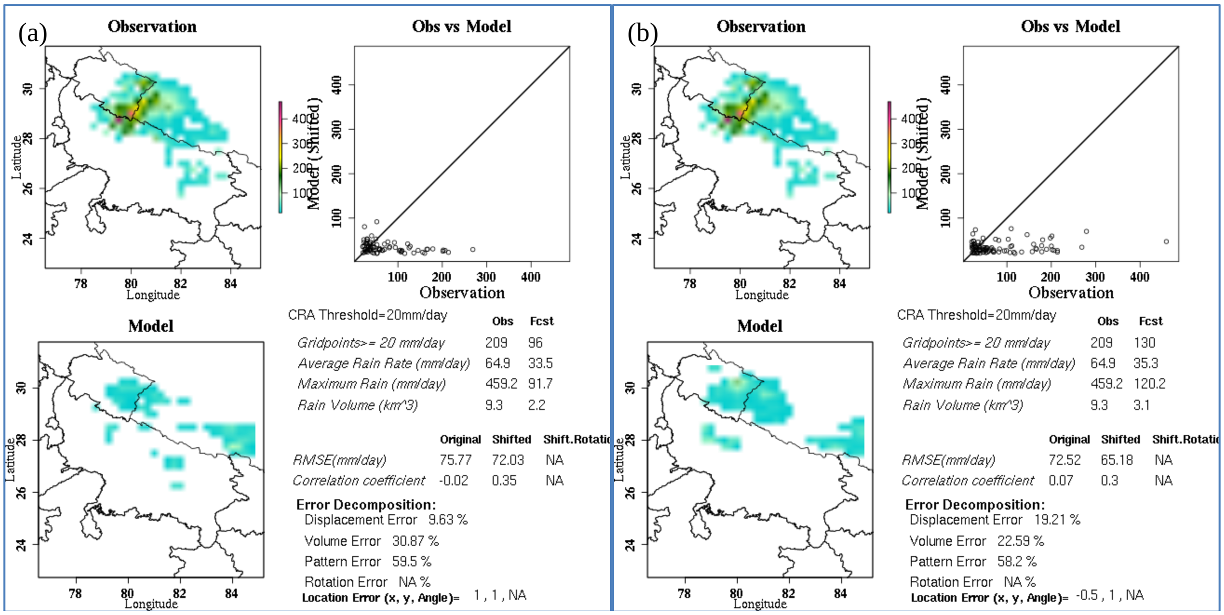


Figs. 10(a-i). RMSE of wind (a) 200, (b) 500 & (c) 850 hPa pressure levels; temperature at (d) 200, (e) 500 & (f) 850 hPa pressure levels and geopotential height (g) 200, (h) 500 & (i) 850 hPa pressure levels over Uttar Pradesh, forecasts from IPW and CNTL runs with respect to ERA5

hPa there were moderate reductions (1.07%-1.97%)**.** The most substantial impact was observed in geopotential height at 200hPa, where IPW outperformed CNTL by 15.33% (Day 1), 8.34% (Day 2), and 4.89% (Day 3)**.** Improvements for wind at 850 hPa is around 3.28-5.47%. These results demonstrate that IPW assimilation consistently enhanced forecast accuracy across wind, temperature, and geopotential height fields. The largest improvements are seen in upper-level geopotential height, especially at 200 hPa. This enhancement is physically linked to improved initialization of lower- and mid-tropospheric moisture, which affects the vertical distribution of latent heat release. In regions of active convection, accurate moisture initialization strengthens or weakens latent heating, which in turn drives changes in vertical motion and modifies mass divergence in the upper troposphere. These dynamic adjustments alter the geopotential field aloft, leading to improved representation of synoptic-scale features such as troughs and ridges. Therefore, the improved moisture field from SOI-CORS IPW assimilation has a cascading effect, ultimately enhancing upper-level geopotential height forecasts.

3.6. *Rainfall analysis*

A Contiguous Rain Areas (CRA) method was used for the CNTL and IPW experiments evaluated against the IMERG rainfall data for spatial verification. The CRA is significant as it evaluates the model's ability to capture the spatial and temporal continuity of rainfall events, which is critical for accurate rainfall prediction and impact assessment. The analysis is conducted for the 28th June rainfall event Figs. 11(a&b). In the CNTL experiment, the RMSE improves from 72.52 to 65.18 mm/day after shifting, while in the IPW experiment, it improves from 75.77 to 72.03 mm/day. The correlation coefficients also show improvement after shifting, increasing from 0.07 to 0.3 in CNTL and from -0.02 to 0.35 in IPW, suggesting better alignment of rainfall patterns with observations in the IPW experiment. The displacement errors are lower in the IPW experiment (9.69%) compared to CNTL



Figs. 11(a&b). CRA for 28th June a) CNTL and b) IPW experiments with respect to IMERGE rainfall

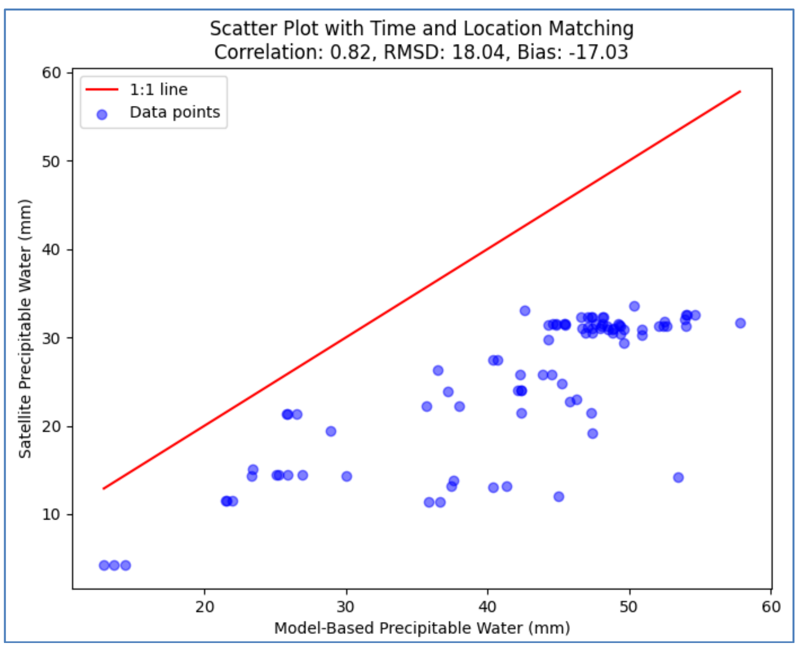


Fig. 12. Comparison of precipitable water from INSAT-3DR and SOI-CORS

(19.21%), indicating that assimilating SOI-CORS IPW data helps reduce spatial or temporal misalignment. However, both experiments exhibit high volume errors (22.59% in CNTL and 30.87% in IPW) and pattern errors (58.2% in CNTL and 59.5% in IPW), highlighting persistent challenges in accurately capturing total rainfall amounts and the spatial/temporal structure of rainfall. High volume and pattern errors indicate that column integrated IPW data alone cannot fully capture the vertical and structural details of precipitation systems. Due to its lack of vertical resolution and cloud information, IPW's impact on rainfall intensity and organization is limited. Therefore, combining IPW with additional observations like satellite-derived humidity profiles or cloud-sensitive measurements could improve the model’s representation of rainfall structure and intensity in future assimilation efforts. Overall, the IPW experiment demonstrates improved performance, but further refinement is needed to address volume and pattern-related inaccuracies.

3.7. *Comparison of INSAT-3DR sounder PW vs CORS PW stations*

Precipitable Water from SOI-CORS stations is compared with that measured by the INSAT-3DR sounder for the study period. Fig. 12 shows the comparison statistics of 18 SOI-CORS stations in terms of the correlation coefficient, bias and RMSE.

The collocation analysis conducted between the GPS-IPW station data and satellite observations aimed to evaluate the quality and accuracy of the GPS-derived precipitable water estimates (Fig. 12). The analysis revealed a strong correlation coefficient of 0.82, indicating a good alignment between the GPS station data and satellite measurements, which suggests that the GPS data effectively captures the variability in precipitable water across different locations and time steps. However, the root mean square deviation (RMSD) of 18.04 highlights substantial discrepancies, indicating that while the GPS data generally follows the trends observed by the satellites, there are significant differences in specific instances. Additionally, the negative bias of -17.03 suggests that the GPS stations tend to underestimate precipitable water, particularly at lower values, which may affect the accuracy of weather predictions derived from this data. Overall, this analysis provides critical insights into the performance of GPS-IPW stations, identifying strengths in capturing trends but also pointing out the need for calibration and improvement to enhance the precision of the observations.

The poor colocation between SOI-CORS PW and INSAT-3DR PW data likely stems from fundamental differences in spatiotemporal sampling and measurement physics. CORS stations provide point measurements of IPW derived from GPS signal delays, which depend on precise ancillary meteorological data (*e.g.*, surface pressure and temperature). In contrast, INSAT-3DR provides area-averaged precipitable water estimates using infrared/microwave sounders, which are sensitive to cloud cover, atmospheric layers, and surface emissivity. Spatial mismatches arise because satellite pixels often blend signals from heterogeneous terrain (*e.g*., mixed land-water grids or mountainous regions), while SOI-CORS stations sample discrete locations. Temporal sampling differences intensify this as GPS-derived IPW is continuous, whereas satellite retrievals are snapshots with potential gaps due to cloud contamination or orbital limitations. Additionally, vertical sensitivity disparities play a role-GPS captures the total column water vapour, while satellite retrievals may underrepresent moisture in cloudy or boundary-layer regions. Systematic biases in GPS processing (*e.g*., errors in estimating zenith tropospheric delay or converting it to IPW using flawed weighted mean temperature formulas) further degrade colocation. These mismatches in resolution, physics and retrieval algorithms create representativeness errors that complicate direct comparisons.

4. Conclusions

This study presents a preliminary evaluation of the impact of assimilating SOI-CORS-derived Integrated Precipitable Water (IPW) data over Uttar Pradesh on numerical weather model performance. A significant RMSE reduction of approximately 63% (from 4.97 to 1.86) when comparing model-derived IPW with observations demonstrates a substantial improvement in accuracy. The assimilation of high-resolution IPW data has led to notable enhancements in both model analysis and forecast accuracy, as confirmed by comparisons with radiosonde observations. Specifically, RMSE reductions of 2% for wind components above 600 hPa and 7% for surface moisture (q) highlight the positive impact of IPW assimilation on initial conditions, leading to a more accurate representation of the atmospheric state and improved forecast skill.

Further verification of forecast performance reveals consistent error reductions across multiple pressure levels, demonstrating that the benefits of IPW assimilation extend beyond initial conditions and influence forecast evolution over time. Wind forecasts exhibit the most notable improvements, with RMSE reductions of 7.71% at 200 hPa and 4.78% at 850 hPa on Day 1, leading to a more accurate depiction of atmospheric circulation patterns. Similarly, temperature forecasts at 200 hPa show systematic RMSE reductions ranging from 3.05% to 4.70% across multiple forecast days, ensuring a more precise representation of the upper atmospheric thermal structure. Geopotential height, a critical variable for understanding large-scale weather patterns, demonstrates the most substantial impact, with RMSE reductions of 15.33% at 200 hPa on Day 1, and sustained improvements at 850 hPa (3.28%-5.47%) over multiple days. These consistent improvements across key atmospheric variables reinforce the importance of assimilating high-resolution water vapour data in numerical weather prediction.

Beyond numerical model improvements, the SOI-CORS network represents a valuable dataset for atmospheric monitoring, hydrological studies, and climate applications. The collocation analysis highlights a strong correlation between GPS-IPW and satellite-derived precipitable water estimates but also reveals significant discrepancies, emphasizing the need for calibration to address biases related to spatial resolution, measurement physics, and retrieval algorithms. Similarly, the Contiguous Rain Areas (CRA) assessment shows that assimilating CORS IPW data improves the spatial alignment of rainfall predictions, reducing displacement errors and enhancing correlation with observations. However, persistent challenges remain in accurately capturing total rainfall amounts and spatial/temporal patterns, underscoring the need for further refinements in precipitation modelling.

The lack of significant improvements after assimilating SOI-CORS IPW data, despite reduced spatial and displacement errors in CRA, points to unresolved data quality and assimilation challenges. First, ancillary data inaccuracies (*e.g.*, faulty surface pressure or temperature inputs at CORS stations) can bias IPW estimates, propagating errors into the model. Secondly, sparse station density limits spatial representativeness, failing to resolve fine-scale moisture gradients critical for rainfall dynamics. Further, vertical representation mismatches, GPS IPW integrates the entire atmospheric column, while models and satellites may prioritize moisture in specific layers, create discordance in assimilation impacts.

To address current limitations, this study highlights the importance of increasing the number of high-resolution meteorological sensors co-located with SOI-CORS stations and expanding station density, particularly in regions with high rainfall variability. Additionally, our findings suggest that future work should include calibration of SOI-CORS IPW data against independent observations such as radiosondes and regional GNSS networks to identify and correct potential biases. Refining assimilation parameters such as, observation error covariance and vertical localization, will also be critical to better align IPW data with model physics and enhance forecast performance. Collectively, these steps will help bridge the gap between point measurements and gridded model systems, improving the utility of SOI-CORS IPW in NWP.

The findings of this study highlight the broader potential of SOI-CORS IPW data beyond real-time forecasting. Its high temporal resolution and dense coverage make it an important resource for monitoring extreme weather events, flood prediction, and drought assessments. Additionally, as advancements in GPS meteorology continue, integrating SOI-CORS data with other observation systems could further enhance atmospheric research and operational forecasting. Future work will focus on conducting additional case studies across different rainfall and thunderstorm events to better understand the impact of IPW assimilation and explore potential enhancements for improving short-term weather predictions. Additionally, further calibration and validation efforts will be necessary to refine the SOI-CORS dataset, ensuring its optimal use in both operational forecasting and long-term climate applications.

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Authors' Contributions

Meenakshi Shenoy: Methodology, Software, Validation, Formal analysis, Investigation, Writing-original draft.
Suryakanti Dutta: Conceptualization, Designing the study, Writing -review & editing, Supervision.
Ashish Routray: Critically reviewing the manuscript, Supervision, Writing -review & editing.
V.S. Prasad: Supervision and provide facilities.

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