NMRF/RR/01/2025

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RESEARCH REPORT

Assessing Upper Tropospheric Humidity During Monsoon Depression Using NCMRWF Unified Model Forecasts

Shubha Singh, Kondapalli Niranjan K., Anumeha Dube,
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National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201 309, INDIA

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Ministry of Earth Sciences

National Centre for Medium Range Weather Forecasting

Document Control Data Sheet

1	Name of the Institute	National Centre for Medium Range Weather Forecasting
2	Document Number	NMRF/RR/01/2025
3	Month of publication	January 2025
4	Title of the document	Assessing Upper Tropospheric Humidity During Monsoon Depression Using NCMRWF Unified Model Forecasts.
5	Type of Document	Research Report
6	No of pages, Figures and Tables	21, Six Figures, No tables.
7	Number of References	25
8	Author (S)	Shubha Singh., Kondapalli Niranjan K., Anumeha Dube., Mohan T. S.,John P. George, Saji Mohandas & V.S. Prasad
9	Originating Unit	NCMRWF

10	Abstract	Water vapour, the most potent greenhouse gas in the atmosphere, substantially influences the atmospheric energy budget by contributing to radiation and latent heating processes. Water vapour radiative effects in the tropics are important for the global climate. In the upper troposphere water vapour plays a critical role in determining cloud radiative feedback. The transport of moisture in the upper troposphere is associated with several key processes such as horizontal winds bringing moisture from lower levels or distant regions. Convective systems such as thunderstorms, contribute to an increase in the upper tropospheric humidity (UTH) by injecting moisture through overshooting cloud tops and detrainment. The subsidence of air masses leads to adiabatic warming and a decrease in relative humidity, impacting UTH. Tropical cyclones contribute to UTH through the evaporation of oceanic moisture and convective processes. Additionally, the tropical tropopause layer (TTL), where deep convective injects water vapour into the stratosphere, influences UTH. These sources interact in complex ways, influencing the distribution and variability of UTH in the upper troposphere. Understanding UTH biases can significantly enhance the accuracy of weather forecasts, particularly in regions prone to convective activity or frequent extreme weather. In this study, we evaluate UTH from NCMRWF unified model (NCUM) forecasts during a passage of monsoon depression. We have used diverse observational sources, Atmospheric sounding, over the Oceans and land regions during the evaluation of depression (17th -23rdAugust 2023). Hence this study is valuable for weather and climate modeling, aiding in the understanding of weather phenomena such as cloud formation, precipitation and heat transfer.
11	Security classification	Unrestricted
12	Distribution	Unrestricted Distribution

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सारांश

वायुमंडल में जलवाष्प सबसे प्रभावी ग्रीनहाउस गैसों में से एक है और यह दोनों दीप्तिमान (रेडिएटिव) और गुप्त ऊष्मा (लेटेंट हीटिंग) प्रक्रियाओं को प्रभावित करके वायुमंडलीय ऊर्जा संतुलन को आकार देने में महत्वपूर्ण भूमिका निभाता है। उष्णकटिबंधीय क्षेत्रों में जलवाष्प का विकिरणीय प्रभाव वैश्विक जलवायु के लिए विशेष रूप से महत्वपूर्ण है। ऊपरी क्षोभमंडल (ट्रोपोस्फीयर) में जलवाष्प बादल विकिरण प्रतिक्रिया (क्लाउड रेडिएटिव फीडबैक) को निर्धारित करने में प्रमुख भूमिका निभाता है। इस क्षेत्र में नमी के परिवहन में कई प्रक्रियाएं शामिल होती हैं, जैसे कि क्षैतिज पवनें निचले स्तरों से या दूरस्थ स्रोतों से नमी लेकर जाती हैं, और संवहनीय प्रणाली (कन्वेक्टिव सिस्टम) जैसे गरज वाले बादल अपने शीर्ष से नमी को ऊपरी क्षोभमंडल में पहुंचाते हैं।

वायुमंडल में वायु के नीचे की ओर उतरने से ऐडियाबेटिक ऊष्मन (गर्मी) होती है, जिससे आपेक्षिक आर्द्रता (रिलेटिव ह्यूमिडिटी) घटती है और इसका प्रभाव ऊपरी क्षोभमंडलीय आर्द्रता (UTH) पर पड़ता है। उष्णकटिबंधीय चक्रवात समुद्र से वाष्पन के जरिए नमी को वायुमंडल में लाते हैं और संवहन (कन्वेक्शन) को बढ़ावा देते हैं। उष्णकटिबंधीय क्षोभमंडलीय परत (ट्रॉपोपॉज लेयर - TTL) भी महत्वपूर्ण भूमिका निभाती है, जहां गहरी संवहन प्रक्रियाएं जलवाष्प को समतापमंडल (स्ट्रैटोस्फीयर) में पहुंचाती हैं, जो आगे UTH को प्रभावित करता है। ये सभी प्रक्रियाएं जटिल रूप से एक-दूसरे के साथ परस्पर क्रिया करती हैं और ऊपरी क्षोभमंडल में UTH के वितरण और परिवर्तनशीलता को आकार देती हैं।

UTH पूर्वानुमानों में त्रुटियों (बायस) को सही ढंग से समझना, विशेष रूप से उन क्षेत्रों में जहां संवहन और चरम मौसमी घटनाएं सामान्य हैं, मौसम पूर्वानुमान को सुधारने के लिए महत्वपूर्ण है। यह अध्ययन एनसीएमआरडब्ल्यूएफ यूनिफाइड मॉडल (NCUM) के पूर्वानुमानों में UTH त्रुटियों का विश्लेषण करता है, जो एक मानसूनी अवदाब (17-23 अगस्त 2023) के दौरान किए गए थे। इस विश्लेषण के लिए समुद्री और स्थलीय क्षेत्रों में किए गए वायुमंडलीय साउंडिंग और रेडियोसॉन्ड से प्राप्त प्रेक्षणीय डेटा का उपयोग किया गया। इस अध्ययन के निष्कर्ष मौसम मॉडलिंग के लिए मूल्यवान हैं, क्योंकि ये बादल निर्माण, वर्षा, और ऊष्मा स्थानांतरण जैसी जटिल घटनाओं को समझने और मानसूनी व्यवहार की बेहतर भविष्यवाणी के लिए महत्वपूर्ण अंतर्दृष्टि प्रदान करते हैं।

Abstract

Water vapour is one of the most potent greenhouse gases in the atmosphere, and it plays a critical role in shaping the atmospheric energy budget by influencing both radiative and latent heating processes. Its radiative effects in the tropics are particularly significant for the global climate. In the upper troposphere, water vapor is a key factor in determining cloud radiative feedback. The transport of moisture to this region involves various processes, including horizontal winds

carrying moisture from lower levels or distant sources, and convective systems like thunderstorms injecting moisture through overshooting cloud tops and detrainment.

Air subsidence can cause warming due to compression, which might occur either adiabatically (without heat exchange with surrounding) or diabatically (with heat exchange with surrounding). The mode of subsidence depends on the exchange of the descending air while interaction with its surrounding environment. In an adiabatic process, compression warming occurs as the air descends and is isolated from heat exchange, while diabatic processes involve heat exchange with the surrounding atmosphere, for instance radiative heating or cooling. These mechanisms minimize the relative humidity and substantially influence upper tropospheric humidity (UTH) (Holton, 2004; Wallace & Hobbs, 2006). Tropical cyclones also contribute to UTH by evaporating oceanic moisture and encouraging convection, which enhances the moisture transport into the upper troposphere. Additionally, the tropical tropopause layer (TTL) plays a significant role, where deep convection injects water vapour into the stratosphere, further influencing UTH. These processes interact in complex ways, shaping the distribution and variability of UTH in the upper troposphere and increased water vapour in stratosphere also. (Fueglistaler et al., 2009; Dessler et al., 2014).

Accurately understanding UTH biases is vital for improving weather forecasts, especially in regions prone to convection and extreme weather events. This study examines UTH biases in forecasts from the NCMRWF Unified Model (NCUM) during the passage of a monsoon depression (17th–23rd August 2023). Observational data from atmospheric soundings and radiosondes over oceanic and land regions were used for evaluation. The findings of this preliminary study, providing some insights into complex phenomena like cloud formation, precipitation, and heat transfer, which are crucial for understanding and predicting monsoonal behavior.

1. Introduction

Relative humidity (RH) is a critical parameter in understanding cloud formation, precipitation, and atmospheric circulation. Changes in RH affect the distribution of latent heating, which in turn influences atmospheric dynamics and determines the threshold for deep convection detrainment (Schneider et al., 2010; Hartmann and Larson, 2002). Studies have shown that environmental RH and atmospheric moisture profiles play a significant role in shaping the size and intensity of tropical cyclones (Holloway and Neelin, 2009; Dunion and Velden, 2004). Accurate representation of RH in Numerical Weather Prediction (NWP) models is essential for reliable forecasts, particularly for convective precipitation, which depends heavily on moisture convergence within cumulus parameterization schemes (Price and Wood, 2002; Derbyshire et al., 2004). Biases in RH representation at levels of large-scale convergence can lead to errors in forecasting convective precipitation and cloud distribution, ultimately impacting radiation computations (Shine and Sinha, 1991). Clouds play a crucial role in the atmospheric radiative budget, and inaccuracies in their forecast can cascade into broader model errors. To address these challenges, ensuring accurate initial conditions for NWP models is paramount, given the chaotic nature of atmospheric systems. Operational weather forecasting centers work to improve the initial atmospheric state by integrating enhanced observations and employing advanced data assimilation techniques (Lorenc et al., 2000; Ingleby et al., 2012). Observational data from radiosondes, satellites, and surface stations are indispensable for verifying and refining moisture analyses and forecasts (Warner, 2011).

Upper tropospheric humidity (UTH) is influenced by a variety of interconnected processes that play a significant role in atmospheric dynamics and global climate. Horizontal transport of moisture from distant regions, convective systems injecting moisture through overshooting cloud tops, and detrainment all contribute to the variability of UTH. Low-pressure systems are particularly important as they enhance UTH through oceanic moisture evaporation and convective processes. Additionally, the tropical tropopause layer (TTL) acts as a critical zone where deep convection injects water vapour into the stratosphere, influencing both UTH and broader atmospheric processes. These interactions are complex, shaping the distribution and variability of UTH in the upper troposphere. Understanding these dynamics is crucial for improving the accuracy of weather forecasts, particularly in regions prone to convective activity and extreme weather events. In this study, we assess UTH using forecasts from the NCMRWF unified model (NCUM) during the passage of a monsoon depression from August 17th to 23rd, 2023. Our evaluation makes use of various observational sources, including satellite observations and radiosonde data from both oceanic and land regions. The research contributes to the advancing weather modeling by optimizing, our understanding of various weather phenomena, both including the cloud formation, precipitation patterns, and heat transfer. While the study also in added gain provides valuable insights, for the further study and refinement required in these areas which could enhance the accuracy and application of weather models."

Water vapour, as the most potent greenhouse gas, also significantly influences the atmospheric energy balance. Its radiative effects, especially in the tropics, are vital for shaping global weather patterns and large-scale atmospheric dynamics (Held and Soden, 2000). Radiative transfer processes near the tropopause actively maintain the sharpness of this boundary, with the abrupt decline in specific humidity above the extratropical tropopause enhancing static stability in the tropopause inversion layer (TIL). This layer, characterized by heightened stability, is maintained through radiative interactions involving lower-stratospheric water vapour, as demonstrated by radiative transfer modeling (Randel et al., 2007) and observational analyses (Hegglin et al., 2009).

Biases in UTH forecasts can similarly impact the representation of these processes, underscoring the importance of accurate moisture analysis in NWP systems. High-resolution observations, such as those from radiosondes, remain essential for assessing forecast skill and addressing inaccuracies in representing both RH and UTH. These efforts are particularly important for improving predictions in regions prone to tropical cyclones, thunderstorms, and other extreme weather events.

2. Description of Model and Data

Since 2012, the National Centre for Medium Range Weather Forecasting (NCMRWF) has operationally used the Unified Model (NCUM) for weather forecasting. Developed collaboratively under the "UM Partnership," involving organizations like the UK Met Office, BoM/CSIRO (Australia), and MoES/NCMRWF (India), the NCUM framework undergoes regular updates to integrate cutting-edge advancements in Numerical Weather Prediction (NWP). A hallmark of the Unified Model (UM) is its seamless approach, utilizing a single dynamical core and consistent parameterization schemes across varying spatial and temporal scales. This adaptability enables effective handling of diverse atmospheric processes with minimal adjustments between resolutions and forecast times. The model's dynamical core, "END Game" (Even Newer Dynamics for General Atmospheric Modelling of the Environment), employs semi-Lagrangian advection and semi-implicit time-stepping to solve compressible, non-hydrostatic equations of motion (Wood et al., 2014). Parameterization schemes further address sub-grid scale processes like convection, turbulence, radiation, and microphysics. The NCUM system has undergone six major upgrades, with the latest regional model, NCUM-R, operational since October 2022. Based on the UK Met Office's "Regional Atmosphere and Land version 3" (RAL3), NCUM-R operates at three resolutions: 4 km (All India), 1.5 km (Delhi & surroundings), and 330 m (Delhi city). The 4 km domain functions year-round, while higher-resolution grids are used during winter for fog and visibility forecasts. The NCUM-R uses a "4D-Var" data assimilation method, integrating observations from Doppler Weather Radars, satellites, and conventional sources (Rabier et al., 1997).

This study utilized NCUM-G and NCUM-R analyses and forecasts to evaluate synoptic weather conditions during the monsoon depression of August 17th–23rd, 2023. Observational data from radiosondes and satellites were used to assess upper tropospheric humidity (UTH) biases. A detailed time series analysis at 300 hPa over Bhopal (23.25°N, 77.41°E) revealed a systematic moist bias in the middle and upper troposphere during monsoon depressions. These biases significantly influence cloud formation, precipitation, and heat transfer, underscoring the importance of accurate UTH representation for enhancing forecast performance and understanding atmospheric processes.

3. Synoptic weather during Monsoon Depression

Monsoon depressions (MDs), which are low-pressure systems forming over the Bay of Bengal during the summer monsoon season (June–September), play a pivotal role in determining rainfall distribution across the Indian subcontinent. These systems, characterized by organized cyclonic circulation, transport substantial moisture and significantly enhance wind patterns, thereby strengthening monsoon circulation. Their impact extends through the lower (850 hPa) and middle troposphere (400 hPa), contributing to the persistence and intensity of monsoon activity (Krishnamurti et al., 1981). Typically, MDs exhibit a vertical axis with a slight westward or no tilt with height, though rare cases of eastward tilts have been documented (Godbole, 1977; Hunt et al., 2016). Specific humidity serves as a critical indicator of moisture content within these systems. Near the surface, high specific humidity reflects the influx of moist air from the warm Bay of Bengal waters, which is essential for sustaining the depression's intensity. Figure 1 visualizes the synoptic atmospheric conditions taken from model analysis, during a monsoon depression from August 17–20, 2023. The figure overlays wind vectors on a colour map representing specific humidity (g/kg) across India and its surrounding regions. The colour gradient ranges from dark purple, indicating low humidity, to green/yellow, showing high moisture content. Throughout the period, specific humidity remains relatively stable but shows a clear spread of higher moisture from the Bay of Bengal toward the Indian mainland, particularly on August 19^{th} –20^{th} 2023.

The wind vectors reveal cyclonic circulation over the Bay of Bengal, indicating wind convergence and rotation typical of monsoon depressions. This circulation intensifies on August 19–20, coinciding with increased moisture over central and northeastern India, suggesting a robust interaction between moisture transport and atmospheric dynamics. Winds from the Arabian Sea associated with southwest monsoon flow, further contribute to moisture transport into the Indian subcontinent. The analysis highlights how the evolution of the monsoon depression from August 17–20, 2023, influenced specific humidity and wind patterns. The intensification of cyclonic circulation and increased moisture transport during this period likely contributed to enhanced precipitation over central and northeastern India. These observations provide valuable insights into the dynamics of monsoon depressions and their critical role in modulating regional weather patterns.

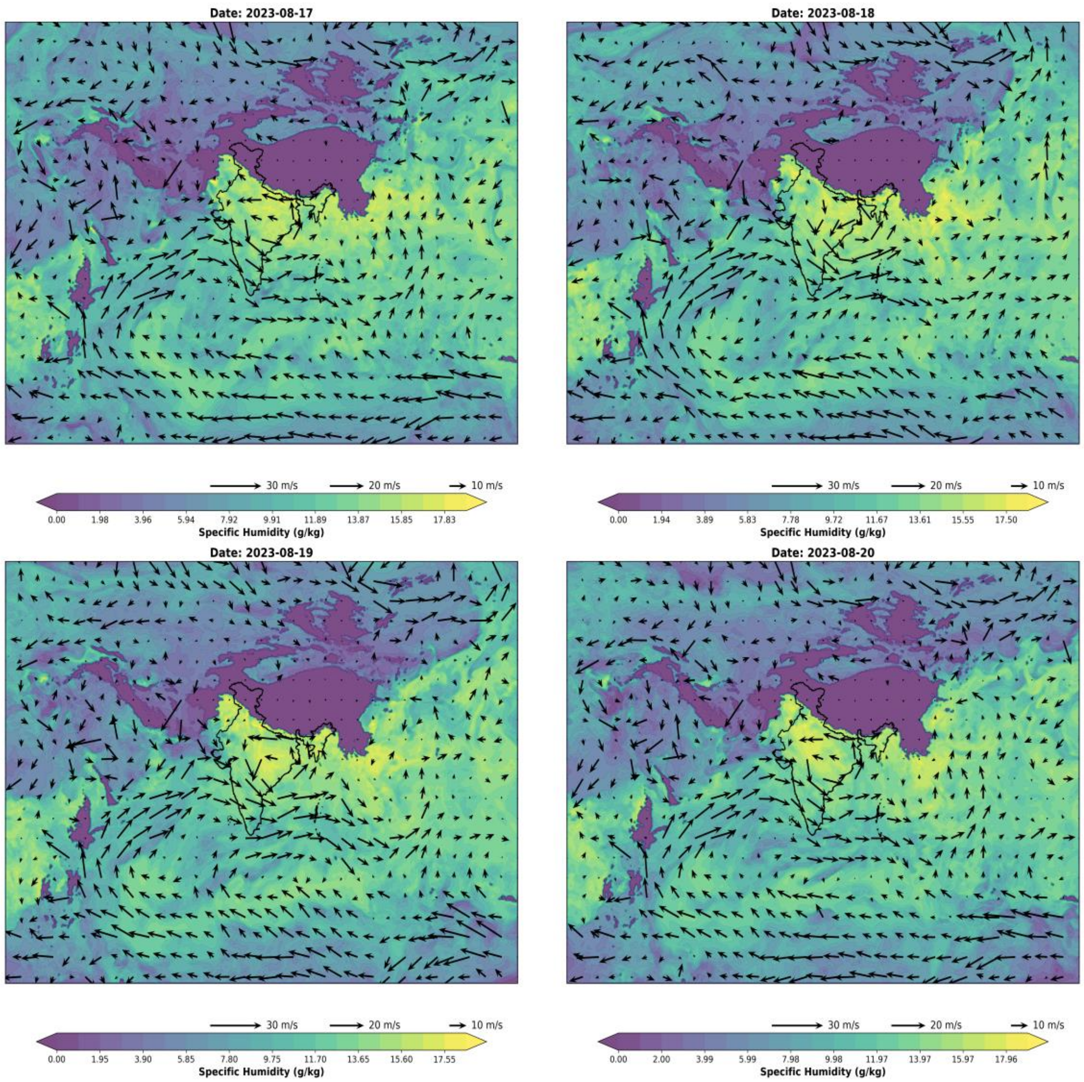


Figure 1. Wind and specific humidity at 850 hPa during the monsoon depression (17th -20th August 2023)

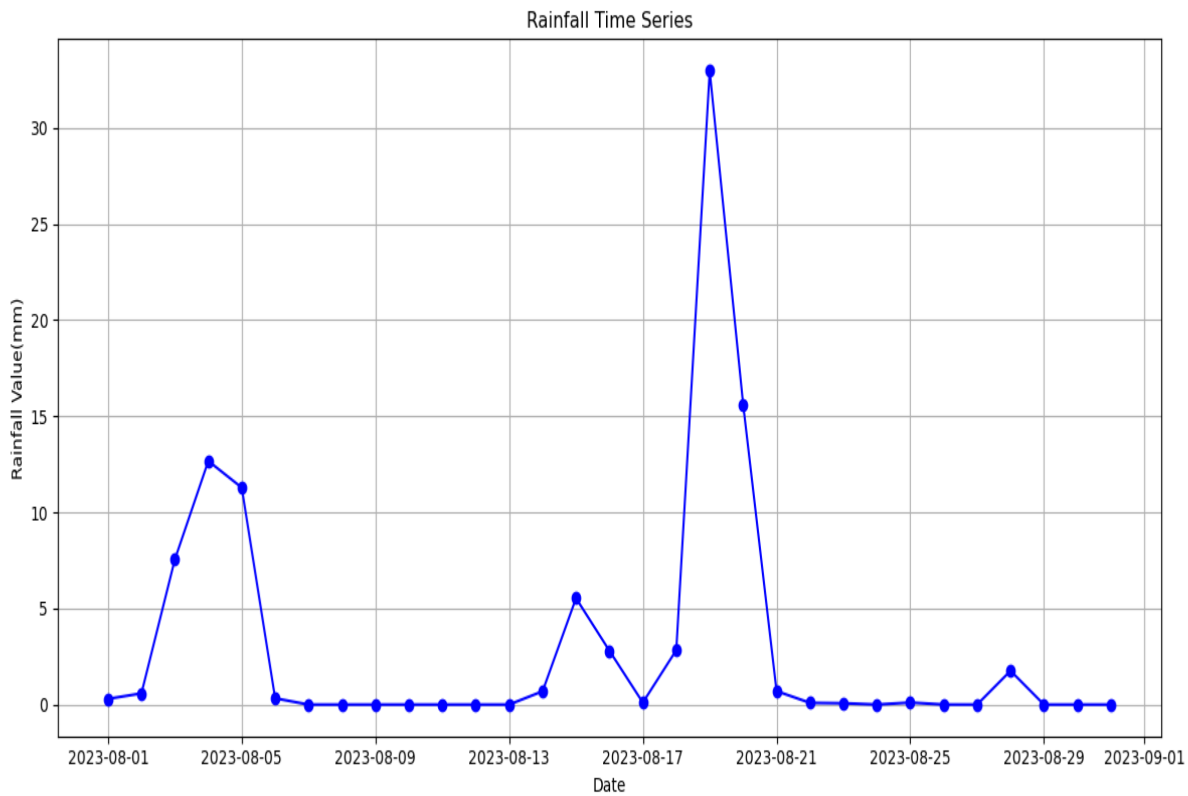


Figure2.Time series plot of observed IMD_MSG rainfall data for Bhopal during August 2023.

The rainfall time series for Bhopal from August 1 to September 1, 2023 is depicted in Figure 2 and it shows the temporal variability in precipitation during this period. The figure indicates an uneven distribution of rainfall, characterized by intermittent heavy rainfall events and dry periods. The most prominent peak in the figure is seen on August 19th with rainfall exceeding 30 mm. This significant peak aligns with the development of a notable monsoon depression from August 17th to 23rd, which likely influenced the intense precipitation observed during this time. Additionally, smaller rainfall peaks are visible on August 4th and 13th, with rainfall amounts of about 10 mm, potentially resulting from localized convective activity or smaller-scale weather systems.

It is also seen from the figure that there is an extended dry spell between August 8th and 12th, followed by a sharp decline in rainfall after the major peak on August 19th. Minimal rainfall persists until the end of the month, interrupted only by minor fluctuations. This pattern suggests the possibility of a monsoon break or a lack of significant weather systems during these intervals. This temporal distribution shown in Figure 2 highlights the episodic nature of monsoon activity, dominated by isolated heavy rainfall events rather than consistent precipitation over the month.

Overall, Figure 2 highlights the influence of monsoon depressions in driving extreme rainfall events, as demonstrated by the peak on August 19th. The figure provides valuable insights into the interaction between synoptic-scale weather systems and local precipitation patterns, underlining the need for accurate forecasting to manage water resources and prepare for potential weather-related impacts in monsoon-prone regions.

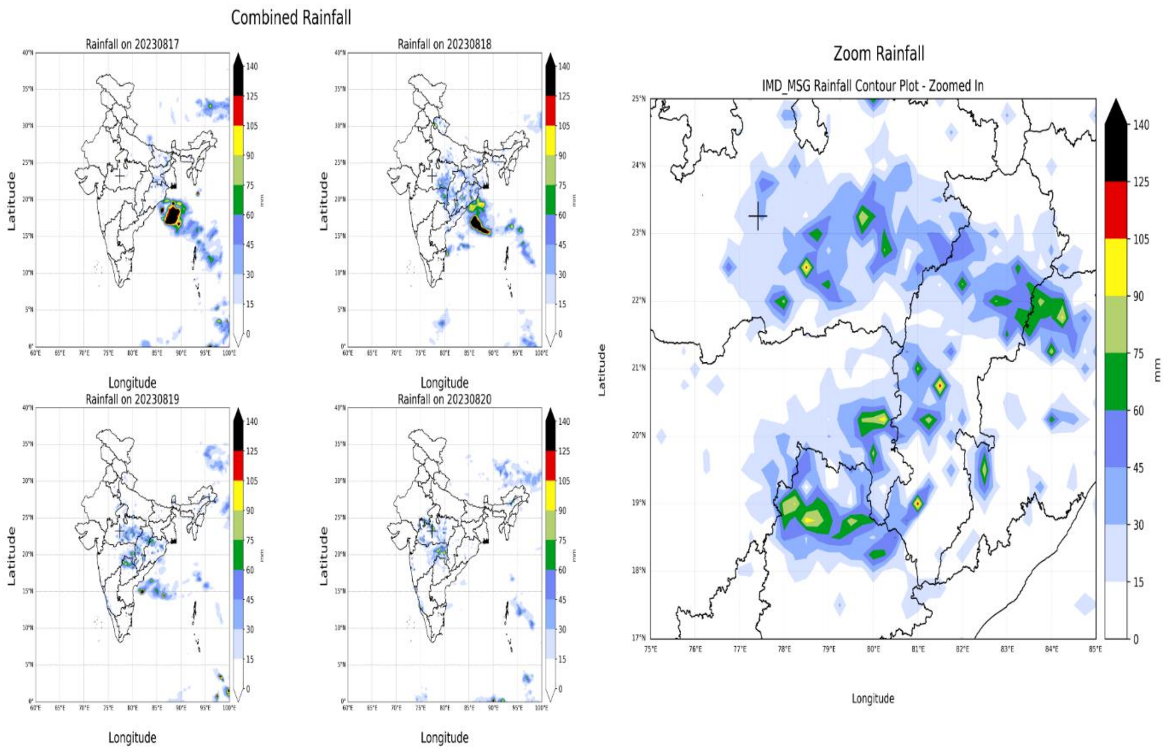


Figure 3. Spatial plots of rainfall in Bhopal (IMD-MSG) showing the evolution of the monsoon depression from August 17th to 20th, 2023. X axis Longitude Y-axis Latitude & and the next one zoom plot for 19th August 2023 the Extreme Rainfall case over Bhopal and adjoining areas.

The spatial distribution of observed rainfall over India during the period from August 17th to 20th, 2023 is presented in Figure 3. The most significant rainfall occurred over central India, (140 mm), particularly on August 19th. As the dates progress, the rainfall intensity diminishes, likely due to the weakening of the weather system. The figure captures the evolving impact of the monsoon depression, which originated in the Bay of Bengal between August 17th and 23rd, 2023. The zoomed-in plot for August 19th focuses on Bhopal and its surrounding regions, providing a detailed view of the localized rainfall activity associated with the depression. It highlights the intense precipitation over central India, while also demonstrating the broader regional influence of the monsoon system. This plot shows the progression and spatial extent of the effect of the depression, which can help in understanding the interplay between intense localized rainfall and larger regional rainfall patterns.

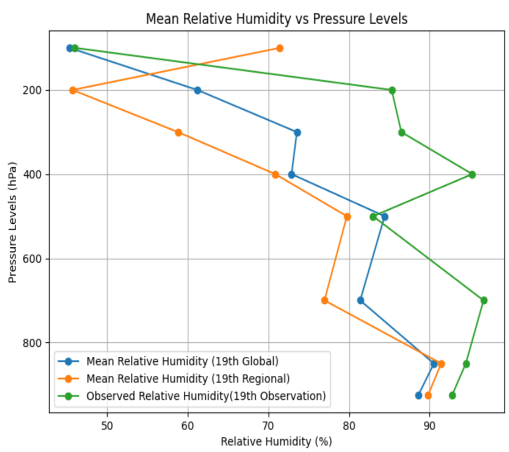
4. Forecast Verification of synoptic condtions during Monsoon depression

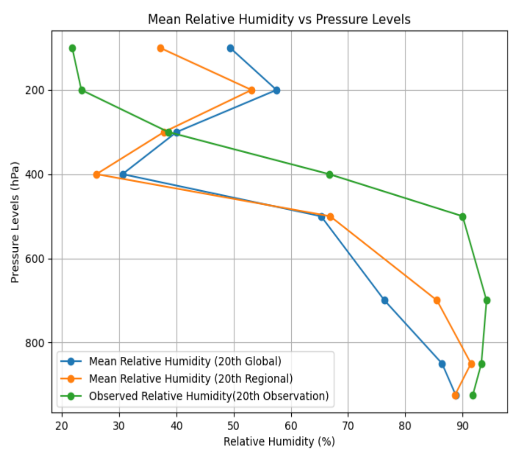
Figure 4. presents relative humidity (RH) and temperature profiles mean over a region (regional as well as Global datasets are taken) from the NCUM Global (NCUM-G) and Regional (NCUM-R) models, compared with observational data over a region, for August 19th and 20th, 2023, provide insights into the vertical atmospheric structure during a monsoon depression. The RH profiles reveal distinct differences between the two models and the observations across pressure levels. On August 19th, the NCUM-R model generally aligns more closely with observational data compared to the NCUM-G model, particularly near the surface and upper levels (200 hPa). However, both models exhibit notable deviations in the mid-troposphere (400–600 hPa), where the observed RH is higher than forecasted values. A similar pattern was observed on August 20th, reaffirming that the regional model is quite comparable in capturing RH distributions at various pressure levels. This suggests the NCUM-R model has an advantage in representing the finer-scale processes critical to monsoonal dynamics.

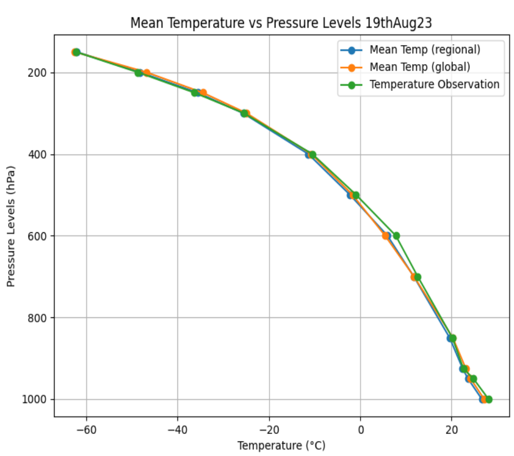
The mean temperature profiles over the regions in Figure 4, is essential for evaluating atmospheric stability, demonstrate a consistent decrease in temperature with height, indicative of the atmospheric lapse rate. Both the NCUM-G and NCUM-R models closely follow the observed temperature lapse rate from 1000 hPa to 400 hPa, reflecting accurate model performance in the lower and middle troposphere. Minor deviations are evident near 200 hPa, where both models slightly underestimate temperatures compared to observations. This could highlight potential biases in the representation of radiative cooling or vertical mixing processes within the upper atmosphere.

Atmospheric stability, indicated by the lapse rate, is a key determinant of weather phenomena such as convection and cloud formation. A stable atmosphere is characterized by a lapse rate smaller than the adiabatic lapse rate, whereas an increased lapse rate suggests instability conducive to stronger convection. The alignment of the NCUM-G and NCUM-R temperature profiles with observed data demonstrates the models' capability to accurately capture vertical temperature gradients, essential for predicting weather phenomena such as cyclones, thunderstorms, and cloud development.

Overall, the analysis highlights the superior performance of the NCUM-R model in capturing RH profiles and the comparable performance of both models in representing temperature profiles, with minor discrepancies in the upper troposphere. These results underscore the importance of such evaluations in identifying biases and improving model physics to enhance forecasting accuracy for synoptic-scale weather systems like monsoon depressions.







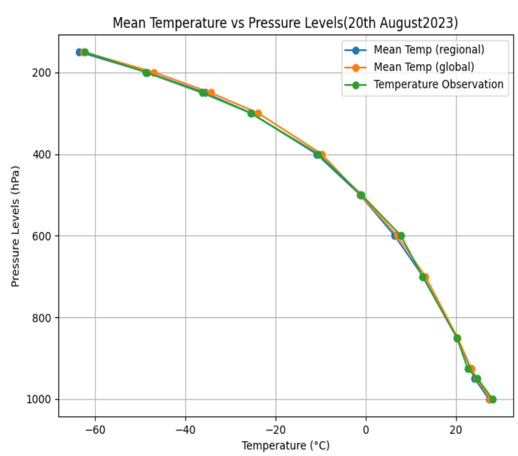


Figure 4. Mean RH and Temperature Profiles for 19th&20th August 2023 with their observational comparison.

A comparison of the biases in RH (top panel) and temperature (bottom panel) is presented in Figure 5 between the model forecasts (NCUM-G and NCUM-R) and observations for August 19th and 20th, 2023, across various pressure levels. Bias is computed as the difference between the model forecast and observed values, with positive bias indicating overestimation and negative bias representing underestimation.

The RH bias plots for the NCUM-G (RH Bias 1) and NCUM-R (RH Bias 2) reveal distinct patterns at different pressure levels. For August 19th, NCUM-G exhibits a positive RH bias in the lower troposphere (surface to 700 hPa), reaching up to 25%. As altitude increases, the bias fluctuates between 10% and 30% in the mid-troposphere (500–700 hPa). From 500 to 200 hPa, the bias is positive, indicating overestimation of RH. On August 20th, similar patterns are observed, with a positive bias of around 22% near the surface, decreasing gradually in the mid-troposphere. However, from 300-200 hPa the bias is negative which indicates an underestimation of RH. The bias in NCUM-R model is smaller than NCUM-G from surface till 500hPa. However, the bias is higher in the mid-tropospheric levels (500-200 hPa) and ranges from 10 to 20%, suggesting an overestimation of RH compared to observations. These biases highlight the challenges in accurately representing moisture processes at different altitudes, with the NCUM-R generally overestimating RH more significantly than the NCUM-G.

The temperature bias analysis from the NCUM-G and NCUM-R models for August 19th and 20th reveals notable differences in their ability to capture vertical temperature gradients compared to observations. In the lower troposphere (surface to 700 hPa), the NCUM-G model consistently exhibits a negative bias, underestimating temperatures, while the NCUM-R alternates between positive and negative biases, generally showing better alignment with observations at these levels. In the mid-troposphere (700 to 500 hPa), both models display periods of positive bias, indicating overestimation, but the NCUM-R performs slightly better, particularly on August 19th, where biases are smaller. In the upper troposphere (500 to 200 hPa), both models exhibit a consistent negative bias, underestimating temperatures, with the NCUM-G showing slightly larger deviations than the NCUM-R. These biases highlight areas where model improvements are necessary, especially in the upper troposphere, as inaccuracies in temperature representation can impact the simulation of atmospheric stability, cloud formation, and thermodynamic processes during significant weather events like monsoon depressions. Additionally, the alternating positive and negative biases observed in NCUM-R reflect its adaptability in capturing diverse atmospheric conditions, showing the model's strengths in providing valuable insights. Meanwhile, NCUM-G continues to offer consistent and reliable performance, complementing the regional model as well, fine-tuning is needed in specific layers to improve accuracy further. Overall, while both models demonstrate reasonable performance, the NCUM-R shows a slightly better capability in capturing the vertical temperature structure, particularly in the mid and lower troposphere, aiding in a better understanding of thermodynamic processes during monsoon depressions. The analysis showcase that both the NCUM-R and NCUM-G are robust and complimentary models each offering unique strengths. In this case NCUM-R is able to comparably well to predict relative humidity and temperature patterns in the lower and middle troposphere as compared to NCUM-G. The temperature and relative humidity biases visualized in Figure 5. reveals that while both Models (NCUM-G and NCUM-R) exhibit biases in upper troposphere, still they share comparable features which can be used for a strong comparable analysis in weather forecasting. NCUM-G and NCUM-R provides unified framework, towards different aspects of atmospheric processes, and facilitates a more detailed and refined understanding of the dynamics of monsoon depressions. The RH and temperature biases shows that model improvements in upper tropospheric humidity and the temperature inaccuracies can be improved on taking the more elaborated study with one complete season or taking more cases of depression which could lead to significant enhancements in forecast accuracy specially in middle and UTH which affects atmospheric stability and cloud formation and another atmospheric dynamics during significant weather events.

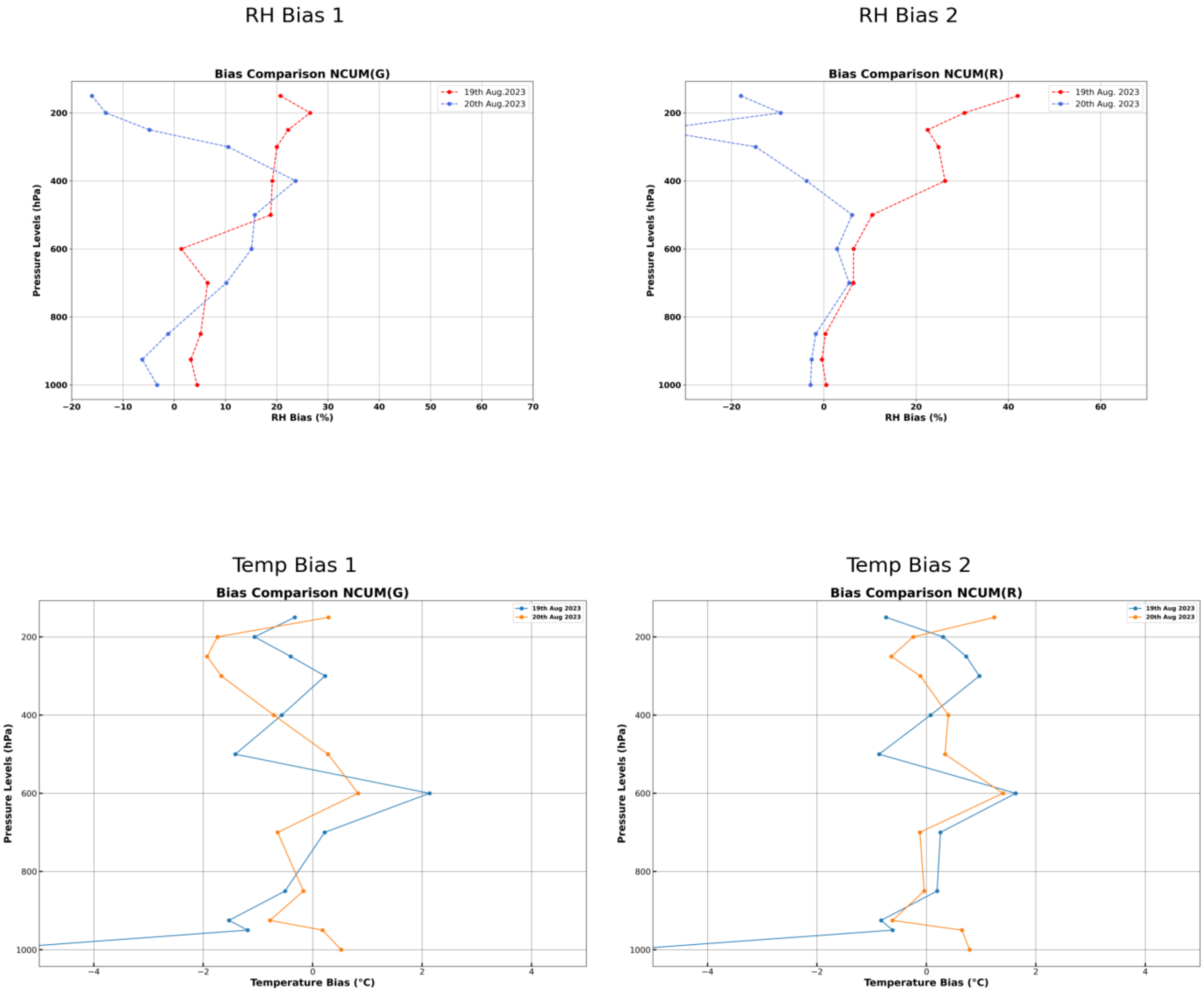


Figure 5. Represents the RH bias and Temperature bias for NCUMG NCUMR for the 19th -20th August 2023(RH bias1 -20 to70, RH Bias2 -20 to 60) (Temp Bias1&Bias2 -4 to 4).

Figure 6. Time series for Day1 Day2 Day3 FCST for NCUMG, NCUMR &Observation at 300 hPa.

Analysis of Day 1 Forecast (Figure 6a)

The time series plot of relative humidity (RH) at 300 hPa from August 10th to 25th, 2023, illustrates the performance of NCUM-G and NCUM-R in comparison with observed values. The 300 hPa level is critical for understanding moisture transport and cloud formation, directly impacting weather systems during monsoon depressions (Holton, 2004; Wallace & Hobbs, 2006).

• **Variability in RH**: Significant peaks and troughs in RH are observed throughout the period. Both models capture the general trend but differ in accuracy at specific points.

• **Early Period (August 10th–12th)**: Between August 10th and 11th, both models follow the observed RH trend, though they overestimate on August 11th and underestimate on August 12th.

• **Mid-Period (August 13th–19th)**: An overestimation of RH is noted on August 14th for both models. On August 17th, a sharp RH decrease is captured by NCUM-R but overestimated by NCUM-G. During the monsoon depression (August 17th–19th), observed RH peaks at 75% and 85%, with NCUM-G and NCUM-R slightly underestimating these values.

• **Late Period (August 20th–25th)**: A significant RH drop from August 20th onward is well-aligned with observations by NCUM-G, while NCUM-R shows some overestimation. Both models demonstrate recovery by August 21st, though from August 23rd to 25th, both models show poor alignment, with overestimation of RH values.

Analysis of Day 2 Forecast (Figure 6b)

Figure 6b. presents the Day 2 forecast of RH, comparing NCUM-G, NCUM-R, and observed values. This forecast highlights subtle differences in model performance.

- **General Trends**: Both models capture the overall trends, with NCUM-G showing a closer match to observations.
- **Over- and Underestimation**: NCUM-G overestimates RH on August 11th, 14th, and from August 23rd to 25th. NCUM-R, in contrast, underestimates RH on most days except August 14th and 20th.
- **Monsoon Depression Period (August 18th–20th)**: A spike in RH is observed on August 19th, with observed values reaching 85%. Both models follow this upward trend but underestimate the peak. On August 20th, RH decreases significantly, with NCUM-G showing a sharper decline compared to NCUM-R, reflecting rapid moisture condition transitions during this period.
- **Late Period (August 21st–25th)**: Both models predict a steady RH recovery, with NCUM-G closely aligning with observations. However, after August 22nd, NCUM-G overestimates RH, while NCUM-R underestimates, except on August 24th and 25th, where NCUM-R aligns better with observations.

Analysis of Day 3 Forecast (Figure 6c)

The Day 3 forecast of RH at 300 hPa, as shown in Figure 6c, highlights the challenges of predicting RH during dynamic weather events like monsoon depressions.

- **Monsoon Depression Peak (August 19th)**: A significant divergence occurs on August 19th, with both models underestimating the observed RH peak. NCUM-R displays larger underestimations compared to NCUM-G.
- **Post-Depression Period (August 20th–25th)**: Following a sharp decrease in RH on August 20th, NCUM-G aligns well with observed data, while NCUM-R shows greater variability. Both models recover in RH values from August 21st onward, with NCUM-G demonstrating a more stable trend. However, NCUM-R continues to exhibit larger fluctuations, particularly during the recovery phase.

5. Summary & Conclusions:

Relative Humidity (RH) is a critical atmospheric parameter that influences key processes such as cloud formation, precipitation, and temperature regulation. During monsoon depressions, RH plays a pivotal role in determining the extent and intensity of cloud cover and rainfall, particularly in the upper troposphere where moisture dynamics are crucial for weather system development. In this analysis, we have evaluated the capability of global (NCUM-G) and regional (NCUM-R) Numerical Weather Prediction (NWP) models in predicting vertical profiles of relative humidity (RH) and temperature during the period of a monsoon depression over Bhopal from August 17^{th} to 20^{th}, 2023. This study focuses on analyzing RH and temperature as they are key prognostic variables influencing cloud formation, precipitation, and overall atmospheric dynamics during significant weather events. Some salient conclusions based on this study are presented below:

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1. RH biases from NCUM-G and NCUM-R reveal systematic overestimations in the lower troposphere and mixed biases in the mid and upper troposphere. NCUM-R, while performing better in the lower levels, tends to overestimate RH in the mid-troposphere.

2. Temperature biases show that both models accurately represent the lower and middle troposphere temperature profiles but underestimate temperatures at higher altitudes (500–200 hPa). This underestimation may impact the simulation of atmospheric stability and cloud dynamics during monsoon depressions.
3. The Day 1, Day 2, and Day 3 RH forecasts reveal that NCUM-G consistently shows a better match with observations compared to NCUM-R, particularly during the peak of the monsoon depression on August 19th.
4. NCUM-R shows higher variability and occasional significant underestimations, especially during dynamic weather transitions like the rapid RH drop on August 20th. However, both models demonstrate improved alignment with observed RH during the recovery phase from August 21st to 25th, indicating better post-event performance.
5. Both models exhibit difficulties in accurately representing RH and temperature at upper tropospheric levels (300–200 hPa), particularly during dynamic transitions such as those associated with monsoon depressions. This suggests a need for enhanced parameterization schemes for moisture transport and radiative processes in the upper troposphere.

Further expanding the study into more elaborate analysis, covering the entire JJAS season over multiple years, and analyzing additional atmospheric parameters, such as vertical wind profiles and CAPE will enhance the understanding of moisture transport processes. A season-long study would allow for better understanding of the models' ability to capture inter-annual variability and refine moisture dynamics, which are crucial for improving forecast accuracy during monsoon depressions and other significant weather events.

6. Author Contributions

Shubha Singh conceptualized the research idea for taking up the study, performed all data analysis, generated computational plots, and prepared the original draft. Kondapalli Niranjan K. and Anumeha Dube provided critical reviews and offered technical insights with their vast & valued research experience to improve the report draft. Mohan T. S. contributed by reviewing and refining specific sections of the manuscript. John P. George, Saji Mohandas, and V. S. Prasad provided expert guidance throughout the study and reviewed the final version of the report. Together with the valuable efforts of all the experienced person this final draft could be brought in shape to be published.

Acknowledgement: I would like to acknowledge Ms. Shivali Gangwar for her invaluable assistance whenever I encountered challenges in my computational work.

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