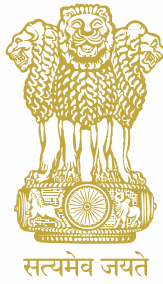


राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केन्द्र
**NATIONAL CENTRE FOR MEDIUM RANGE
WEATHER FORECASTING**

पृथ्वी विज्ञान मंत्रालय, भारत सरकार
MINISTRY OF EARTH SCIENCES, GOVERNMENT OF INDIA



वार्षिक रिपोर्ट
ANNUAL REPORT
2024 - 2025

Annual Report: 2024-25

Published by National Centre for Medium Range Weather Forecasting (NCMRWF),
Ministry of Earth Sciences (MoES)

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FOREWORD

It is with great pride and enthusiasm that we present the Annual Report 2024-25 of the National Centre for Medium Range Weather Forecasting (NCMRWF). This report highlights our commitment to advancing numerical weather prediction (NWP) through cutting-edge research, technological innovations, and operational excellence. Over the past year, NCMRWF has significantly enhanced its forecasting capabilities, strengthened collaborations, and embraced emerging technologies like Artificial Intelligence (AI) and Machine Learning (ML) to improve prediction accuracy. Our vision remains steadfast in providing state-of-the-art numerical weather guidance, ensuring societal benefits through improved forecasting of high-impact weather events. This year marks a major milestone—30 years of excellence in operational NWP since our first forecast in 1994.

Advancements in kilometer-scale Earth system modeling, refined convective parameterization schemes, and urban modeling have greatly improved predictive capabilities across diverse geographical scales. We have also strengthened extreme weather guidance through the Hurricane Analysis and Forecasting System (HAFS) and enhanced the global ocean analysis-forecast system for more accurate atmospheric and oceanic predictions. Our research has also focused on AI/ML applications, leading to advancements in AI-driven weather forecasting, radar-based nowcasting using U-Net, and precipitation downscaling models. In parallel, we have prioritized forecast verification, model diagnostics, and tailored dissemination of forecast products. The implementation of a structured pricing policy for NWP data has further streamlined dissemination.

Infrastructure improvements have been another key focus. We engaged Central Public Works Department (CPWD) to maintain office and residential buildings and enhance horticultural development. A complete overhaul of our office fire-fighting system has also been initiated. A landmark achievement has been the successful testing of the World Meteorological Organization (WMO)-WIS 2.0 framework for observational data transfer, strengthening global data-sharing capabilities. Additionally, we have taken a strategic leap into cloud computing by subscribing to the National Government Cloud (NGC). A key milestone of 2024-25 was the inauguration of the 22.4 PetaFLOPS supercomputing systems, 'Arunika & Arka,' by the Prime Minister of India. This acquisition, the largest within our ministry this year, along with the deployment of cloud-based services, has significantly strengthened our computational infrastructure.

Collaboration remains a cornerstone of our success. Strengthening partnerships with national and international meteorological agencies, formalizing Memorandums of Understanding (MoUs), and promoting stakeholder engagement have augmented our research and operational capabilities. Training programs, workshops, and knowledge-sharing initiatives continue to empower the next generation of meteorologists and researchers. The BIMSTEC Centre for Weather and Climate (BCWC) has played a vital role in promoting regional cooperation and resilience against weather extremes.

Looking ahead, our strategic initiatives will focus on further integrating AI/ML into research and operational forecasting, optimizing ensemble prediction systems, and advancing NWP science. The coming years promise transformative developments in NWP, aligning with our mission to provide accurate and timely forecasts for national safety and well-being. As we navigate the dynamic landscape of NWP science, I extend my sincere gratitude to the dedicated scientists, researchers, and technical staff at NCMRWF for their unwavering commitment. I also acknowledge the continued support of the Ministry of Earth Sciences (MoES) and our valued collaborators in shaping the future of weather and climate prediction.

Dr V. S. Prasad
Head, NCMRWF

ANNUAL REPORT 2024-25

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VISION & MISSION

VISION STATEMENT

“Seamless Prediction of Weather and Climate for the benefit of the Society”

The vision of the NCMRWF is to provide seamless weather and climate predictions using mathematical models that benefit society. This involves integrating advanced scientific methods and technologies to deliver accurate and reliable forecasts across all scales. By focusing on precision and continuity, the vision aims to support informed decision-making, enhance preparedness for weather and climate risks, and contribute to societal resilience and sustainability.

MISSION STATEMENT

“Continuously develop advanced numerical weather prediction systems, with increased reliability and accuracy over India and neighbouring regions through research, development and demonstration of new and novel applications, maintaining highest level of knowledge, skill and technical bases.”

The objective of the centre is to enhance the accuracy and reliability of NWP systems for India and neighbouring regions. This involves:

- Advancing research and development in weather and climate modelling.
- Demonstrating innovative applications for improved forecasting capabilities.
- Continuously updating technical knowledge and skills to maintain excellence.
- Addressing societal needs by providing precise and actionable weather and climate insights.

RESEARCH AND DEVELOPMENT

The Research & Development (R&D) section highlights the advancements made in numerical weather prediction (NWP) over the past year. Efforts have focused on improving the integration of new observational data, refining forecast models, and adopting innovative technologies such as Artificial Intelligence and Machine Learning (AI/ML). These developments aim to enhance forecasting accuracy, operational capabilities, and the ability to address complex weather phenomena effectively. The R&D initiatives highlight the commitment to strengthening predictive systems and supporting informed decision-making in the face of evolving climate and weather challenges.

a. Observation Processing

The NCMRWF Observation Reception, Processing, and Monitoring (NCObsProM) system has achieved significant advancements in observation reception, processing, and monitoring, enhancing both global and regional Numerical Weather Prediction (NWP) systems. The observation network has expanded with increased reception of conventional and remote sensing data from global sources, supported by enhanced bilateral agreements for timely sharing. Key additions include data from advanced remote sensing instruments such as NOAA-21 ATMS and CrIS radiances, the scatterometer sea surface winds from Oceansat-3 and HY-Scat missions. Decoders were updated to efficiently process these datasets, ensuring their accurate assimilation into NWP systems.

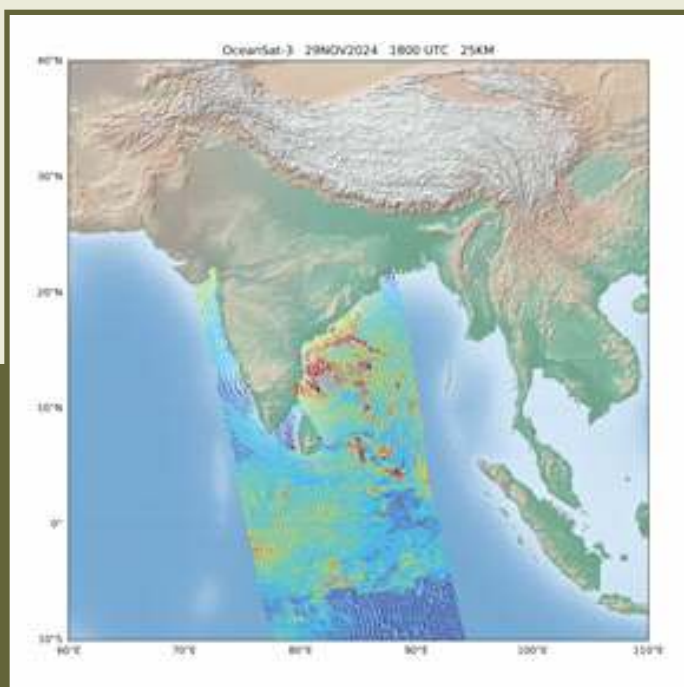


Figure 1: Oceansat-3 Scatterometer derived sea surface winds at 18 UTC of 29 November 2024. Tropical cyclone Fengal located near the coast of Tamil Nadu and Pondicherry is seen in the observation.

Technological improvements feature the integration of advanced open-source software like the NCEP BUFR decoder, ECcode, and AAPP for real-time decoding and efficient data assimilation. This has been complemented by the inclusion of multispectral and hyperspectral radiances and GNSS-RO, significantly improving the simulation accuracy. Furthermore, GNSS-ZTD/IPW data from the Survey of India (SoI) and FY-3E satellite data have been incorporated, enhancing capabilities in tropical wind monitoring. Automated monitoring system manages six-hourly assimilation cycles, supplemented by time-series analyses to maintain data quality and coverage. The development of new capabilities for processing Indian DBNet data has also enabled enhanced cyclone simulations. With a strong focus on quality control, routine observation monitoring and feedback to providers like IMD ensure data integrity and reliability.

Validation experiments have demonstrated the high quality of Oceansat-3 Scatterometer winds, which are comparable to its predecessors. Figure 1 illustrates Oceansat-3 Scatterometer-derived winds at 18 UTC on November 29, 2024, during Cyclone “Fengal” near the Tamil Nadu coast. Observing System Experiments (OSEs) are currently being conducted to evaluate the impact of these datasets, particularly during cyclone seasons.

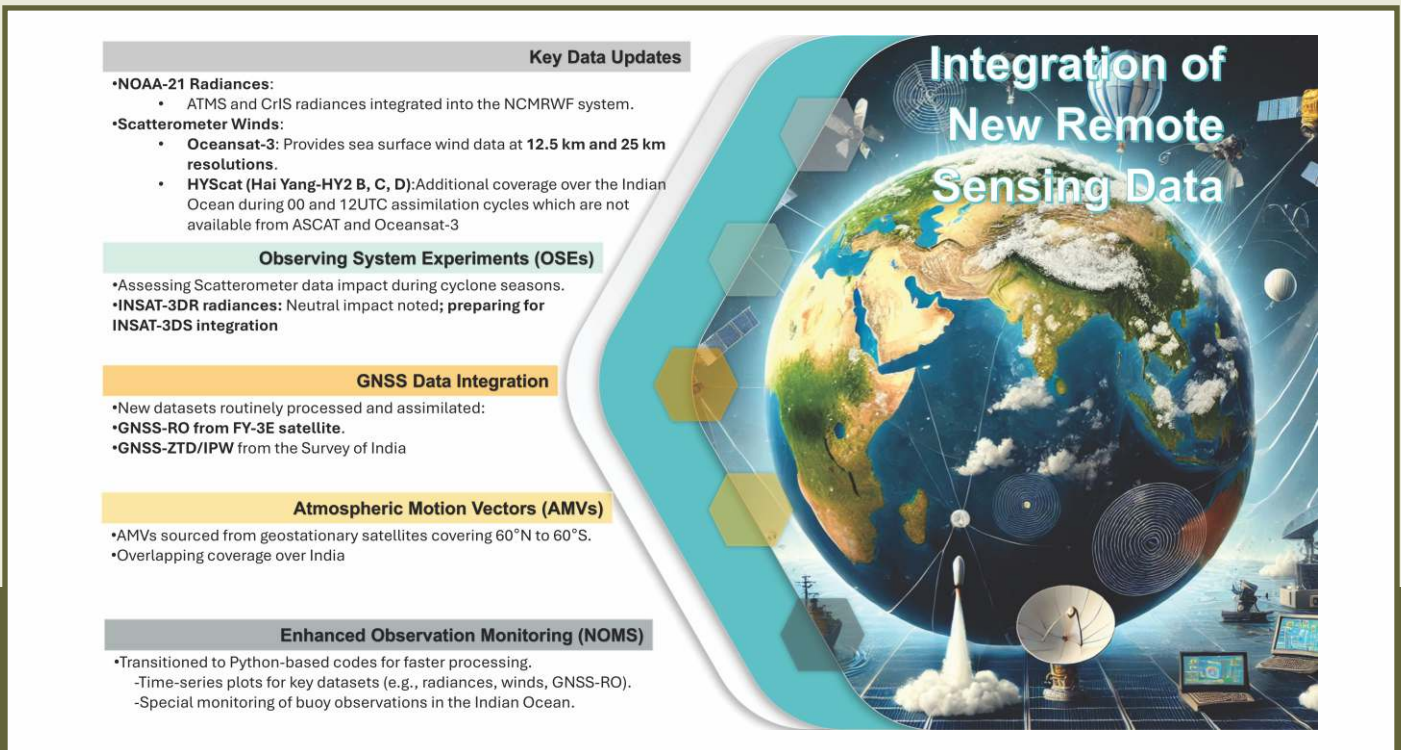


Figure 2: Schematic illustrating the advanced remote sensing data integrated into NCMRWF Analysis-Forecast System.

Further advancements include the integration of radiance observations from the third-generation Indian geostationary meteorological satellite INSAT-3DR into the NCMRWF Global Forecast System (NGFS) and NCMRWF Unified Model (NCUM). This advanced satellite features a 19-channel multi-spectral sounder payload, comprising 18 narrow spectral channels in the shortwave infrared, middle infrared, and longwave infrared regions, along with one visible channel. The mid-wave water vapor channels, with wavelengths of 7.44, 7.03, and 6.53 μm , were specifically utilized in the study to analyze moisture at low, mid, and upper levels.

NCMRWF has also modernized its observation monitoring system (NOMS) by transitioning to Python-based tools, enabling faster processing and enhanced visualization of observational data. Monthly reports on geostationary satellite-derived Atmospheric Motion Vectors (AMVs) and other critical observations are now routinely published and linked to global intercomparison platforms. These advancements support the continuous enhancement of weather prediction accuracy and ensure system preparedness for future observational datasets.

b. Data Assimilation Advancements

NCMRWF has made significant progress in data assimilation (DA) techniques to enhance NWP capabilities. NCMRWF's DA systems integrate millions of observations from global sources daily to generate high-quality analyses of the atmosphere, ocean, sea ice, and land. These analyses serve as the initial conditions for the global and regional NWP models for NCMRWF and MoES sister organizations. The operational global DA system employs the Hybrid 4D-Var approach, which combines variational and ensemble methods to incorporate flow-dependent background information. This method addresses the limitations of the conventional 4D-Var system by utilizing ensemble forecasts to include day-to-day variations in weather characteristics. Currently, a 22-member global ensemble forecast from the Global Ensemble Forecasting System is used routinely in the Hybrid 4D-Var DA system. Over the years, this system has undergone continuous refinement, resulting in enhanced forecast accuracy.

(i) Coupled Data Assimilation

Recognizing the critical role of air-sea interactions and land-atmosphere coupling in weather prediction, NCMRWF has successfully developed and tested a Coupled Data Assimilation (DA) system, marking a significant milestone in enhancing medium-range weather forecasts. The system integrates multiple components—atmosphere, ocean, sea ice,

and land—through a weakly coupled DA framework, with each component employing specialized DA techniques tailored to its unique requirements, as illustrated in Figure 3.

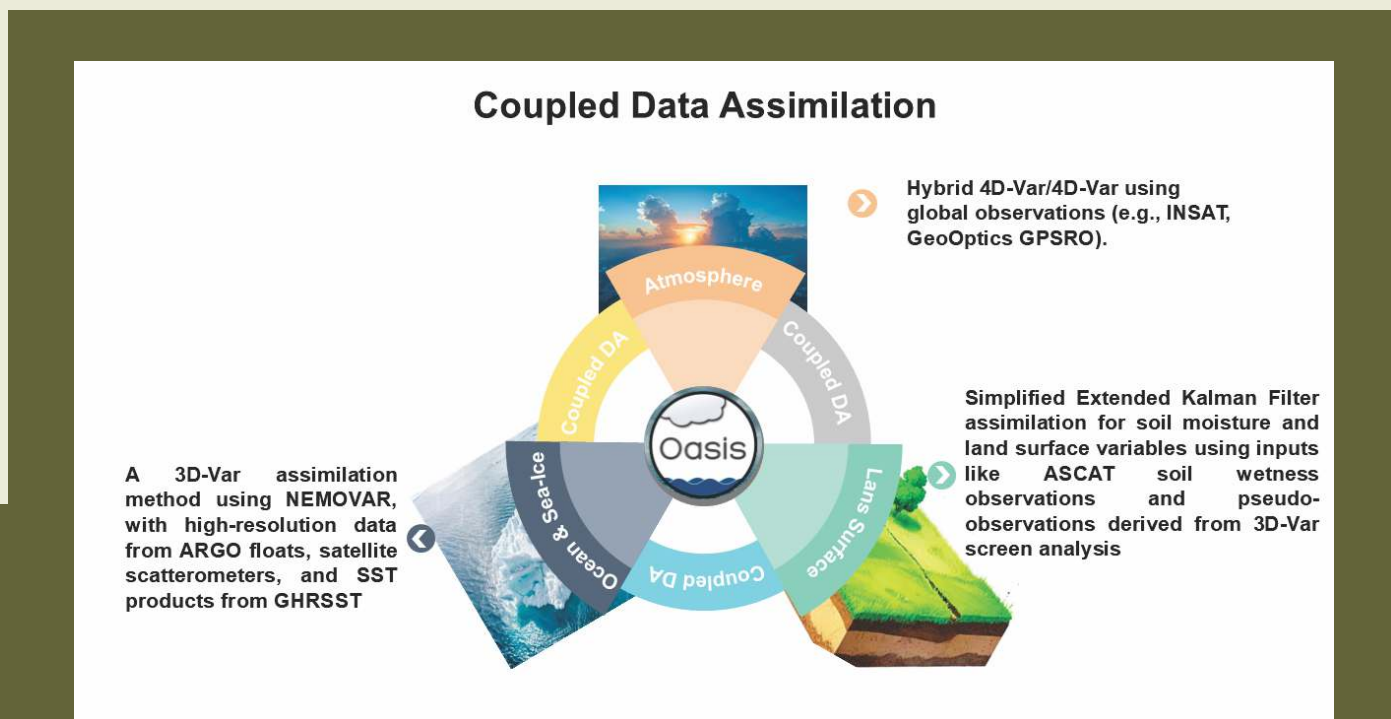


Figure 3: Schematic illustrating the various components of Earth system augmented to the NCMRWF coupled data assimilation system

The Coupled Global Assimilation-Forecast System (CNCUM-G) incorporates advanced atmospheric, land surface, ocean, and sea ice models to deliver accurate global weather predictions. The atmospheric component uses the Unified Model (version 11.9) with a 10 km horizontal resolution, 70 vertical levels extending up to 80 km, and a 4-minute step, employing Incremental 4D-Var for data assimilation. For land processes, soil moisture analysis uses the Simplified Extended Kalman Filter, assimilating ASCAT soil wetness data and pseudo-observations from 3D-Var screen analysis. The ocean and sea ice components are modeled using the NEMO model (version 3.6) with a $\frac{1}{4}^\circ$ resolution, 75 vertical levels, and a 20-minute time step, employing 3D-Var FGAT (NEMOVAR) for assimilation. Information exchange between the components occurs hourly via the OASIS3 coupler. The system employs science configurations—GA8.0 (Global Atmosphere), GL9.0 (Global Land), GO6.0 (Global Ocean), and GSI8.1 (Global Sea Ice)—to optimize simulation accuracy. Preliminary results from experimental forecasts demonstrate promising improvements in forecast skill, particularly for rainfall prediction over the Indian region, as discussed in Section 2c.

(ii) INSAT-3DR Radiance Assimilation

The assimilation of radiance observations from India's third-generation geostationary meteorological satellite, INSAT-3DR, into the NCMRWF Global Forecast System (NGFS) has initiated. Assimilation experiments were conducted for April 2024 with 6-hourly updates using the NGFS model to evaluate the impact of INSAT-3DR data. Figure 4 illustrates the frequency of observations received and assimilated during the month. Only 0.3% of the total observations passed the quality control checks for assimilation.

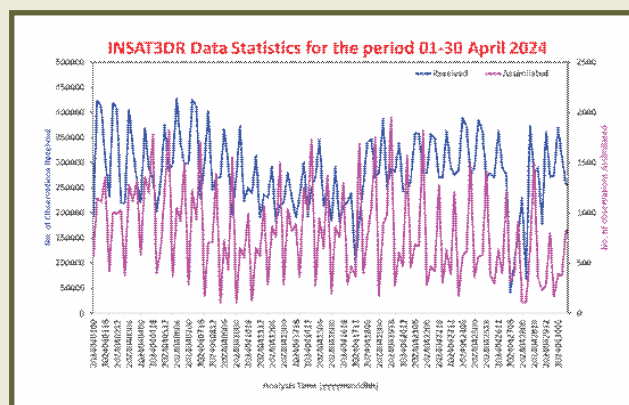


Figure 4: Frequency of INSAT-3DR data received and assimilated in NGFS

Statistical analyses were performed on observation frequency, bias, root mean square error (RMSE), standard deviation, and scatter plots. Figure 5 shows the bias in the background (without bias correction), with bias correction, and in the analysis (with bias correction) for low-level moisture on 18 UTC, 19 April 2024. The spatial distribution highlights a significant reduction in error, with the mean bias decreasing from 0.58°C in the background to 0.03°C in the analysis. RMSE calculations reveal improvements of 20%, 62%, and 54% for low, mid, and upper-level moisture channels, respectively, when comparing the bias-corrected analysis to the bias-corrected background.

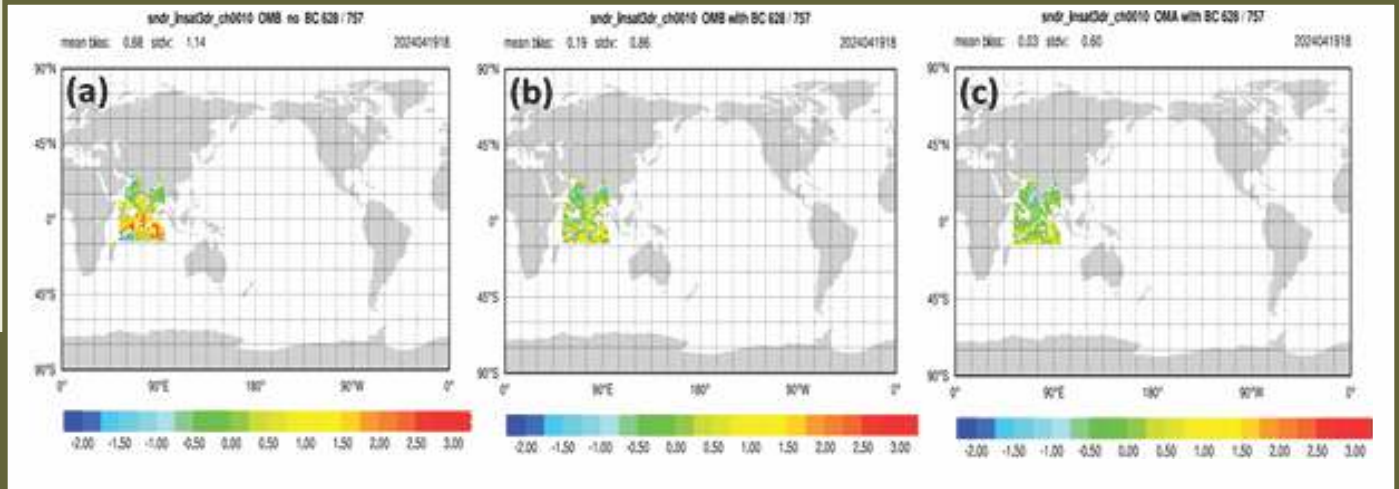


Figure 5: Bias in the (a) background without bias correction, (b) background with bias correction, (c) analysis with bias correction

Figure 6 presents scatter plots of observations and background (without and with bias correction) and analysis for low-level moisture on 18 UTC, 19 April 2024, showing notable improvements in analysis accuracy. This initial analysis indicates that assimilating INSAT-3DR observations positively impacts the global analysis field and model forecasts. Daily and monthly statistics confirm that bias correction significantly enhances the analysis field across all assimilated channels, reducing errors to a range of -2 to +2 K.

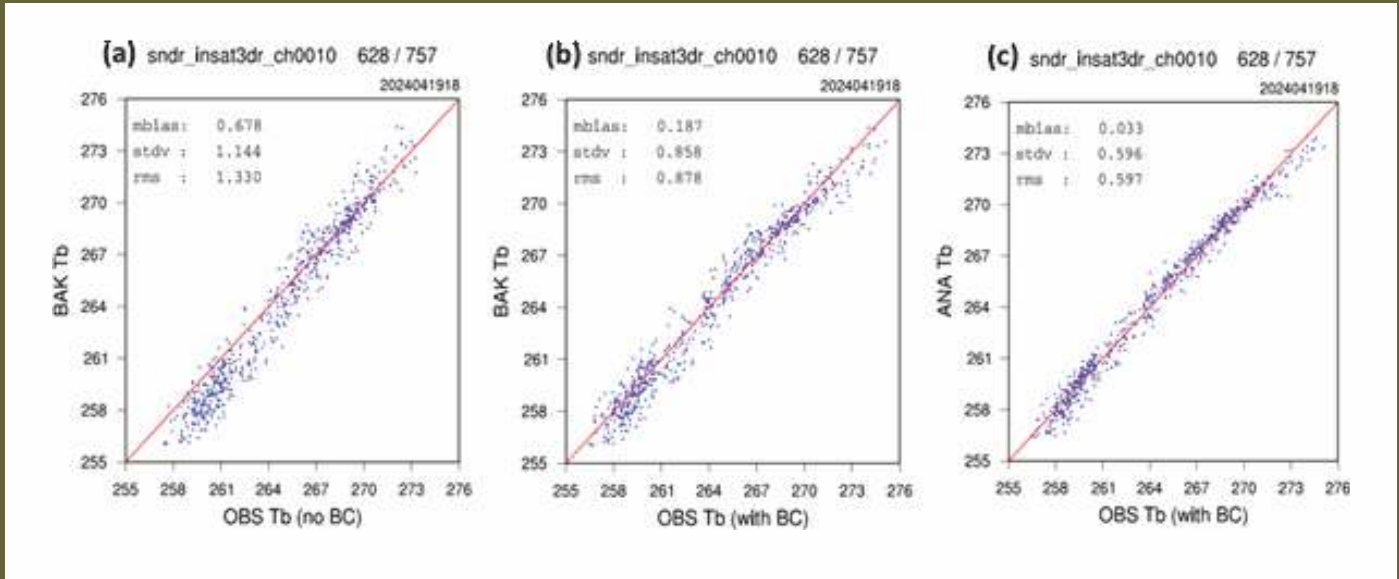


Figure 6: The scatter plot between the observation and background without bias correction, with bias correction and analysis for low-level moisture at 18UTC 19April 2024.

(iii) A hybrid four-dimensional ensemble variational data assimilation approach

The operational Ensemble Prediction System at the Global scale in NCMRWF (NEPS-G) provides flow-dependent forecast error information to the deterministic data assimilation system. At present, NEPS-G uses an Ensemble

Transform Kalman Filter (ETKF) method to generate perturbations in its initial conditions. As part of the NEPS-G upgrade roadmap, NCMRWF is exploring four-dimensional variational data assimilation (4DEnVar), an ensemble-based alternative to 4DVar. Further, efforts are underway to implement a hybrid four-dimensional ensemble variational data assimilation approach for each perturbed ensemble member (En-4DEnVar). This advanced system will assimilate the same observations as hybrid 4DVar while enabling the inclusion of additional data. Preliminary integration of the En-4DEnVar based NEPS-G system has been successfully tested on the current High-Performance Computing (HPC) system. With additional computational resources required, detailed testing and potential operational deployment are planned for the next advanced HPC system.

c. Model Developments

NCMRWF employs a seamless and integrated modeling framework (Figure 7) to provide reliable forecasts across multiple spatial and temporal scales. The global deterministic model underpins medium-range weather predictions, while the regional model enhances the resolution and accuracy of localized forecasts. Urban-scale modeling addresses the unique challenges of forecasting in densely populated regions, such as heat islands and air quality issues. The ensemble prediction system (EPS) delivers probabilistic forecasts, improving the predictability of extreme weather events. Additionally, coupled models for subseasonal-to-seasonal (S2S) predictions enhance the representation of ocean-atmosphere interactions, crucial for understanding monsoon variability and extremes at longer lead times. Experimental advancements, including kilometer-scale modeling, a regional cloud NWP model, and a global coupled NWP model, aim to refine the representation of fine-scale atmospheric processes, cloud dynamics, and coupled interactions. This section provides an overview of NCMRWF’s advancements and activities across its diverse modeling systems, emphasizing their scientific and operational significance.

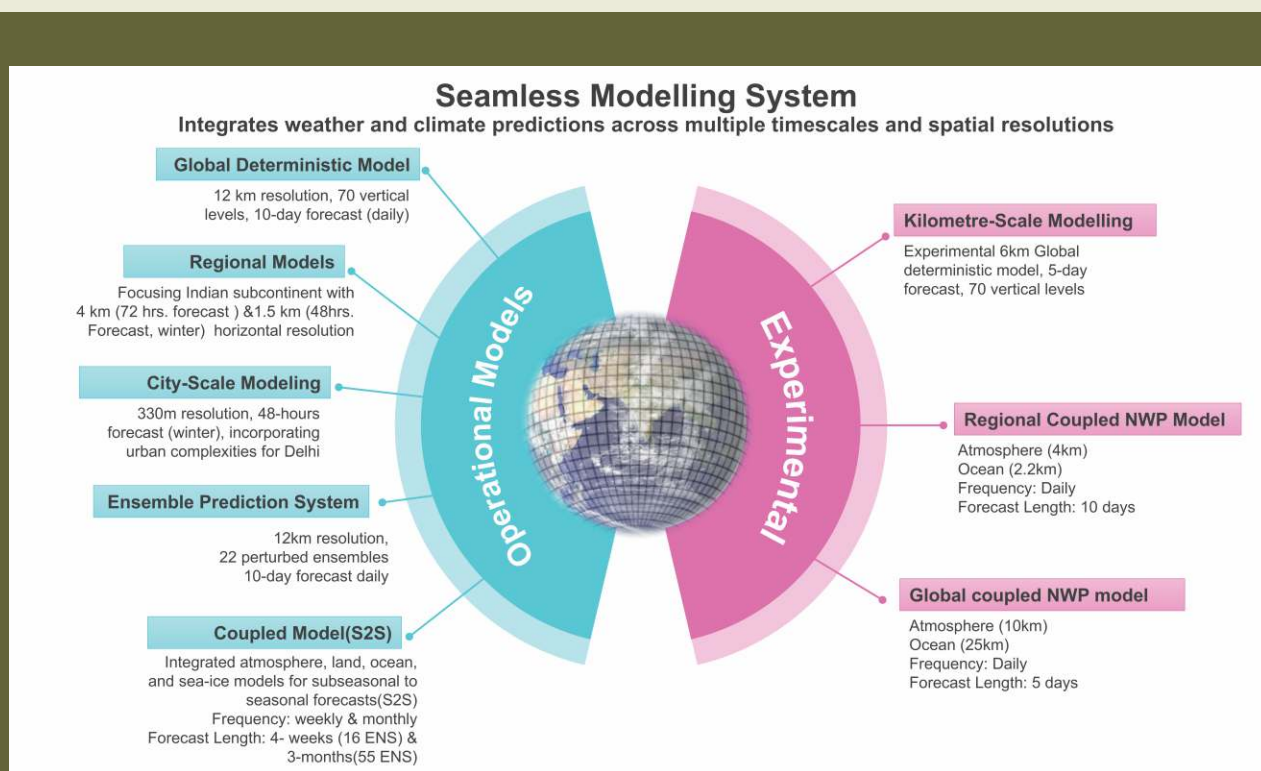


Figure 7: Schematic illustrating the seamless modelling system operational with experimental developments at NCMRWF

(i) Advancements in Kilometer-Scale Modelling of the Earth System

The NCMRWF’s 6km global model, based on the UK Met Office Unified Model (UM), employs a high-resolution grid (N2048E) with 4096 longitude points and 3072 latitude points, achieving an effective spatial resolution of 6km. The model

features 70 vertical levels extending up to 80km, using the ENDGame dynamical core for efficient atmospheric simulations. Ancillary fields crucial for defining the grid, orography, and surface characteristics were developed using datasets like Global Land One-km Base Elevation (GLOBE) v1, Harmonised World Soil Database (HWSD), and MODIS, processed via Ancillary Tools and Suites (ANTS) software. Vegetation and surface parameters were derived from IGBP and MODIS data, aligning with the Joint UK Land Environment Simulator (JULES) framework. The model employs GA7 physics with the UM version 10.8, providing 5-day forecasts with a 3-minute timestep. Performance optimization ensures computational efficiency, with sensitivity analyses guiding the configuration. Key ancillary datasets include climatologies for SST, sea ice, ozone, and aerosols, ensuring comprehensive environmental representation. The model setup aligns with the GA7 configuration and the PS43 operational suite, optimized for monsoon forecasting.

NCMRWF also evaluated the impact of convection representation on NCUM-6G performance, focusing on small-scale deep convection. Global NWP models, particularly in the "grey zone" (scales ~10 km), face challenges in balancing explicit and parameterized convection. Using the Unified Model Convection Scheme 5A, simulations compared control (CTRL) conditions with parameterized convection against explicit convection (EXPL) conditions where parameterization was disabled. The results highlight improvements in capturing precipitation and convection processes at fine resolutions (Figure 8).

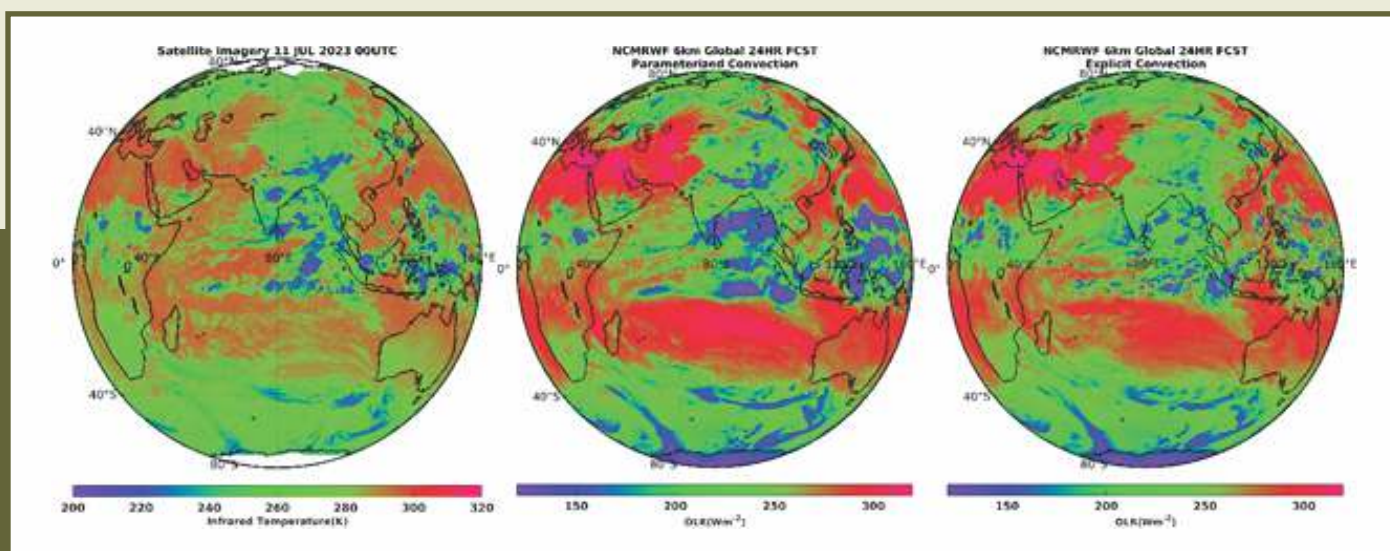


Figure 8: (Left) Gridded infrared imagery at 00 UTC on 11 July 2023. (Middle) 24-hour forecast of outgoing long-wave radiation (OLR) for 00 UTC on 11 July 2023 from the global 6 km NCUM model with parameterized convection. (Right) Same as the middle panel but for the explicit convection experiment.

(ii) Progress in Coupled NWP System

The implementation of the coupled NCMRWF Unified Model Global (CNCUM-G) NWP system represents a major advancement in operational weather forecasting. Developed under the "UM Partnership" framework, CNCUM-G seamlessly integrates atmospheric, land surface, oceanic, and sea ice components to deliver high-resolution global weather forecasts. This system utilizes the Unified Model (Version 11.9) for atmospheric simulations, operating at a 10 km horizontal resolution with 70 vertical levels, and employs incremental 4D-Var data assimilation to effectively incorporate diverse observational data. The CNCUM-G system differs significantly from its parent UM coupled system, particularly in observation pre-processing. NCMRWF has developed an indigenous pre-processing framework to handle atmospheric, oceanic, sea ice, and land observations received through GTS and other sources, including INSAT satellite data and GeoOptics GPSRO observations. These inputs are processed into the "obstore" format, facilitating rigorous quality control and subsequent assimilation. The data assimilation system in CNCUM-G employs a weakly coupled approach. Atmospheric data are assimilated using 4D-Var methods while ocean and sea ice data utilize 3D-Var, and land data are handled by the Extended Kalman Filter (EKF). The system incorporates advanced scientific configurations, including Global Atmosphere (GA8.0), Global Land (GL9.0), Global Ocean (GO6.0), and Global Sea Ice (GSI8.1), with seamless

hourly coupling achieved through the OASIS3 coupler. Experimental forecasts using CNCUM-G are executed on the NCMRWF HPC system, ensuring high computational efficiency.

The performance of CNCUM-G during an extreme rainfall event highlighting its capabilities against uncoupled NCUM-Global (NCUM-G) configuration is presented here. Figure 9 illustrates the observed and model's simulated rainfall event over Himachal Pradesh and Uttarakhand on July 10, 2023. The observed accumulated rainfall, based on IMD+NCMRWF merged data, is shown in Figure 9 (a, e). Forecasts from the NCUM-G Atmospheric model for Day-1, Day-3, and Day-5 are presented in Figures 9(b-d), while those from CNCUM-G are shown in Figures 9(f-h). The spatial distribution and intensity of rainfall in CNCUM-G is accurately captured in the Day-1 forecast, outperforming the uncoupled configuration. Additionally, rainfall forecasts at longer lead times exhibit improved accuracy in the coupled system compared to the uncoupled configuration. Importantly, the CNCUM-G forecasts demonstrate better representation of both the spatial structure and intensity of rainfall, further solidifying its advantage in predicting complex weather phenomena over longer lead times. More simulations with advanced verification diagnostics are planned in the near future to further evaluate the performance of the coupled system and its ability to predict mean states and high-impact weather events.

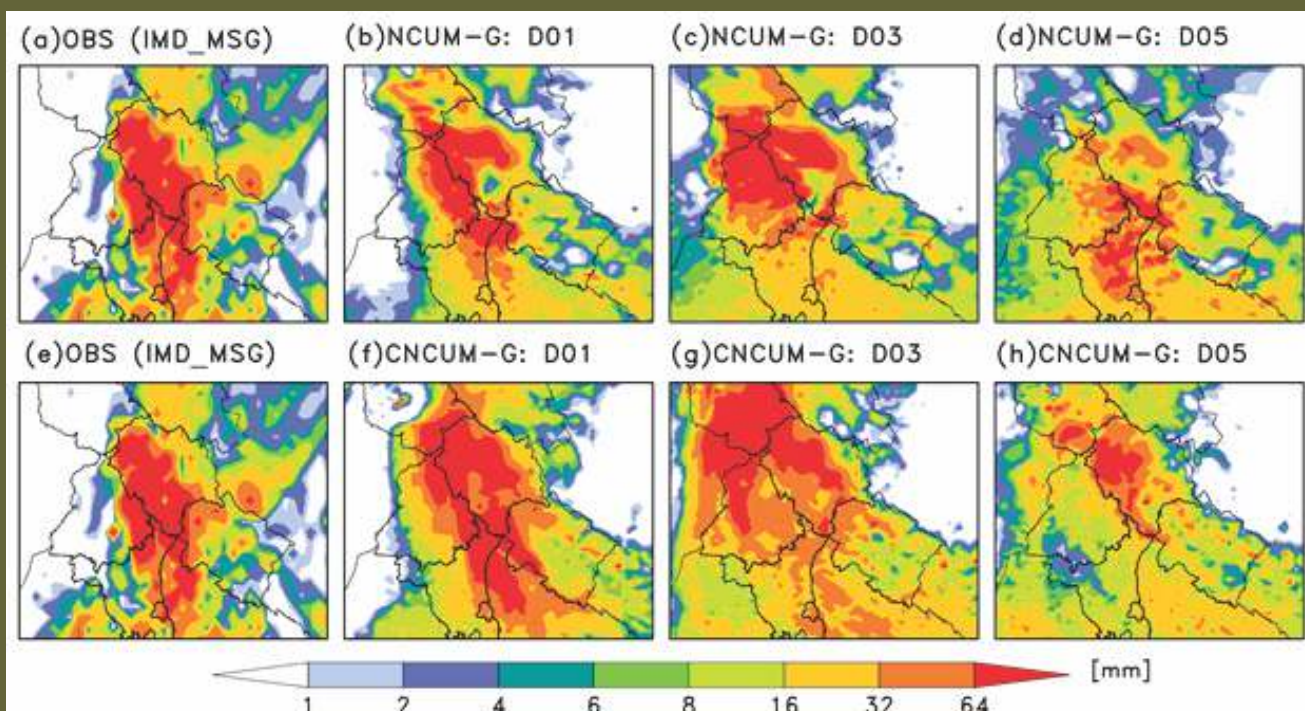


Figure 9: (a, e) Observed rainfall from IMD+NCMRWF merged data; (b-d) NCUM-G model forecasts for Day-1, Day-3, and Day-5; (f-h) Corresponding forecasts from the coupled NWP model.

(iii) Advances in Convective Parameterization for Global Operational Models

The Global NCUM model has achieved significant advancements in convective parameterization with the introduction of the GA8 (Mass Flux Scheme) and preliminary Met Office convective parametrization scheme (CoMorph-A), both of which were evaluated during the 2024 monsoon season. GA8 represents an upgrade to the mass-flux convection parameterization, designed to improve the representation of deep and shallow convection by explicitly accounting for entrainment and detrainment processes. This scheme enhances the simulation of convection dynamics across multiple scales, leading to reduced biases in short-range precipitation forecasts, particularly over the west coast, and improved statistical skill scores relative to its predecessor, GA7.

CoMorph-A, a scale-aware convection scheme, introduces a novel approach to parameterizing convection by enabling buoyant ascent from multiple atmospheric levels and supporting the coexistence of plumes within a single grid box. This flexibility allows CoMorph-A to better capture interactions between convective processes and large-scale atmospheric dynamics. CoMorph-A also showed enhanced performance in medium-range forecasts, particularly in regions beyond the west coast, although its skill scores at specific rainfall thresholds require further refinement. However, some issues related to the convection intermittency, and convective memory are improved in the GA8 mass-flux convection scheme.

Comparative analysis during the monsoon season revealed that GA8 outperformed both GA7 and CoMorph-A in short-range forecasts, especially over the west coast, while CoMorph-A showed strengths in medium-range forecasts and other regions (Figure 10). These developments highlight the ongoing efforts at NCMRWF to refine convective parameterization schemes, enhancing the predictive capabilities of the Global NCUM model for critical weather phenomena such as monsoon-related convection.

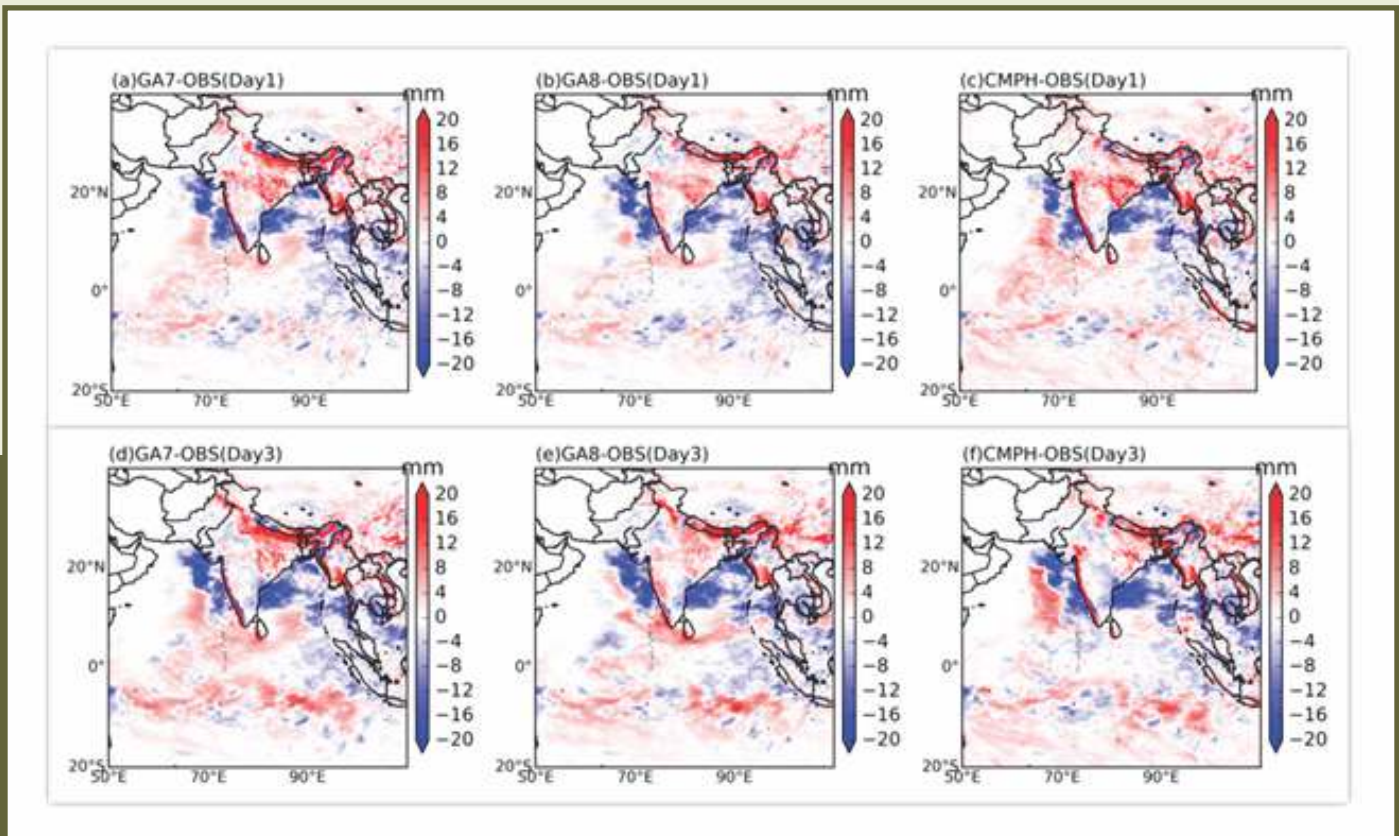


Figure 10: Spatial map of mean biases computed against GPM observations for Day-1 model simulations (a) GA7; (b) GA8 and (c) CoMorphA and Day-3 simulations (d) GA7; (e) GA8 and (f) CoMorphA

(iv) High-Resolution Land Use and Land Cover for the Indian Region

A Regional Ancillary Suite (RAS) generates ancillary files for NCUM-R and the high-resolution DM-Chem model. Previously, RAS utilized Climate Change Initiative (CCI) data with 300m resolution. However, a high-resolution Land Use Land Cover (LULC) dataset with 56m source resolution (ISRO-LULC) was developed in collaboration with the Indian Institute of Remote Sensing (IIRS), ISRO.

Key improvements include:

- Upgraded RAS suite to process ISRO-LULC data in partnership with the UK Met Office
- Higher resolution vegetation distribution compared to CCI data

Figure 11 illustrates the enhanced detail in vegetation patterns between CCI and ISRO-LULC datasets, highlighting the importance of high-resolution data for accurate land cover representation. This upgrade demonstrates the potential for improved model performance through better representation of land surface characteristics, which is crucial for regional climate modeling and environmental studies.

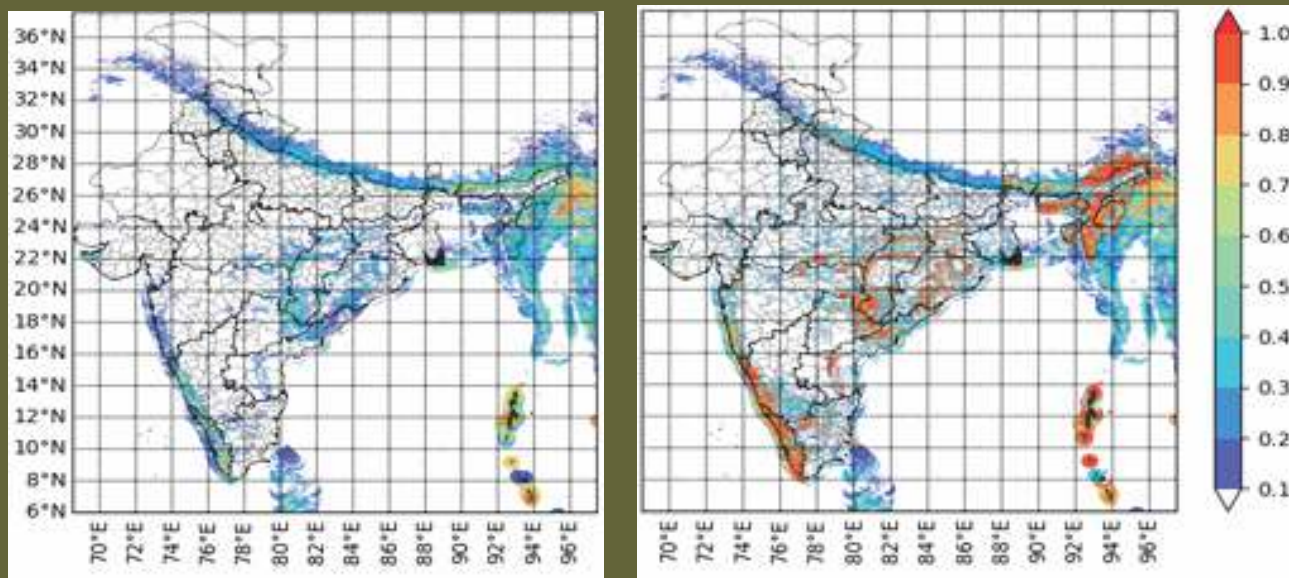


Figure 11: Vegetation distribution from (a) CCI and (b) ISRO-LULC.

(v) Urban Modelling Studies

The Met Office Reading Urban Surface Exchange Scheme (MORUSES) has been operational in the Delhi fog model since 2022, utilizing local urban data. Recognizing India's diverse urban landscapes, Bhubaneswar, a planned city, was selected to examine the impact of urban data in contrast to unplanned Delhi. A high-resolution (330 m) model configuration, based on the Unified Model, was developed for Bhubaneswar, akin to the Delhi fog model. The MORUSES scheme was implemented using high-resolution urban morphology data specific to Bhubaneswar, with the ISRO-LULC dataset for land use and land cover. Figure 12 highlights the near-surface temperature performance of the 330 m model across various Bhubaneswar locations. Results confirm that integrating ISRO-LULC data with the MORUSES scheme delivers promising outcomes. This study underscores the potential of MORUSES for advanced urban modeling within the NCUM-R model framework.

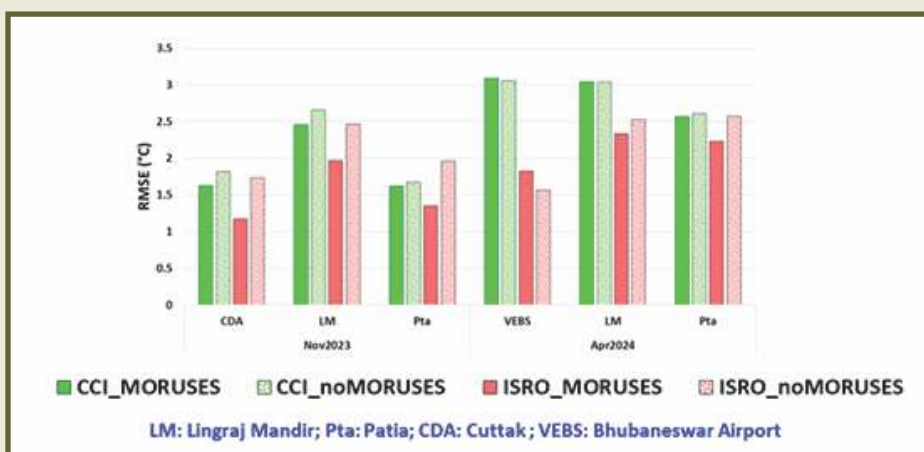


Figure 12: Near-surface temperature performance of the 330 m model across various locations in Bhubaneswar

(vi) Operational Weather Forecasting System for Amarnath Yatra

During the 2024 Sri Amarnathji Yatra period, the Amarnath Model (AM) was operationally run over the Amarnath Yatra domain with a 1.5km resolution. On August 12, 2024, heavy rainfall prompted the suspension of the Amarnath Yatra along the Baltal route (34.26, 75.41). The AM model successfully predicted this event, demonstrating its effectiveness in forecasting critical weather conditions that impact important religious pilgrimages.

The model's performance was evaluated against observations, revealing several key strengths:

- Accurate prediction of rainfall in the Baltal area one day in advance.
- Precise representation of rainfall distribution over slopes and identification of heavy rainfall hotspots.
- Successful capture of peak rainfall maxima and timing in time series verification at the Baltal location.

These results in Figure 13 showcase the Amarnath Model's capability to provide high-resolution, localized weather forecasts in complex terrain regions. Its ability to predict critical weather events makes it a valuable tool for managing and planning religious pilgrimages, potentially saving lives and resources.

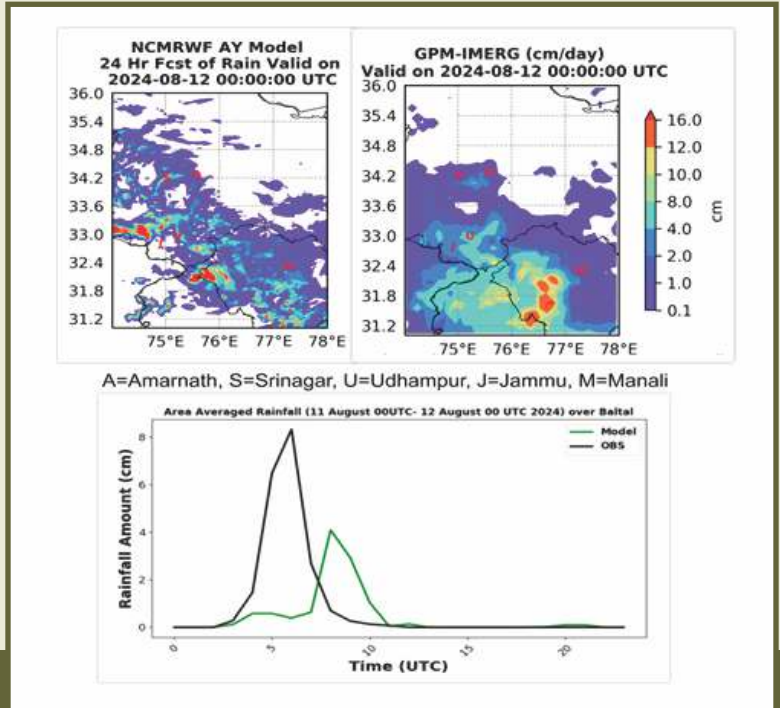


Figure 13: The daily rainfall (cm/day) and its diurnal variability are compared between IMERG and AM model run from 00Z 11 August 2024. Panels a and b show analysed and predicted daily rainfall and c shows the hourly rainfall at Baltal sea (shown as red circle). Locations of Amarnath (A), Srinagar (S), Udhampur (U), Jammu (J) and Manali (M) are also marked

(vii) Improved Lightning Forecasting Scheme in the NCMRWF Global Model

Accurately forecasting lightning remains a significant challenge in NWP models. Lightning is a complex phenomenon influenced by various atmospheric processes, making its representation in global models inherently difficult. The NCMRWF Global Model employs the Price and Rind (1992, hereafter PR92) lightning parameterization scheme, which estimates lightning flash count based on empirical relationships with cloud-top height. However, the original PR92 scheme tends to overestimate lightning flash counts spatially and quantitatively compared to observations from the IITM Lightning Location Network (IITM-LLN). To address these limitations, this study introduces modifications to the PR92 scheme while retaining its core empirical cloud-top height relationship. The storm identification criteria have been experimented by incorporating additional convective parameters, including cold cloud thickness, convective vertical velocity, and vertical wind. These parameters were selected based on their established roles in the dynamics of convective storms and their ability to enhance the physical realism of parameterization.

In the final revised PR92 scheme, storm regions are identified within model columns where the vertical wind exceeds 0.25 m/s during October-April and 0.5 m/s during May-September, reflecting seasonal variations in convective activity. Additionally, the cold cloud thickness—calculated as the difference between the -40°C isotherm level and the 0°C level—must fall within the range of 5.5–12 km. These thresholds were determined through sensitivity tests and empirical validation, ensuring they capture the dynamic nature of convective storms effectively.

The revised scheme demonstrates significant improvements in both the spatial and quantitative accuracy of lightning predictions compared to the original implementation in the NCUM-G model (Figure 14). For example, biases in flash counts were reduced, and the spatial distribution of lightning activity aligned more closely with observations from IITM-

LLN. These enhancements emphasize the potential of integrating physically consistent convective parameters into lightning parameterization schemes. The enhanced PR92 scheme highlights the importance of combining empirical approaches with dynamic convective diagnostics to improve lightning forecasting in global models. Future work will focus on further refining the parameterization through additional observational constraints and expanding its application to other regions and weather systems.

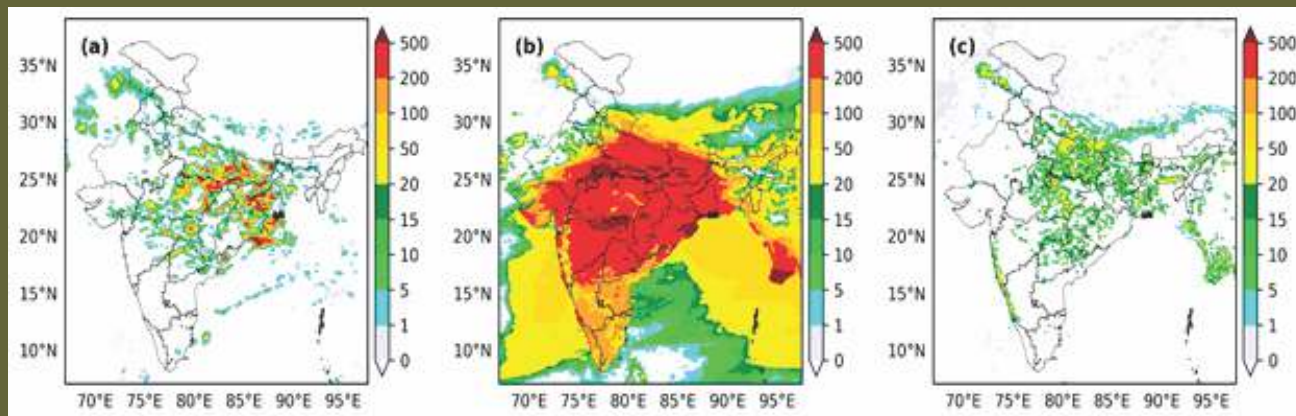


Figure 14: Flash counts on 20230714 obtained from (a) LLN observation (b) Offline calculation (c) Revised Pr92

(viii) Advanced Cloud Microphysics in Regional Model

The study demonstrates how advanced cloud microphysics schemes can significantly improve tropical cyclone track forecasts by accurately representing complex microphysical processes and their impact on large-scale atmospheric dynamics. The track forecast of Tropical Cyclone (TC) 'Vayu' was improved using a double moment microphysics scheme called Cloud AeroSol Interacting Microphysics (CASIM) and a Bimodal (BM) cloud fraction scheme. The model with CASIM and BM (RA3) showed better predictive skills than the previous operational version (RA2T) in forecasting the recurved cyclonic track.

Key factors contributing to this improvement include:

- Ice production processes in CASIM
- Better vertical distribution of liquid water content due to improved coupling of turbulence in mixed-phase clouds by BM
- Modified potential vorticity (PV) tendency associated with latent heating distribution

These factors altered the beta drift effect, driving TC recurvature as observed. The PV field distortion caused by diabatic heating within the TC influenced environmental steering winds, affecting TC motion. The primary reason for differing movements between experiments lies in the cloud pressure rebalancing term in the BM scheme, which altered lower tropospheric heating profiles. When combined with enhanced ice processes in CASIM, this produced distinct characteristics in latent heating and PV tendencies, modifying internal vortex symmetry. Figure 15 illustrates the environmental steering flow at 500hPa from IMDAA reanalysis, RA3, and EXP2, showing the eastward location of EXP2 compared to RA3. This explains the eastward push in the TC track and subsequent landfall falsely predicted by EXP2.

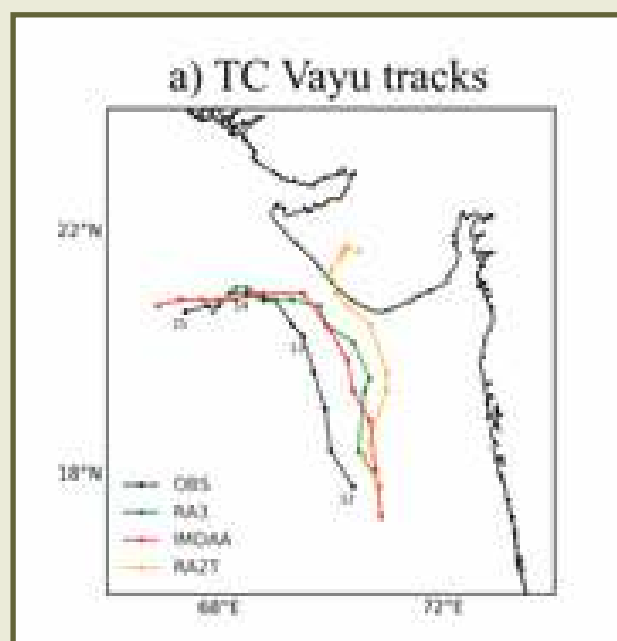


Figure 15: a) Vayu cyclone tracks (12-15 June 2019) from IMDAA compared against RA3 and RA2T versions of NCU-M-R along with the observed (OBS) track.

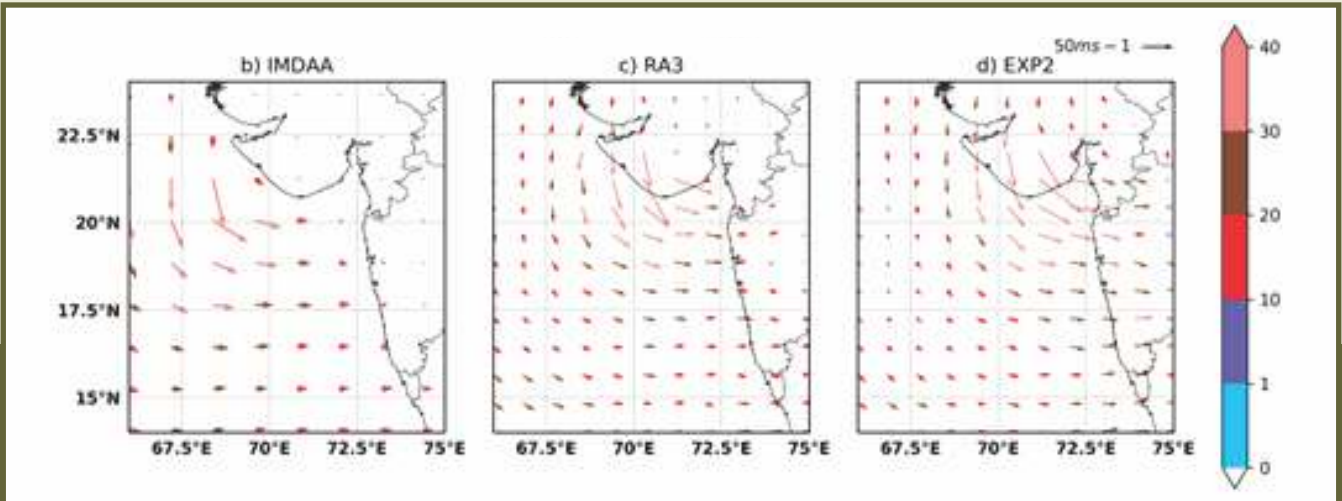


Figure 15: The environmental flow (ms-1) at 500 hPa from (b) IMDAA reanalysis, and the two experiments (c) RA3 and (d) EXP2 are valid for 18 UTC of 13th June 2019.

(ix) Optimizing Ensemble Size & Resolution in NEPS-G

Ensemble Prediction Systems (EPSs) are valuable tools in weather forecasting, enabling the quantification of uncertainty in predictions. The NEPS-G, a global EPS model operational at NCMRWF, runs at a 12 km resolution with a lagged ensemble of 22 perturbed members (from the 00 and 12 UTC cycles). Enhancing horizontal resolution and increasing ensemble size are crucial for improving EPS performance. However, optimizing the system configuration requires balancing computational efficiency with forecast accuracy. To assess the impact of ensemble size, a study tested configurations with 7, 13, 19, 24, 31, 37, and 44 members using recent modeling upgrades at a 20 km resolution over the Indian domain during a two-week period. Preliminary results (Figure 16) show that forecast skill improves with larger ensemble sizes.

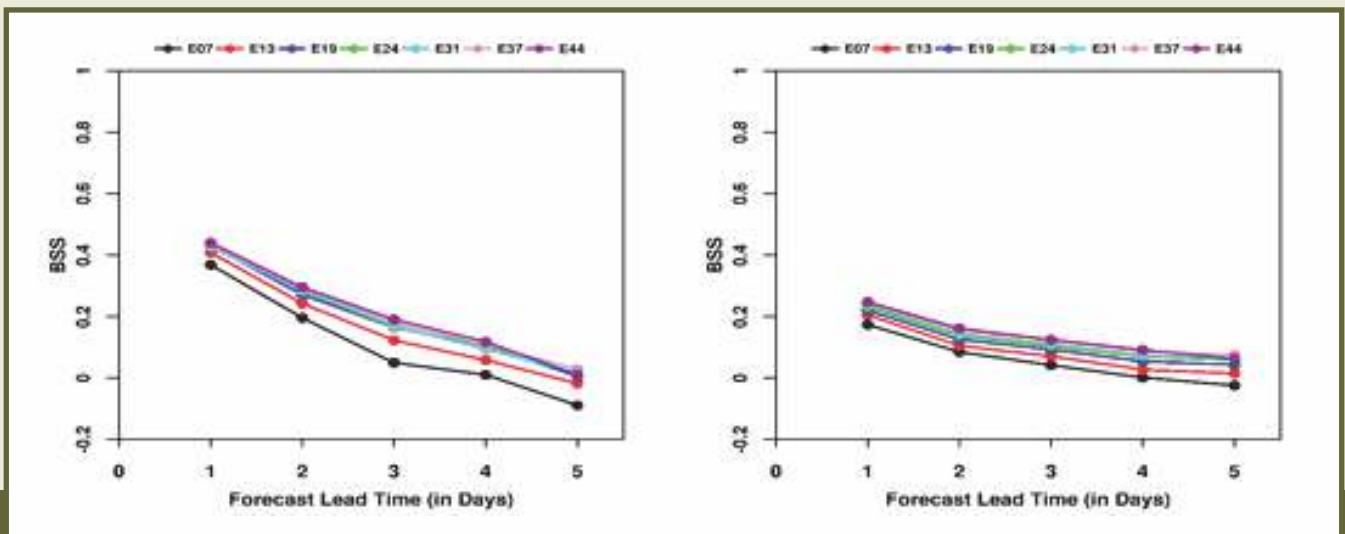


Figure 16: Brier skill score for temperature at (left) 200 hPa and (right) 850hPa calculated with respect to the sample climatology for threshold greater than 1 standard deviation. Skill score has been shown for the ensemble sizes 7, 13, 19, 24, 31, 37, & 44 perturbed members.

To extend this work and optimize computational resources at NCMRWF, a new experiment was conducted. The global ensemble was simulated at 12 km resolution for the first 5 days and truncated to 20 km for the remaining 5 days. All 10-day forecasts used a 22-member ensemble for the 00 UTC cycle, evaluated against the current operational setup with 11

perturbed members over a one-month period. Early results (Figure 17) suggest that increasing ensemble size enhances spread across lead times. However, reducing resolution beyond day 5 may increase RMSE for surface variables, as seen for Mean Sea Level Pressure (MSLP) in Figure 17 (right panel).

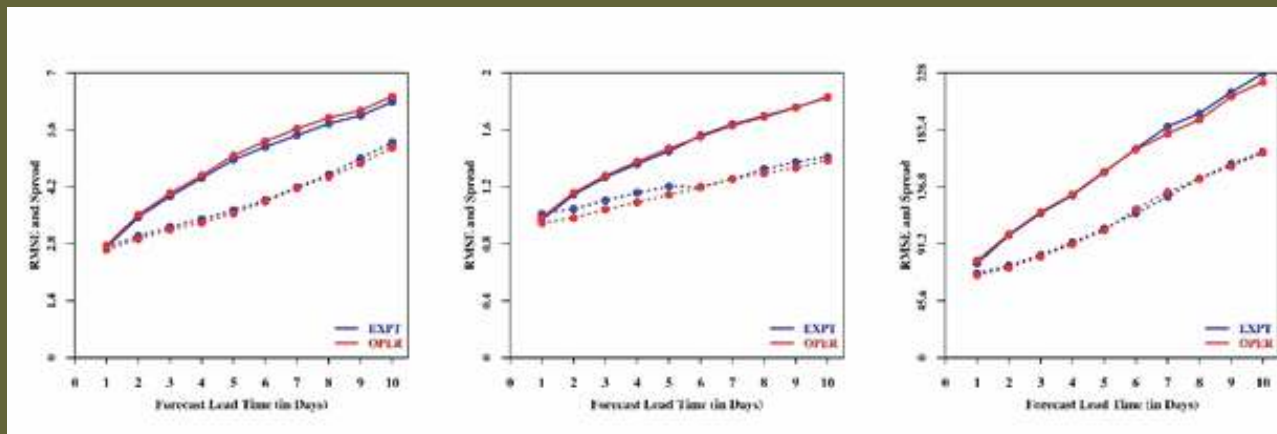


Figure 17: RMSE and spread relationship for the variables: (left) zonal wind at 200hPa, (middle) zonal wind at 10m, and (right) MSLP. 'EXPT' refers to the experimental setup with 22 members, using a 12 km resolution for days 1–5 and a 20 km resolution for days 6–10. 'OPER' represents the current operational setup with 11 members at a 12 km resolution for all 10 days. Solid lines represent RMSE, while dashed lines indicate the spread

d. Hurricane Analysis and Forecasting System (HAFS)

The Hurricane Analysis and Forecasting System (HAFS) is an advanced, high-resolution coupled atmosphere-ocean-wave model designed for tropical cyclone (TC) research and forecasting. It provides high-resolution TC forecasts across all global tropical ocean basins and utilizes a fully compressible, non-hydrostatic dynamical core. The system supports multiple physics suites, making it a versatile tool for both operational and research applications. HAFS uses the Finite Volume Cubed-Sphere (FV3) dynamical core for its atmospheric component, while the ocean component is based on the Modular Ocean Model version 6 (MOM6). The model is configured with a 3 km resolution parent domain and a 1 km resolution moving nest over the North Indian Ocean (NIO), with 82 vertical levels. It is initialized using NCEP GFS initial and boundary conditions for the atmosphere, and the ocean component is initialized with data from the Real-Time Ocean Forecast System (RTOFS). The ocean undergoes a cold start initialized with RTOFS data.

As a test case, we have shown the simulation of Cyclone Mocha, an Extremely Severe Cyclonic Storm (ESCS), developed over the Bay of Bengal in May 2023. It reached peak intensities with maximum sustained winds of 270 km/h (165 mph), as recorded by the Joint Typhoon Warning Center (JTWC), and a minimum central pressure of 908hPa. The India Meteorological Department (IMD) recorded slightly lower values of sustained winds at 215 km/h (130 mph) and a central pressure of 938hPa. Mocha caused devastating impacts across Myanmar and parts of Bangladesh, resulting in 463 fatalities, 719 injuries, over 100 missing, and damages amounting to \$2.24 billion.

The simulation of Cyclone Mocha began at 06 UTC on May 11, 2023, and ran for 96 hours without data assimilation. Preliminary results from HAFS for Cyclone Mocha showed its ability to capture critical features, including the storm's track, intensity, rapid intensification phases, and landfall

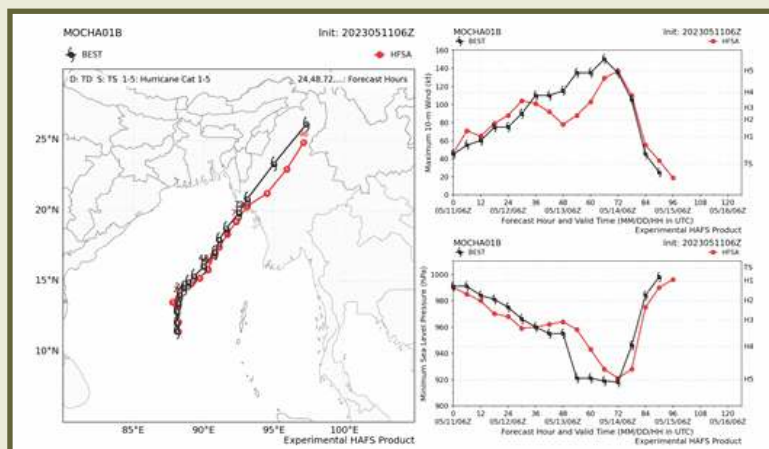


Figure 18: Track (a) and intensity forecasts; (b) Maximum 10-m Wind (kt); (c) Minimum Sea Level Pressure (hPa) for Cyclone MOCHA, initiated at 0600 UTC on 11 May 2023.

characteristics (Figure 18). The model closely matched observed maximum sustained winds and central pressure, aligning well with IMD best track data. It successfully replicated the rapid intensification phase, peak intensity, and subsequent weakening post-landfall. These results demonstrate HAFS's potential to enhance disaster preparedness by providing early and accurate predictions of cyclonic events in the North Indian Ocean. However, further validation and operational refinements are required to fully leverage the system's capabilities for future storm scenarios.

e. High-resolution global ocean analysis-forecast system

A high-resolution, eddy-resolving global ocean forecast system with ~10 km horizontal resolution (ORCA12) has been successfully configured and tested at NCMRWF using version 3.6 of the NEMO (NEMO v3.6) model and version 5.2.1 of the Los Alamos National Laboratory Community Ice Model (CICE v5.2.1). The upgraded physical models incorporate several advanced features, including a non-linear free surface (where cell thickness throughout the water column varies with time), an improved momentum advection scheme, modified freshwater input to land with enhanced vertical mixing at runoff points, a Lagrangian Iceberg Model (for tracking icebergs), and multi-layer thermodynamics.

The data assimilation system is based on a multivariate incremental three-dimensional variational first guess at the appropriate time (3DVAR-FGAT) technique, configured at a 1/4° horizontal resolution (ORCA025) using the ORCA12 model as the background. Figure 19 illustrates the spatial distribution of the background fields, including sea surface temperature (SST) and sea surface salinity (SSS), comparing the high-resolution ORCA12 configuration with the lower-resolution ORCA025 configuration used in the data assimilation system.

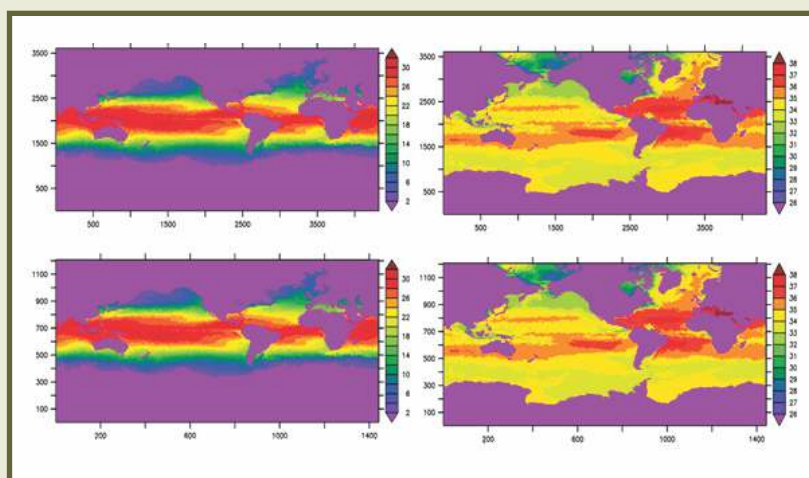


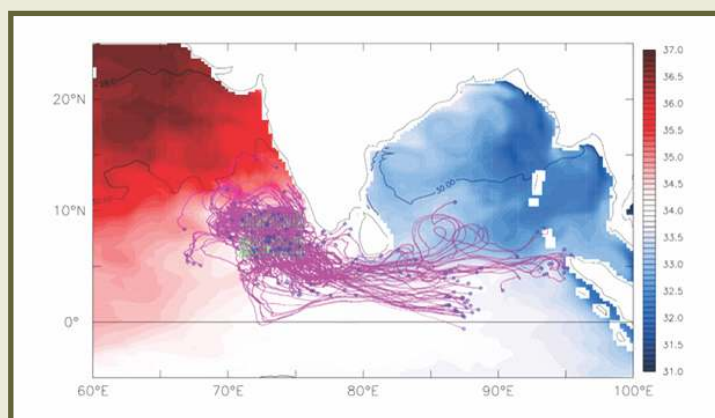
Figure 19: Spatial distribution of the model background fields (SST; left panel, and SSS; right panel) for the data assimilation system. Upper and lower panels are background fields from the ORCA12 and ORCA025 configurations.

i. 3D Ocean Pathways using Lagrangian Trajectories

Lagrangian trajectories are utilized to study three-dimensional (3D) pathways, transport, and mixing in the Indian Ocean, using daily NEMOVAR ocean analysis data generated by NCMRWF. These trajectories track virtual fluid particles through 3D, time-varying velocity fields, enabling the tracing of sources and pathways at various depths while analyzing associated temperature and salinity fields. Additionally, specialized tools have been developed using Lagrangian analysis to monitor and forecast eddy movements and ocean fronts, leveraging NEMOVAR analysis and forecast fields.

During March to May, the Indian Ocean warm pool region attains the highest sea surface temperatures globally, preceding the southwest monsoon onset. The Arabian Sea Mini Warm Pool (ASMWP), a key part of this region, is influenced by the upper ocean dynamics, which play a crucial role in forming the monsoon onset vortex. This study demonstrates that the mixing of contrasting water masses—low-salinity water from the Bay of Bengal and saltier water from the Arabian Sea—regulates the temperatures of the ASMWP, significantly impacting its dynamics (Figure 20).

Figure 20: Sea Surface Salinity averaged over the period March to May 2024 overlaid with the back trajectories of virtual particles seeded in the Arabian Sea warm pool region. Green Points are seeding points in May 2024 and blue circles are back tracked end points in Feb 2024. The 28°C and 30°C isotherms are overlaid as thick black lines.



f. Application of Artificial Intelligence and Machine Learning

NCMRWF has integrated Artificial Intelligence (AI) and Machine Learning (ML) techniques into its weather forecasting systems to enhance accuracy and efficiency (Figure 21). These advancements include AI-driven models that complement traditional NWP methods, improving the analysis of high-dimensional datasets. A notable application is radar-based nowcasting using U-Net, which facilitates precise short-term rainfall predictions by leveraging neural network architectures. Additionally, ML algorithms are employed for bias correction and downscaling, reducing systematic errors in large-scale models and enhancing regional forecast reliability. AI/ML methods are also utilized for predicting extreme weather events, such as heatwaves, and intense rainfall, by analyzing historical data and identifying patterns. These innovations significantly strengthen NCMRWF's ability to provide timely, accurate forecasts, supporting disaster preparedness and mitigation efforts.

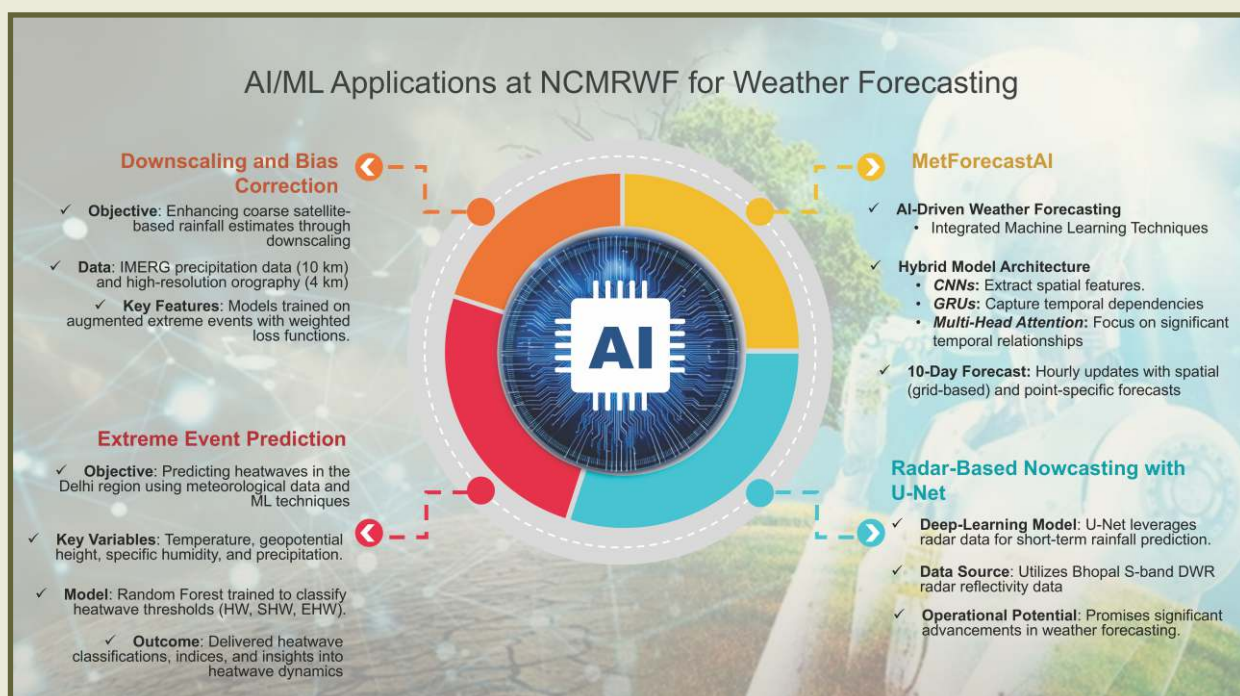


Figure 21: Schematic illustrating the activities related to the AI/ML applications for Weather Forecasting at NCMRWF

i. AI-Driven Weather Forecasting

NCMRWF has developed an AI-driven forecasting system capable of predicting key meteorological parameters, such as temperature, pressure, humidity, and wind components, offering high-resolution 10-day forecasts at hourly intervals. Initial testing focused on the Gangetic Plains, utilizing the IMDAA reanalysis dataset (2013-2023) for training and validation. The system employs machine learning techniques, including data normalization, feature engineering, and a hybrid model combining CNNs, GRUs, and Multi-Head Attention to ensure accurate predictions. Evaluations using 2023 data demonstrated the system's ability to capture regional variations in temperature and pressure, with strong correlations between forecasted and observed values (Figure 22, Left panel). Preliminary results for surface temperature forecasts at a specific location (28.92°N, 78.0°E) showed high accuracy, with minimal error growth over the forecast horizon. Metrics such as RMSE, MAE, bias, and correlation coefficient over the 10-day forecast horizon revealed gradual error growth, with RMSE increasing from 3.2°C on Day 1 to 4.0°C on Day 10 (Figure 22, Right panel). Bias showed an initial overestimation, stabilizing near zero later. High correlation coefficients (above 0.80) and R-squared values further validated the model's reliability, and scatter plots emphasized its accuracy (Figure 23), with minimal bias and strong agreement with observed values, demonstrating robustness in handling both spatial and temporal variability of meteorological conditions.

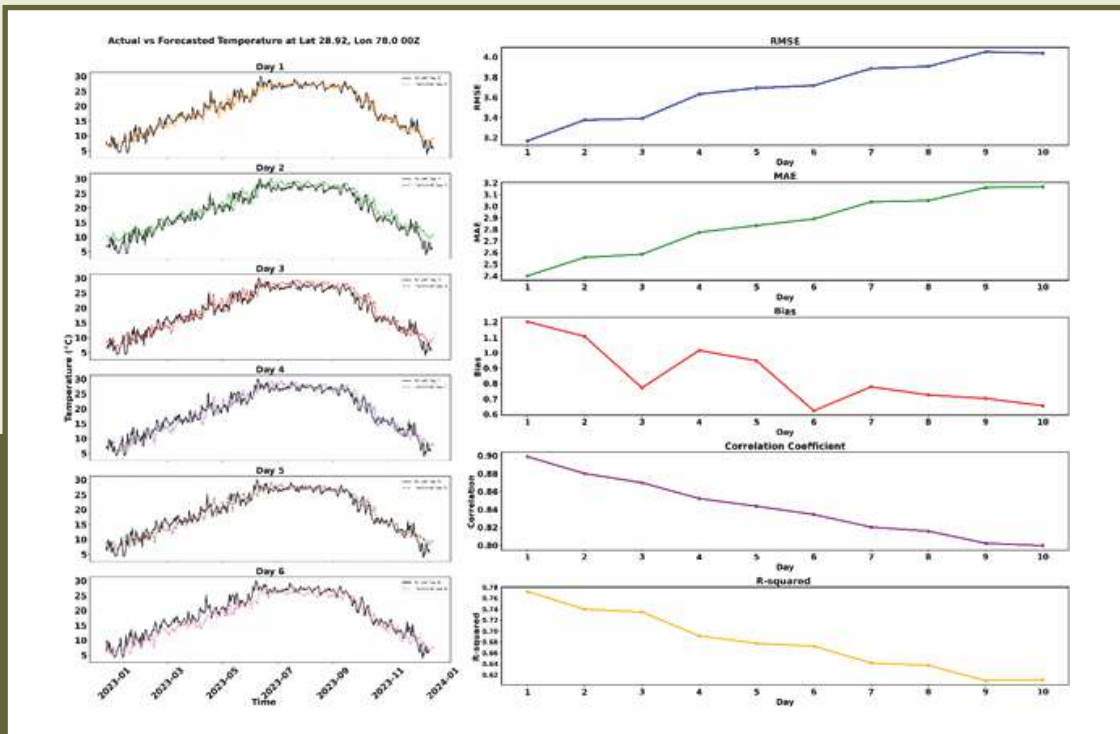


Figure 22: (Left panel) Temporal evolution of actual vs. forecasted surface temperature at a specific point location (28.92°N, 78.0°E) over Days 1 to 6. (Right Panel) Error metric trends for surface temperature forecasts, including RMSE, MAE, bias, correlation coefficient, and R-squared over the 10-day forecast horizon.

Unlike traditional NWP models, this system relies entirely on AI techniques, eliminating the need for physical model assumptions. The hourly forecasts facilitate temporal analysis, which is particularly beneficial for short-term weather predictions. The system's scalable architecture allows for the inclusion of additional parameters or regions, making it a versatile tool for meteorological forecasting. By utilizing the IMDAA reanalysis data from 2013 to 2023, the system has been trained and tested on a comprehensive and reliable dataset, ensuring robust performance across diverse conditions.

Looking ahead, future developments aim to expand the parameter set by incorporating additional meteorological variables and refining prediction algorithms for enhanced accuracy. Currently in a trial phase focusing on the Gangetic Plains, the system is set to expand across the entire Indian region, ensuring broader utility and relevance. Long-term goals include generating forecasts at various atmospheric levels, integrating more parameters for improved comprehensiveness and accuracy, and incorporating the system into operational weather forecasting frameworks for real-time applications.

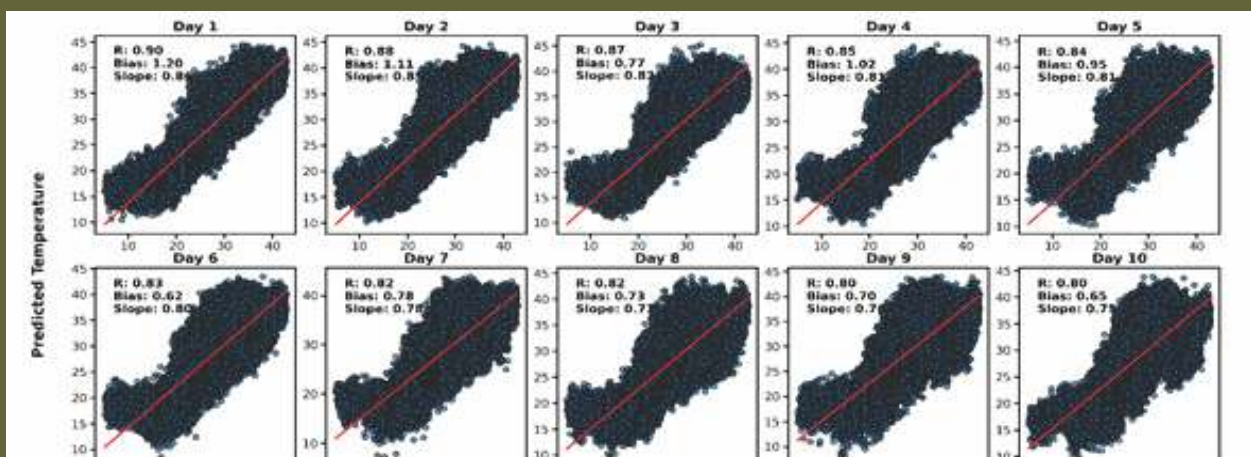


Figure 23: Scatter plots of actual vs. forecasted surface temperature values for each forecast day (Days 1 to 10).

ii. Radar-Based Nowcasting Using U-Net for Short-Term Rainfall Prediction

Radar-based nowcasting with U-Net offers an advanced deep-learning approach for short-term rainfall prediction using radar data. By identifying spatial patterns and relationships, U-Net proves highly effective in weather forecasting applications. In this study, quality-controlled Bhopal S-band DWR radar reflectivity data were processed and resampled to a uniform grid. Precipitation rates were then derived from the predicted reflectivity using Z-R relationships. The U-Net architecture, with its encoder-decoder structure, captures spatial patterns efficiently. The encoder reduces spatial resolution through pooling and convolutional layers, while the decoder reconstructs the patterns using upsampling and convolutional layers. Skip connections between encoder and decoder layers preserve critical spatial information, ensuring semantic continuity across scales. Unlike traditional advection-based nowcasting systems, which lose accuracy within 30 minutes, the U-Net-based approach maintains a high correlation for up to 60 minutes (Figure 24). This demonstrates its ability to predict both the spatial distribution and temporal evolution of rainfall reliably. Following rigorous training, testing, and validation, the model produced accurate hourly rainfall predictions, highlighting its potential for operational weather forecasting.

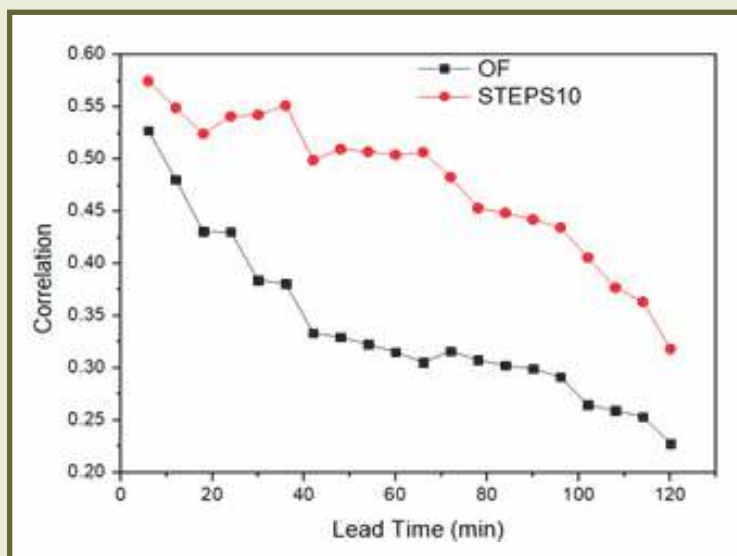


Figure 24: Comparison of Radar-Based Nowcasting Methods: Optical Flow vs. U-Net

iii. Precipitation Downscaling Using Random Forest and XGBoost

Enhancing the resolution of coarse satellite-based rainfall estimates is crucial for accurate precipitation modelling. This study compares the effectiveness of Random Forest (RF) and XGBoost algorithms in downscaling precipitation estimates by incorporating orographic features such as elevation, slope, aspect, curvature, and ruggedness (Figure 25). The analysis utilizes IMERG satellite precipitation data at 10 km resolution and high-resolution orography data at 4 km. To address data imbalances, both models were trained using augmented extreme precipitation events and weighted loss functions. Evaluation metrics, including Mean Squared Error (MSE), R² Score, Correlation Coefficient, and F1-score (Table 1), were used to assess performance. The results reveal distinct strengths of each model. Random Forest demonstrates superior interpretability and generalization, albeit with a slightly higher test MSE. Conversely, XGBoost achieves a higher correlation and lower training MSE but is more complex and less interpretable. The study concludes that both RF and XGBoost are effective tools for precipitation downscaling. RF excels in stability and interpretability, while XGBoost provides marginally better accuracy, offering valuable insights for improving rainfall predictions.

Metric	Random Forest (RF)	XGBoost
Train MSE	14.03	12.87
Test MSE	21.59	22.21
Test R ²	0.35	0.29
Correlation Coefficient	0.88	0.97
Weighted F1-Score	0.53	0.54

Table 1: Evaluation Metrics for Precipitation Downscaling with RF and XGBoost

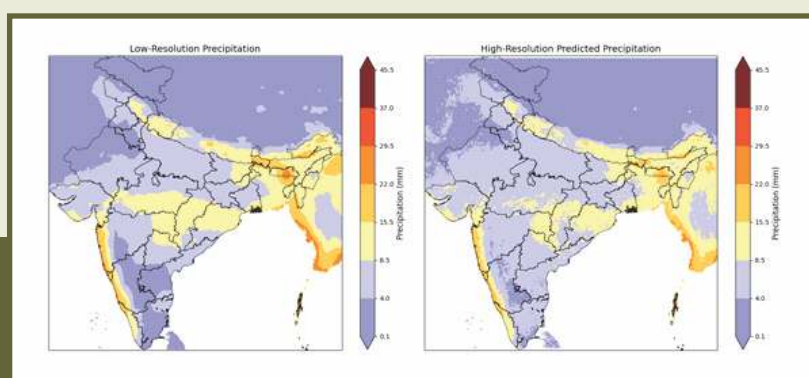


Figure 25: Comparison of IMERG (10km) with the downscaled to 4 km product using XGBoost method.

iv. Bias correction of IMDAA Reanalysis Temperature using AI/ML Techniques

The Indian Monsoon Data Assimilation and Analysis (IMDAA) is a high-resolution regional reanalysis covering 1979–2020, developed by NCMRWF, the UK Met Office, and IMD. IMDAA reveals persistent temperature biases of -7 to -8°C in both maximum and minimum temperatures, highlighting the need for bias correction. To improve accuracy, this study applied advanced machine learning techniques, including support vector machines (SVM), random forests (RF), extreme gradient boosting (XGB), and multiple linear regression (MLR) on temperature data. Training was done using pre-monsoon months (MAMJ) from 1979–2018, and models were tested on MAMJ data from 2019–2020. Key atmospheric features were selected using the minimum root mean squared error (RMSE), including 6-hourly rainfall, low cloud cover, 2-meter relative humidity, and wind velocity.

Results showed (Figure 26) significant improvements in bias correction and prediction accuracy, with XGB and RF models achieving 20–80% reductions in RMSE, especially for maximum temperatures (Tmax) in coastal and northern regions. Minimum temperature (Tmin) predictions also showed notable improvements, particularly in northern plains and southern peninsular areas. While northeastern India, with sparse station density, showed smaller gains, the machine learning models consistently outperformed traditional numerical weather prediction models. These findings highlight the potential of XGB and RF to enhance temperature reanalysis and forecasting, offering valuable tools for addressing climate change and urbanization impacts across diverse climates.

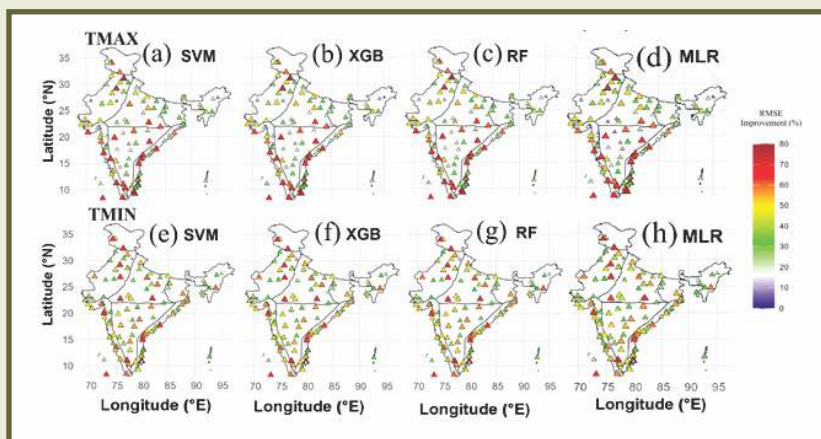


Figure 26: The RMSE improvement in percentage for Tmax (a-d) and Tmin (f-h) stations over the Indian domain

v. Seasonal Temperature Correction Using Convolutional Auto Encoder (CAE)

A Convolutional Auto Encoder (CAE) model was developed and trained to efficiently process both spatial and temporal temperature data, as shown in Figure 27. This CAE was specifically applied to correct biases in the maximum temperature forecasts derived from the NCUM-Coupled Model Outputs, utilizing the IMDAA Reanalysis Data as a reliable benchmark for accurate adjustments. Furthermore, a tailored CAE-based method was created to address spatial errors, with a particular focus on enhancing temperature predictions for the Delhi region. This method was rigorously validated using sample datasets, demonstrating a significant improvement in the accuracy of local temperature forecasting, as illustrated in Figure 28.

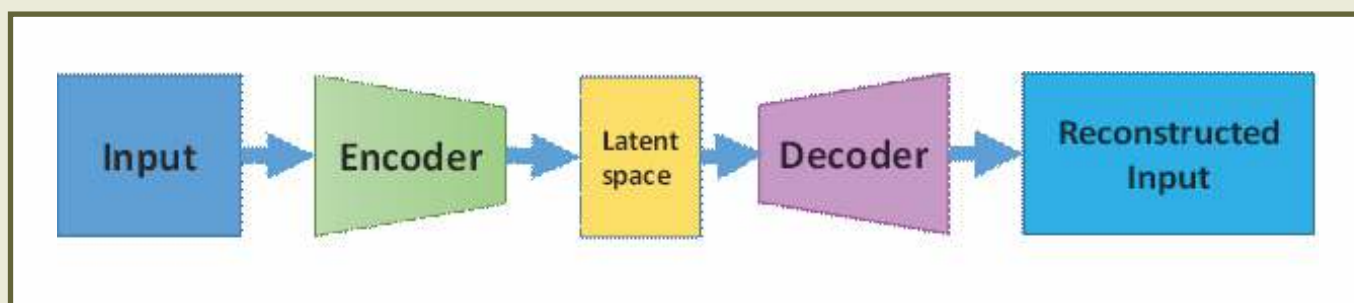


Figure 27: Convolutional Auto Encoder (CAE)

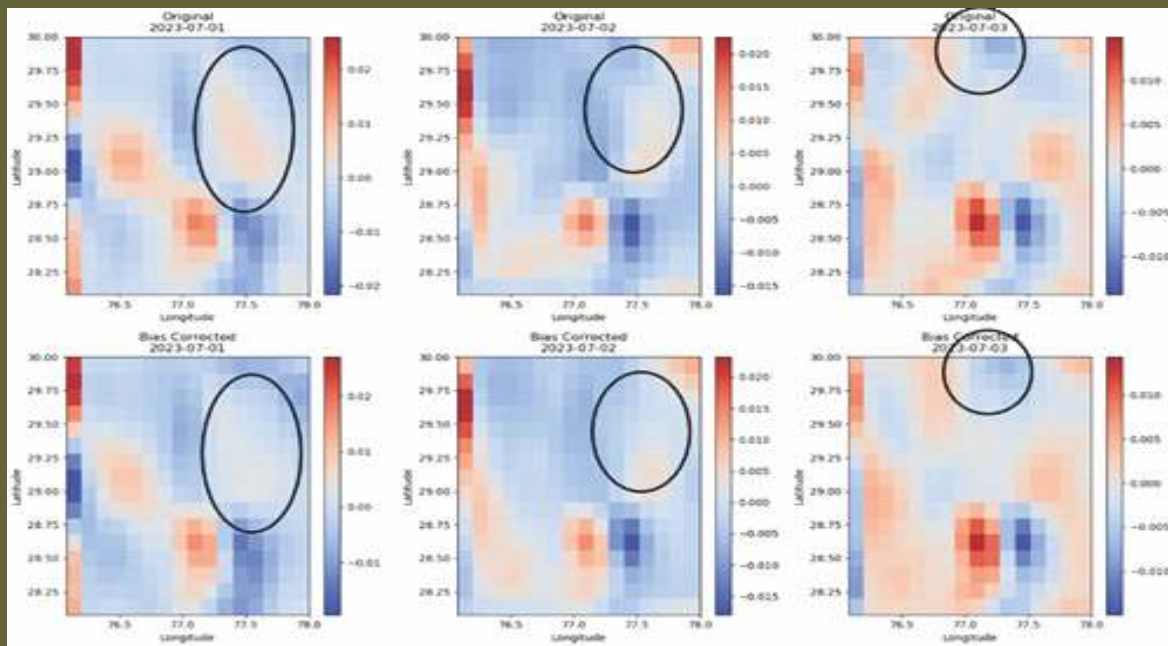


Figure 28: A comparison of the unmodified and bias-adjusted temperature data from the NCUM-Coupled Model

vi. Predicting Heatwaves in the Delhi Region Using the Random Forest Method

This study focused on predicting heatwaves in the Delhi region by integrating meteorological parameters, advanced statistical approaches, and machine learning techniques. The methodology is summarized in a flowchart (Figure 29), providing a clear visualization of the process. The study considered critical atmospheric variables such as temperature, geopotential height, specific humidity, and precipitation—factors essential for understanding the dynamics of extreme heat events. Patterns influencing Delhi's heatwaves, particularly from northwest India, were identified to capture dominant spatial and temporal variations. To ensure data consistency, the predictors were pre-processed through spatial and vertical refinement and standardization. Long-term trends were removed via detrending to isolate variations directly related to heatwave occurrences. Daily anomalies relative to climatological norms were computed, enabling a focus on deviations that characterize heatwave events. High-quality input data were ensured through the use of IMDAA reanalysis datasets for import and preprocessing. The refined dataset was used to train a Random Forest model for the classification and prediction of heatwave thresholds, including Heat Waves (HW), Severe Heat Waves (SHW), and Extreme Heat Waves (EHW). The model outputs provided heatwave classifications and indices, delivering critical insights into the occurrence, intensity, and dynamics of heatwaves in the Delhi region.

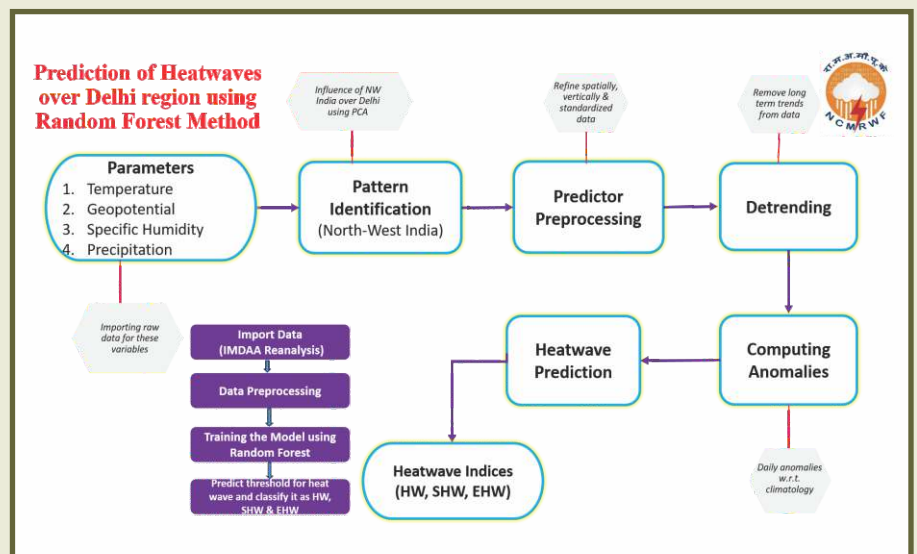


Figure 29: A typical flow of heat wave prediction over the Delhi region using the Machine Learning method

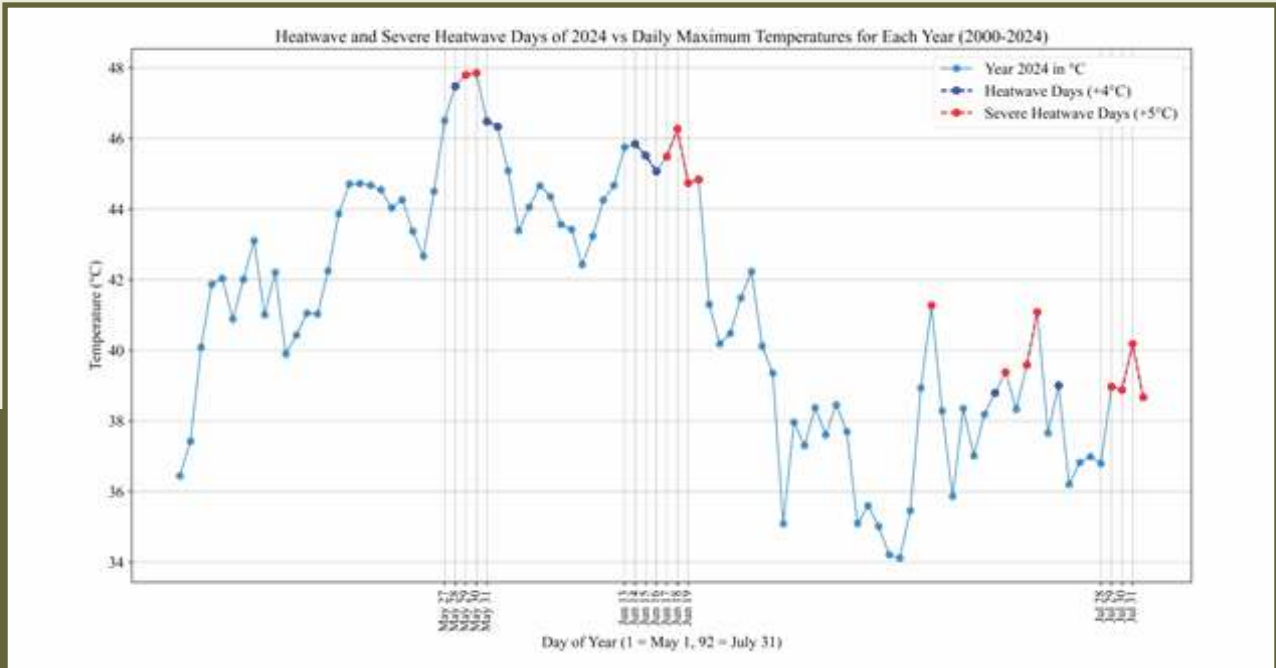


Figure 30: Time series of the maximum temperature from NCUM-Global model with the heatwave and severe heatwave marked by blue and red colors.

For instance, Figure 30 illustrates the maximum temperature from May 1 to July 31 for Delhi during 2024. A light blue line shows maximum temperature values, with predicted heatwave days marked by blue dots and severe heatwave days by red dots. Heatwave conditions are color-coded: light blue for no heatwave, dark blue for heatwaves, and red for severe heatwaves. A total of 8 heatwave days and 14 severe heatwave episodes were recorded, meeting criteria of +4°C and +5°C above climatological norms, respectively. Temperatures peaked in late May and early June, with several heatwave and severe heatwave events. A sharp rise during this period resulted in extreme heat conditions. After June, there were more false heatwave and severe heatwave alarms. In particular, May 27–31 and June 13–19 saw consecutive days exceeding the +4°C threshold.

vii. Brainstorming Session on AI/ML Initiatives at NCMRWF

A brainstorming session on AI/ML initiatives was held at NCMRWF on 24 February 2025, bringing together all scientists to deliberate on advancements and future strategies. The half-day workshop showcased various applications of AI/ML in weather forecasting and climate modeling. Key presentations included cyclone track error improvements, rainfall bias correction methods, lightning prediction, and heat wave forecasting. The session emphasized the need to streamline AI/ML activities across four key areas: operationalizing AI-based weather models, temperature and rainfall bias correction, building momentum for AI partnerships, and downscaling model outputs. The proposed reshuffling of scientists' responsibilities aims to optimize expertise and advance collaborative efforts towards enhancing operational weather forecasts using cutting-edge AI/ML technologies.

OPERATIONAL HIGHLIGHTS

This section highlights the key operational achievements during the reporting period, emphasizing the summary of forecasts with a particular focus on the southwest and northeast monsoon circulations, their associated rainfall patterns, and extreme weather events over the Indian subcontinent. It also provides an overview of the performance metrics and accuracy statistics of NCMRWF forecasts, showcasing their reliability and robustness. Furthermore, the section underscores the system's ability to deliver accurate and timely weather predictions, supported by comprehensive validation measures. The introduction of special forecast products demonstrates innovative approaches aimed at enhancing user-specific applications and informed decision-making.

a. Summary of Forecasts

i. Forecast Verification and Diagnostics

Forecast verification and model diagnostics play a critical role in evaluating and improving NWP models. This section briefly discusses the performance of NCMRWF model forecasts particularly during southwest monsoon season (June–September 2024), with a specific focus on systematic errors and extreme weather guidance over the Indian subcontinent. Figure 31 illustrates the performance of the NCUM-Global model in predicting rainfall during the monsoon season highlighting systematic biases and regional variations. The mean error (ME) analysis for (b) 24-hour, (c) 72-hour, and (d) 120-hour predicted rainfall reveals a consistent wet bias along the West Coast and central India. A dry bias is evident over the Bay of Bengal, and this bias intensifies with increasing lead time. Additionally, the model exhibits a wet bias over core monsoon regions, Northeast India, and the Arakan Coast. These findings emphasize areas where model improvements are needed to better capture the spatial and temporal distribution of rainfall. For a comprehensive analysis of systematic errors, refer to the NCMRWF Monsoon Reports, available on the NCMRWF website.

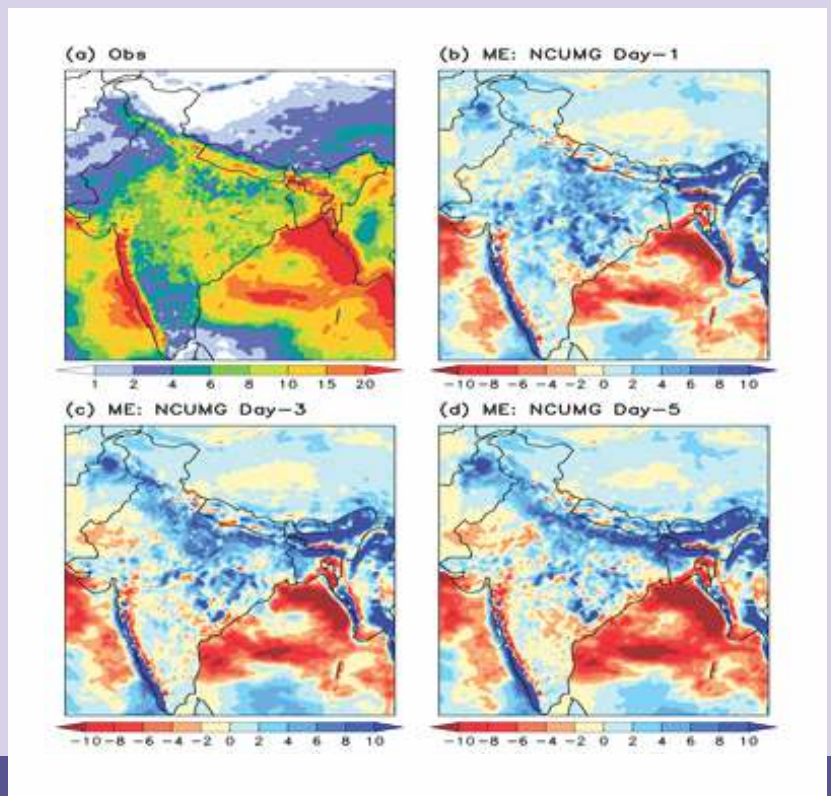
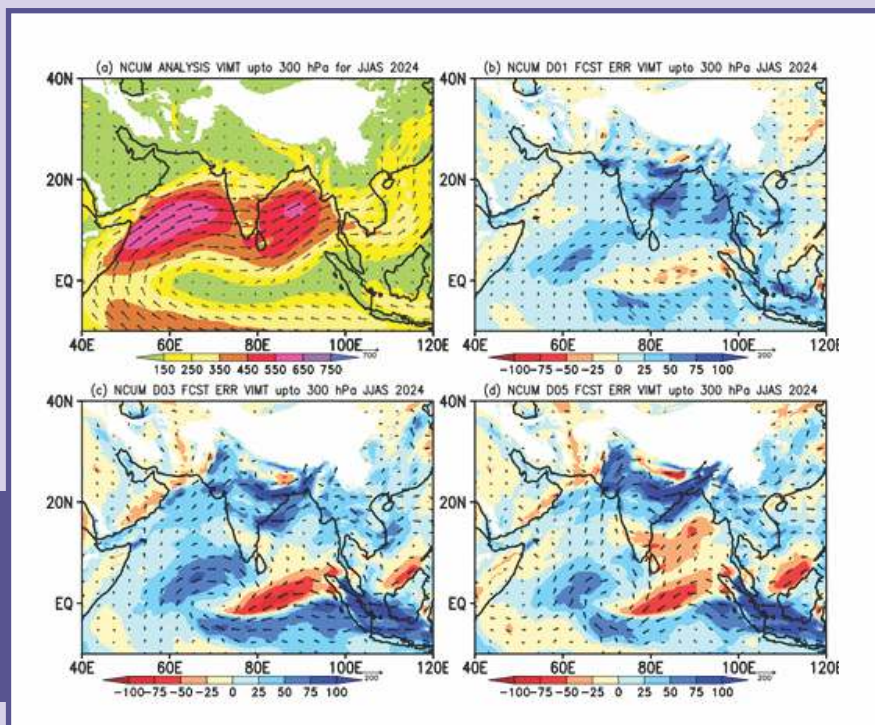


Figure 31: Observed and NCUM-G forecast rainfall (mm) averaged during Jun-Sept 2023. Panel (a) Observed (IMD-NCMRWF) rainfall analysis. Systematic error in rainfall for (b) Day-1 (c) Day-3, and (d) Day-5 forecasts.

The wet and dry biases observed above are likely influenced by factors such as moisture advection from the adjoining seas and the prevailing dynamical and thermodynamic instability conditions. Figure 32 illustrates the vertically integrated moisture transport (VIMT), highlighting significant moisture availability in the Arabian Sea and the Bay of Bengal. Systematic errors in VIMT, depicted in Figures 32b-d, directly correlate with the rainfall biases. The wet bias in rainfall, particularly along the West Coast and central India, can be attributed to an overestimation of net moisture transport, which intensifies with increasing lead time. These findings highlight the importance of accurately modeling moisture advection processes to reduce forecast biases.

Figure 32: (a) Analysis Mean VIMT (kgms-1) during JJAS 2024. systematic error in the (b) Day-1, (c) day-3, and (d) Day-5 forecasts.



ii. Model Guidance on Extreme Weather

NCMRWF regularly verifies its operational models across all seasons, focusing on extreme weather events critical to India, such as tropical cyclones, heatwaves, cold waves, and droughts. This section provides an overview of the model guidance and verification process for these events. Detailed reports and analyses are available on the NCMRWF publication page. Figure 33 highlights heatwaves and cold waves observed in May and December 2024, respectively. The left panel of Figure 33 demonstrates that the NCUM-G model effectively predicted spatial extreme temperatures over north-northwest India up to five days in advance. Similarly, the cold wave episode on December 15, 2024, was fairly forecasted. These results show that NCMRWF's high-resolution NWP models can reliably predict the intensity of heat and cold days well ahead of time.

However, traditional verification methods, such as grid-based or visual inspections, reveal occasional location mismatches and reliability issues. To address these, NCMRWF employs advanced spatial verification techniques like the Method for Object-Based Diagnostic Evaluation (MODE). For instance, Figure 34 showcases the heatwave episode on May 28, 2024, analyzed using MODE. The top panels depict temperature distributions from forecasts and observations, while the bottom panels highlight objects with temperatures exceeding 45°C.

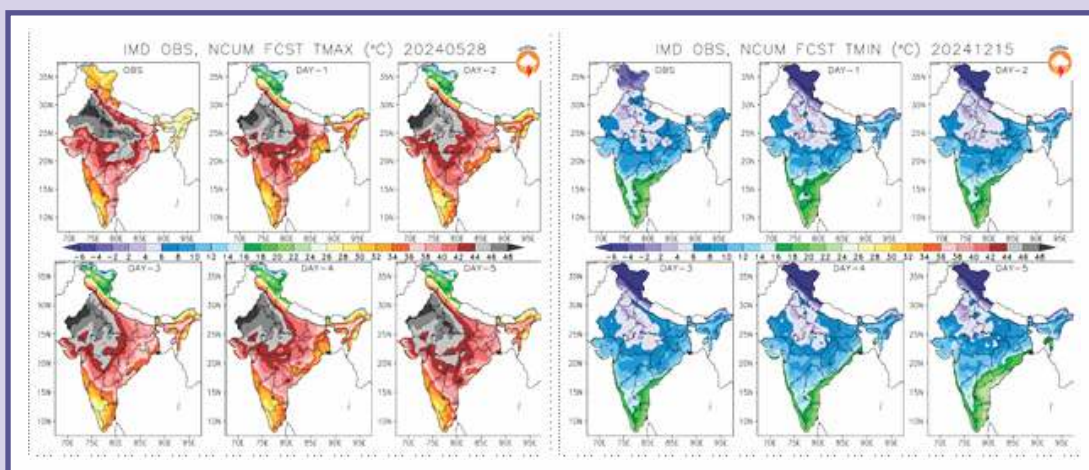
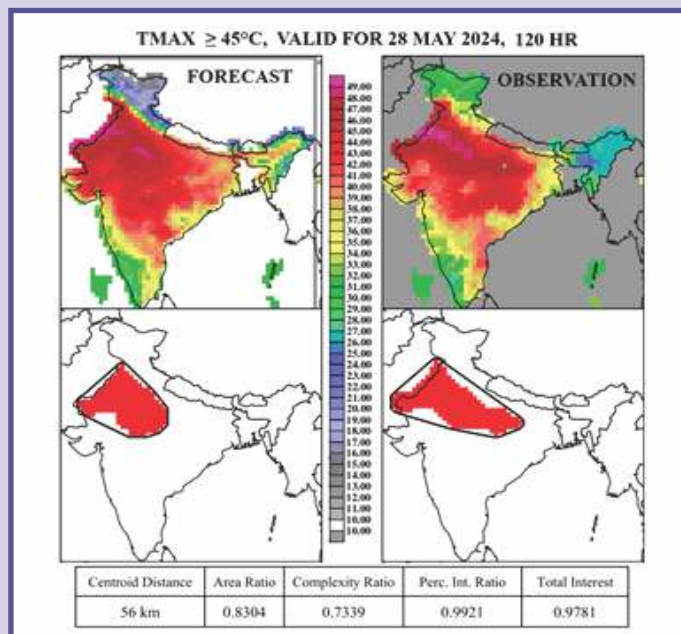


Figure 33: (Left panel) Tmax verification for the heatwave on 28 May 2024 and (Right panel) Tmin verification for the cold wave on 15 December 2024.

This object-based verification captures key model performance characteristics. For example, the centroid distance between forecasted and observed objects remains within 200 km up to a five-day lead time (Figure 34). The area ratio of forecasted objects is close to 1, indicating strong agreement with observations. Additionally, forecasted and observed maximum temperature objects exhibit similar intensity, with a Percentile Intensity Ratio around 0.99. The structural accuracy of forecasted temperature objects is supported by high Complexity Ratio values, reflecting the model's ability to capture spatial and intensity characteristics effectively.

Figure 34: (Left panel) Spatial verification of heatwaves using MODE, showing Tmax objects ($\geq 45^{\circ}\text{C}$) at a 120-hour lead time, valid for 28 May 2024.



IMD forecasters use real-time data from NCMRWF's global, regional, and ensemble NWP models for cyclonic storm guidance over the North Indian Ocean. NCMRWF employs a UKMO-based TC tracker that identifies cyclones using maximum relative vorticity at 850hPa and minimum MSLP. The tracker uses seven parameters, including orography, surface temperature, winds, and MSLP, to determine storm position and intensity every 6 hours up to 120 hours. An example of 'DANA' cyclone predicted track from NCMRWF modeling system is shown in Figure 35. Further, verification includes errors in direct position errors of cyclone track (Figure 35d) against IMD's best track data in addition to position, intensity (MSW and MSLP), and landfall location/time.

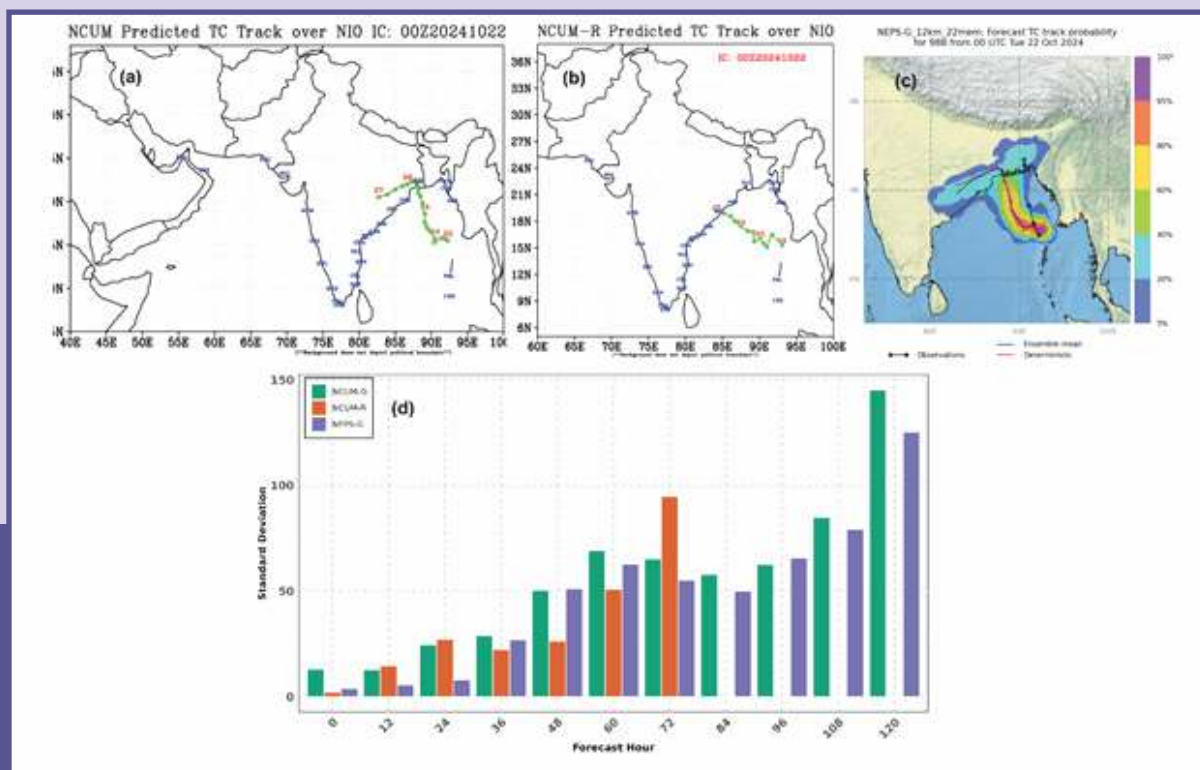


Figure 35: Predicted track of cyclone 'DANA' using NCMRWF models: (a) Global, (b) Regional, and (c) Ensemble Prediction System. (d) Mean Direct Position Error (DPE) comparison for three cyclonic storms (REMAL, DANA, and ASNA) over the North Indian Ocean (NIO).

In addition to many other products, NCMRWF provides real-time forecasts of visibility and air quality for Delhi and neighboring regions during winter using its high-resolution DM-Chem model. It integrates a prognostic aerosol chemistry scheme, urban morphology, aerosol-cloud interactions, irrigation effects, and an aerosol-based visibility scheme. The model demonstrates skill in forecasting moderate fog events, with visibility below 500 m, and captures the diurnal variation of near-surface weather parameters. Figure 36 illustrates the model's evolution, air quality guidance (left panel), and fog forecasting performance (right panel), highlighting its utility for extreme weather guidance in the Indo-Gangetic Plain.

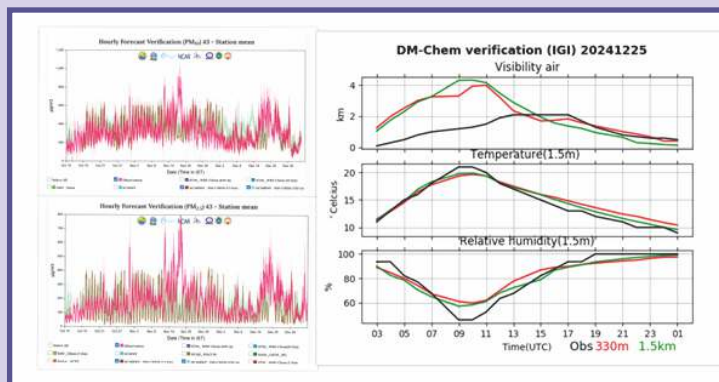


Figure 36: (Left panel) Verification of PM₁₀ and PM_{2.5} from NCMRWF DM-Chem 1.5km and 330m with observations (Right panel) Verification of DM-Chem 1.5km and 330 m during fog.

iii. Model Guidance over Cryosphere at S2S time scale

The Ministry of Earth Sciences (MoES) initiated cryosphere prediction on a sub-seasonal to seasonal (S2S) timescale using the Coupled Seamless Prediction System from NCMRWF. This system includes an Atmospheric Model with ~60 km resolution and an Ocean and Sea-Ice Model with a 25 km resolution, producing a 16-member ensemble forecast every Thursday for the next 4 weeks. A hindcast experiment covering 23 years (1993-2015) was conducted.

Figure 37 shows the hindcast climatology of mean sea-ice concentration from the NCMRWF S2S system and the biases based on the Operational Sea Surface Temperature and Ice Analysis (OSTIA). Additionally, products such as sea-ice thickness, drift, and temperature are produced regularly over the Arctic and Antarctic Oceans.

The hindcast plots reveal marginal biases during the summer months over both poles. NCMRWF, in collaboration with NCPOR, now generates weekly forecast products over the Arctic and Antarctic using the 16-member ensemble system. These include weekly mean, anomaly, and tendency plots for sea-ice concentration, thickness, temperature, and velocity, which are shared with NCPOR and hosted on both NCMRWF and NCPOR websites.

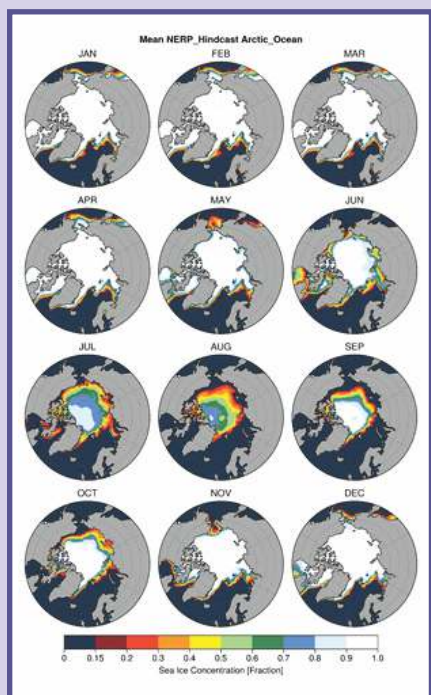


Figure 37: (a) Monthly Climatology of mean sea ice concentration (fraction) over the Arctic from NCMRWF S2S Hindcast (1993-2015).

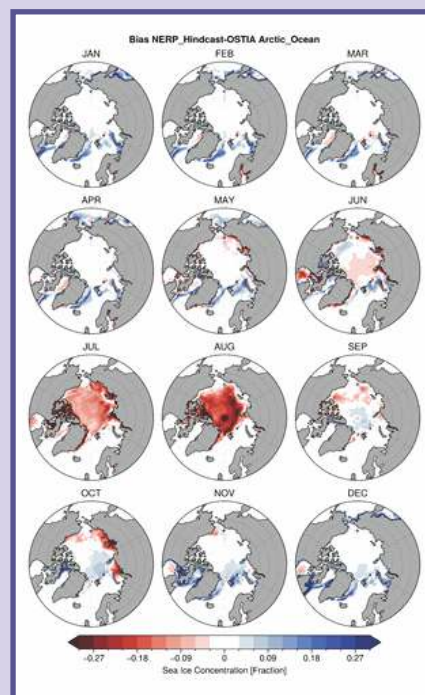


Figure 37: (b) Biases in comparison to the Operational Sea Surface Temperature & Ice Analysis (OSTIA) in Monthly Climatology of mean sea ice concentration (fraction) over the Arctic from NCMRWF S2S Hindcast.

iv. Evaluation of GFS-GSM and FV3 based NWP Models

This study evaluates the performance of three NWP models in forecasting extreme rainfall over India during the monsoon season. The baseline model, CTRL, utilizes the Global Forecast System (GFS) with the Global Spectral Model (GSM) and the Revised Simplified Arakawa-Schubert (RSAS) convection scheme. EXP-1 builds upon this by incorporating a modified RSAS (mRSAS) scheme to enhance the representation of convective processes. The advanced EXP-2 model employs the Finite Volume Cubed-Sphere (FV3) dynamical core with a cubed-sphere grid, significantly improving the resolution of convection and small-scale atmospheric processes. The models differ in convective process representation, spatial resolution, and computational methods, which significantly influence forecast accuracy.

These models were assessed to understand their capabilities in predicting heavy rainfall events critical for disaster preparedness and mitigation. Rainfall forecasts were validated against the Integrated Multi-satellite Retrievals for GPM (IMERG) dataset, using metrics like Probability of Detection (POD) and False Alarm Ratio (FAR) for thresholds from 25 mm/day to 205 mm/day over a 4-day lead time. EXP-2 consistently outperformed CTRL and EXP-1 at higher rainfall thresholds (e.g., >85 mm/day), reflecting higher predictive capability for extreme events (Figure 38). This trend persisted across lead times, with EXP-2 showing greater resilience, particularly for thresholds above 100 mm/day. EXP-2 recorded the lowest FAR, especially for rainfall intensities >85 mm/day, demonstrating a reduced tendency to over-predict extreme events. By Days 3 and 4, EXP-2 maintained an advantage, producing fewer false alarms compared to CTRL and EXP-1. The analysis highlights the EXP-2 superior ability to predict extreme rainfall, balancing higher POD and lower FAR. This reliability is crucial for operational meteorology and disaster preparedness in regions prone to high-impact weather. The FV3 model's cubed-sphere grid and enhanced dynamical representation improve the resolution of convection and small-scale processes, making it a robust tool for forecasting extreme rainfall events & supporting early warning systems.

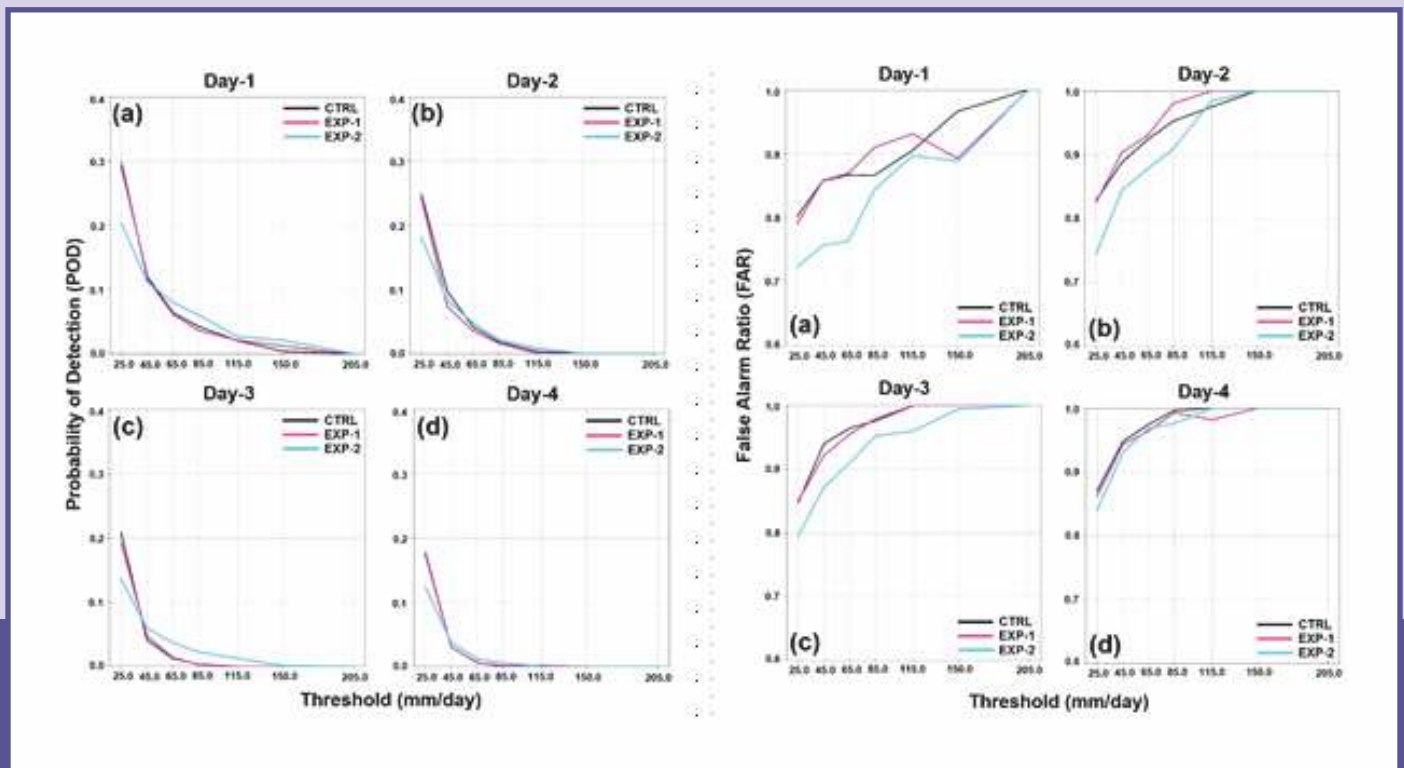


Figure 38: (left) Temporal Forecast Verification Using Categorical Skill Scores with different thresholds of moderate to extremely heavy rainfall (25-205 mm). POD between IMERG Rainfall Observations with (a) Day-1, (b) Day-2, (c) Day-3 and (d) Day-4 Forecasts of Control Experiment (CTRL), GFS with mRSAS scheme (EXP-1), and FV3 (EXP-2), during September 2021. (right) Similar to the left panel but for False Alarm Ratio (FAR)

b. Forecast Dissemination

i. Weather Forecasting Services

The NCMRWF has been delivering advanced weather forecasting services that cater to diverse sectors and regional stakeholders (Figure 39). Utilizing its seamless modeling framework, NCMRWF generates an array of sophisticated products that are instrumental in disaster management, renewable energy optimization, and multi-sectoral planning. These products, supported by high-resolution NWP models, are particularly valuable during extreme weather events, enhancing public safety and resilience.

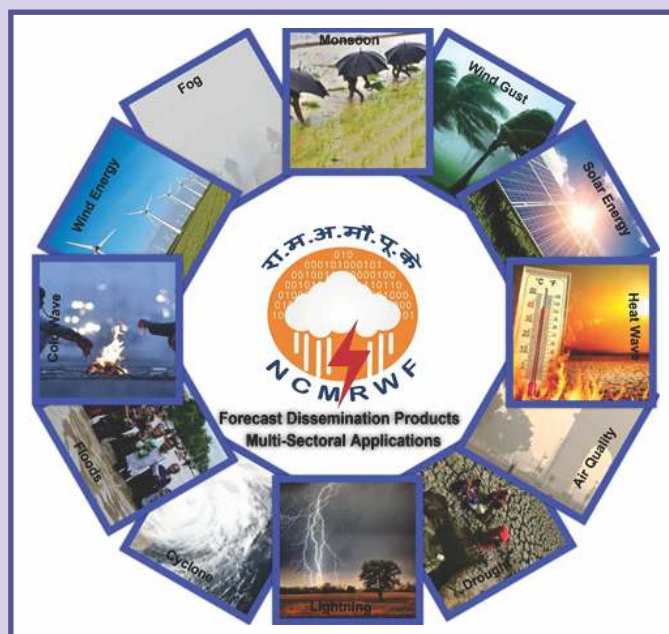


Figure 39: Schematic illustrating the diverse products that cater to diverse sectors and regional stakeholders

As part of its commitment to regional collaboration, NCMRWF actively supports neighboring countries through the Severe Weather Forecast Program (SWFP) for South Asia, and initiatives under Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES), BIMSTEC Centre for Weather and Climate (BCWC). These efforts promote regional meteorological capabilities, strengthen cooperation, and encourage the exchange of critical weather information. Additionally, NCMRWF disseminates Subseasonal to Seasonal (S2S) bulletins, leveraging coupled modeling systems to provide medium- to long-term weather insights. These bulletins are invaluable for planning in agriculture, water resource management, and disaster preparedness.

In the energy sector, NCMRWF plays a crucial role by providing tailored forecasts for solar and wind power generation. These forecasts, updated at one-hour intervals and shared with stakeholders such as the National Institute of Wind Energy (NIWE) and private companies, support the integration of renewable energy into India's power grids. The Centre's contributions extend to optimizing energy production and minimizing grid disruptions, with five new organizations adopting its NWP data in the past year.

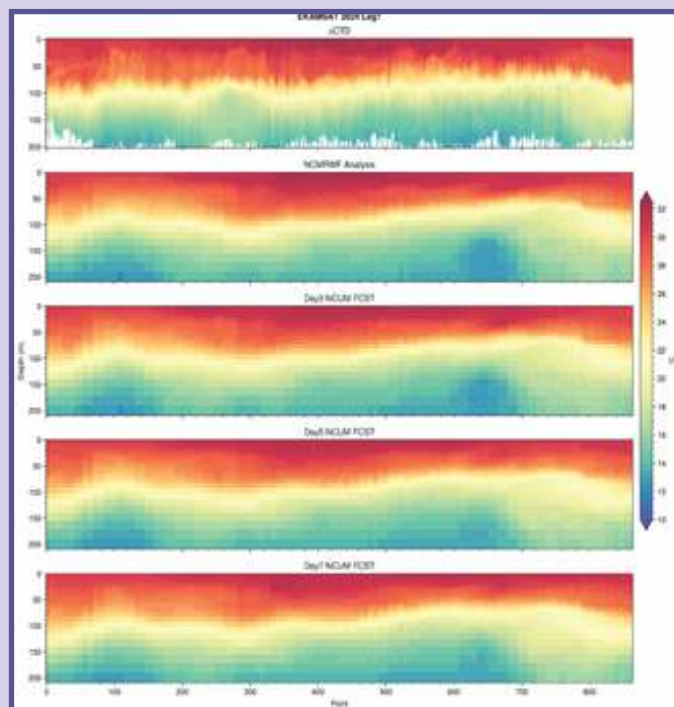
NCMRWF's dissemination framework also includes partnerships with IMD, and other MoES sister organizations along with public and private agencies across India. Key sectors benefiting from these services include defense, disaster management, and renewable energy. To ensure efficient data delivery, a dedicated team manages data dissemination, maintains comprehensive records of model performance, and collaborates with stakeholders to continually enhance forecast accuracy.

ii. Forecast dissemination for Ocean Expeditions

The global coupled model provides daily ocean and sea-ice forecasts at a coarse resolution of 60 km, extending up to 15 days. These forecasts are routinely shared with users to support various applications. For instance, ocean state forecasts were provided daily during the EKAMSAT (Enhanced Knowledge of the Arabian Sea Marine Environment through Science and Advanced Training) research cruise, using the 15-day forecast data. Figure 40 illustrates the verification of the SST vertical profile observed during the cruise, demonstrating a good agreement between the observational data and the model's analysis and forecasts.

Additionally, extended range or multi-week ensemble forecasts generated by the model are shared with the India Meteorological Department (IMD) for use in their Decision Support System (DSS). Similarly, multi-week ensemble forecasts of polar sea ice are regularly shared with the National Centre for Polar and Ocean Research (NCPOR) to support their operational needs.

Figure 40: Profile of temperature (uCTD; deg. C) from the Indo-US collaborative observational campaign EKAMSAT (top), valid for 26th April to 15th May 2024 along with analysis and forecasts with lead times 3, 5 and 7 days. Going from left to right, the northernmost survey line station was WP03 (17°49.812' N, 89°28.350' E), and the southernmost was WP04 (02°00.000' N, 84°15.000' E).



iii. Implementation of Pricing Policy for NWP Data

NCMRWF is also working to commercialize its data through a structured pricing mechanism by recognizing the growing demand for its services. The centre is adopting the MoES pricing policy for the commercialization of NWP model data, effective from 1st August 2024. The pricing will vary based on the user's selection of data parameters, such as spatial coverage, number of fields, forecast length, and interval. This policy was established by a committee formed by the MoES and is non-negotiable, meaning it will not be altered in response to petitions or requests from any organization or institution. Before the implementation, NWP data users were informed about the pricing policy and the methodology for calculating the cost of data for each user. This included several private sector companies in the renewable energy sector, specifically those involved in wind and solar forecasting. To facilitate payments for NWP data charges, the necessary administrative processes have been completed on the 'Bharatkosh' portal, including the creation of a new payment category, NCMRWF DATA FOR USERS, and the mapping of this category to the NCMRWF's Drawing and Disbursing Officer (DDO). Buyers of NCMRWF's NWP data can choose from various payment plans—monthly, quarterly, half-yearly, or annually—based on their preference. If an organization fails to make the advance payment, data sharing will be suspended after a notice period of 15 days. Payment for NWP data, including GST, is made through the "Bharatkosh" portal, and once the payment is confirmed, the receipt is shared with designated NCMRWF officials. The data is then provided within one week of receipt validation. Currently, the data is shared via both FTP and API servers. However, in the near future, data will only be shared through API. Buyers are advised to make the necessary arrangements to receive data through this me

c. Special Forecast Products

i. Gálvez–Davison Index (GDI) for tropical convection

A key self-reinforcing process, the moisture-convection feedback mechanism, amplifies convection in tropical environments and forms the basis for the formulation of the Gálvez–Davison Index (GDI). This index is primarily based on atmospheric moisture layers and equivalent potential temperature (EPT, θ_e), which serves as the core concept for GDI computation. EPT integrates moisture content and thermal properties of an air column, making it a valuable parameter for assessing atmospheric stability, convective potential, and cloud formation. By capturing the potential for further moistening of the air column, EPT provides critical insights into convective dynamics. The GDI is calculated as the algebraic sum of Column Buoyancy Index (CBI), Mid-Tropospheric Warming Index (MWI), Inversion Index (II), and a

Terrain Correction (TC) factor, expressed as:

$$GDI = CBI + MWI + II + TC$$

Moisture and temperature data from 1000 to 500hPa levels are used for GDI computation, with the 950hPa level considered essential to incorporate boundary-layer information. This is particularly important in cases where trade wind inversions occur below the 850hPa level. Typical GDI values, ranging from less than -20 to greater than +50, correspond to various stages of convection and associated cloud formations, as outlined in Table 2.

GDI > 45	High potential for scattered to widespread thunderstorms	
+35 to +45	Potential for scattered thunderstorms and/or widespread shallow convection	
+25 to +35	Potential for scattered shallow convection and isolated to scattered thunderstorms	
+15 to +25	Potential for isolated to scattered shallow convection and a few isolated thunderstorms	
+5 to +15	Potential for isolated to scattered shallow convection. Any T-storm brief and isolated	
-20 to +5	Isolated to scattered shallow convection. Strong subsidence inversion likely.	
GDI < -20	Fair conditions. Any convection should be shallow, isolated and produce very light rain.	

Table 2: GDI threshold values and associated types of convection

An example of the spatial validation of an extreme rainfall event over the West Coast, as simulated by the NCUM global model is shown in Figure 41 valid on July 29, 2024. The figure depicts GDI values and their associated convection stages, as defined in Table 1, across the Indian region. It highlights zones of potential deep convection, along with areas of shallow and suppressed convection, particularly over most of the northwestern regions, the West Coast, and adjoining oceanic areas. This analysis emphasizes the utility of GDI in identifying convective patterns and has been operationalized as part of the forecasting framework.

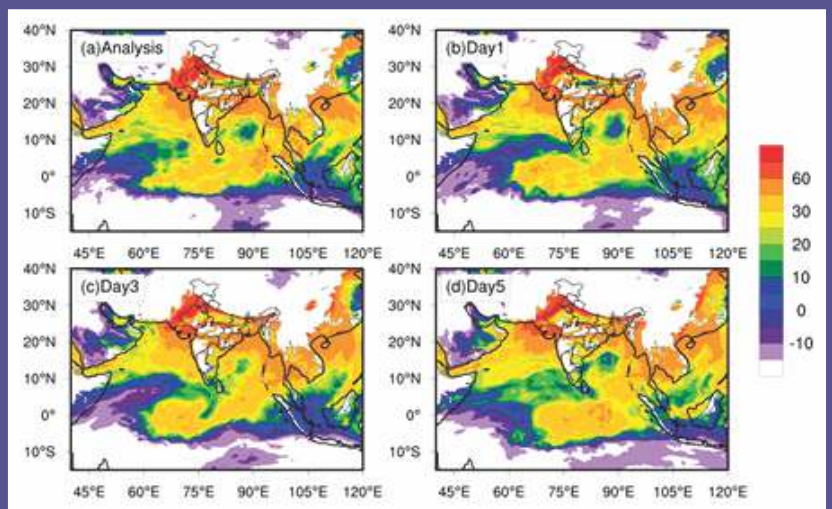


Figure 41: Spatial validation map of GDI for a typical case study of extreme rainfall event that occurred over Westcoast and surrounding regions on 29th July 2024 from NCUM global forecast a) Analysis; and (b)-(d) are Day-1 Day-3 and Day-5 forecasts valid on 29th July 2024 respectively.

ii. MoES Grand Ensemble (MGE) for Improved Prediction

Ensemble Prediction Systems (EPSs) often struggle with under-dispersion, where the forecast spread fails to adequately capture uncertainties. To address this, two high-resolution (~12 km) global EPSs operational at MoES—NCMRWF-NEPS and IITM-GEFS—were combined to form the Multi-Model Grand Ensemble (MGE). This 42-member ensemble, created by pooling 23 members from NEPS and 21 from GEFS using the 00UTC runs, improved the quantification of forecast uncertainty. MGE demonstrated significant advancements, including enhanced ensemble spread, improved reliability, and higher accuracy for probabilistic rainfall predictions across four regions of India during the monsoon seasons from 2019 to 2022. It consistently achieved the lowest CRPS across all lead times (Figure 42), indicating a closer match between forecast probabilities and observed values, while its higher Brier Skill Score (BSS) for moderate rainfall (20–50 mm/day) reflected statistically significant improvements. Reliability was enhanced with reduced bias and better alignment between forecast probabilities and observed frequencies, particularly for Day-5 forecasts. MGE also achieved a better balance between ensemble spread and RMSE, effectively representing uncertainties without compromising reliability. Now generating daily forecasts for rainfall and 2m maximum temperature at NCMRWF, MGE marks a significant step forward in advancing weather prediction capabilities.

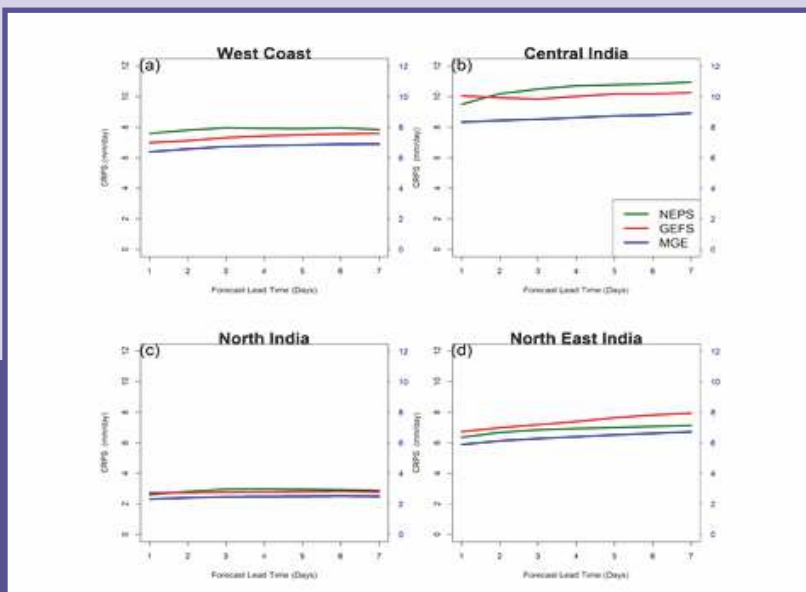


Figure 42: CRPS over 4 different regions in India. CRPS values for MGE are lower than both NEPS and GEFS for all lead times

To enhance the reliability and accuracy of MGE, two parametric post-processing methods, ensembleBMA (BMA) and ensembleMOS (EMOS), were applied. EMOS utilized Generalized Extreme Value (GEV) and Censored and Shifted Gamma (CSG) distributions for rainfall, while BMA employed the Gamma distribution. For temperature, both methods used Gaussian distributions. Bias correction was implemented for rainfall forecasts across three Indian domains during the monsoon seasons (2020–2022) and for temperature forecasts across three regions during the summer seasons (2019–2022). Evaluation metrics such as CRPS, BSS, reliability diagrams, and Symmetric Extreme Dependency Score (SEDS) for extreme rainfall were used to assess performance. Key outcomes included up to a 22% improvement in CRPS for rainfall in 2020 over the west coast (Figure 43) and statistically significant BSS improvements at a 95% confidence level. EMOS demonstrated robust skill in forecasting extreme rainfall and temperature events, especially over complex terrains. The daily bias-corrected MGE forecasts for rainfall and 2m maximum temperature are now operationally generated at NCMRWF, offering significantly higher accuracy and reliability across diverse Indian regions (Figure 44).

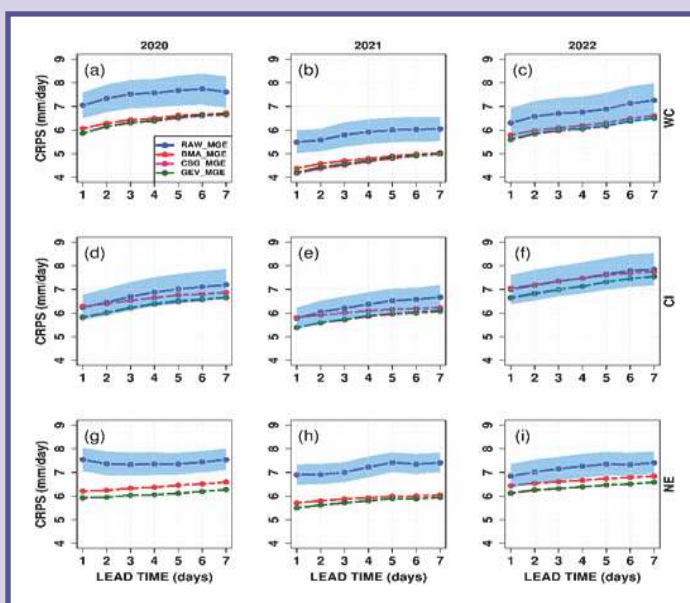


Figure 43: CRPS values for post-processed MGE are lower than raw MGE for all regions, years and lead times.

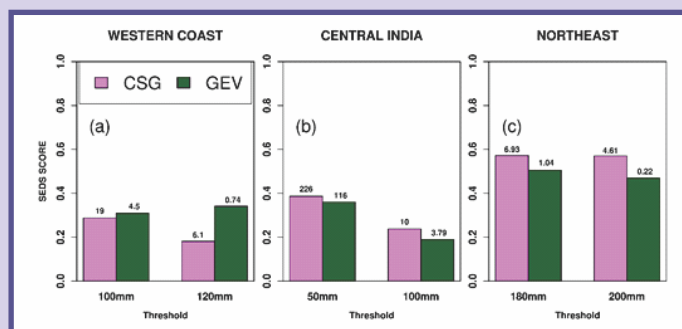


Figure 44: SEDS score for Day-3 forecasts from the median of CSG_MGE and GEV_MGE for rainfall exceeding different thresholds in the WC, CI and NE regions. The numbers on the bars indicate the base rate (x10-5)

COMPUTATIONAL INFRASTRUCTURE UPGRADES

a. Inauguration of Supercomputing System 'Arunika'

NCMRWF has made a significant increase in computational capabilities with the installation of the state-of-the-art supercomputing system, 'Arunika'. This advanced infrastructure marks a major milestone in India's efforts to enhance weather and climate research, enabling the country to deliver more accurate and timely forecasts while strengthening disaster preparedness and climate resilience.

Arunika is an Atos BullSequana XH2000 DLC System, powered by AMD Milan 7643 processors with 48 cores per node and a total of 2115 computational nodes, achieving a peak performance of 7.47 PetaFLOPS (RPeak). The system is supported by 2.247 Petabytes of high-speed DDN storage and a cutting-edge HDR 200 Gbps interconnect, ensuring seamless data processing and communication for weather and climate modeling.

Power Efficiency: The data center operates with a total power capacity of 2.295 MW, designed to accommodate a 30% future HPC expansion, while achieving an efficient Power Usage Effectiveness (PUE) of ~1.2.

Cooling System: Features advanced liquid-cooled racks for 95% heat dissipation through liquid cooling, supplemented by 5% air cooling, ensuring energy efficiency.

Rack Configuration: Comprises 25 liquid-cooled racks and 7 air-cooled racks for optimal performance.

Arunika operates on the RHEL operating system and uses advanced tools such as PBS Pro for workload management, SMC xScale for cluster management, and development suites like the AMD AOCC compiler and NVIDIA SDK for AI/ML workloads. These tools provide a robust foundation for executing complex weather models and running high-resolution simulations.

Arunika significantly enhances NCMRWF's ability to process complex atmospheric data and execute critical weather applications including Artificial Intelligence (AI) and Machine Learning (ML) applications for predictive analytics and data assimilation. The system dedicates specific computational resources for AI/ML applications, offering 1.9 PetaFLOPS of standalone computational power. This capability focuses on developing innovative models to improve forecast accuracy and address challenges in extreme weather prediction. Arunika represents a transformative step in India's weather forecasting capabilities, enabling improved forecasts for extreme weather events such as cyclones, heatwaves, and droughts. Its deployment enhances data assimilation, model resolution, and disaster preparedness, contributing to India's global leadership in weather and climate research.

In a landmark event, the Prime Minister of India inaugurated the new supercomputing systems, Arunika (NCMRWF, Noida) and Arka (IITM, Pune), acquired by the MoES. Together, these systems bring the Ministry's total computing power to 22 PetaFLOPS, elevating India's position in global meteorological research and operational forecasting. The deployment of Arunika emphasizes India's commitment to leveraging advanced computational technologies for national meteorological initiatives and sustainable development goals.



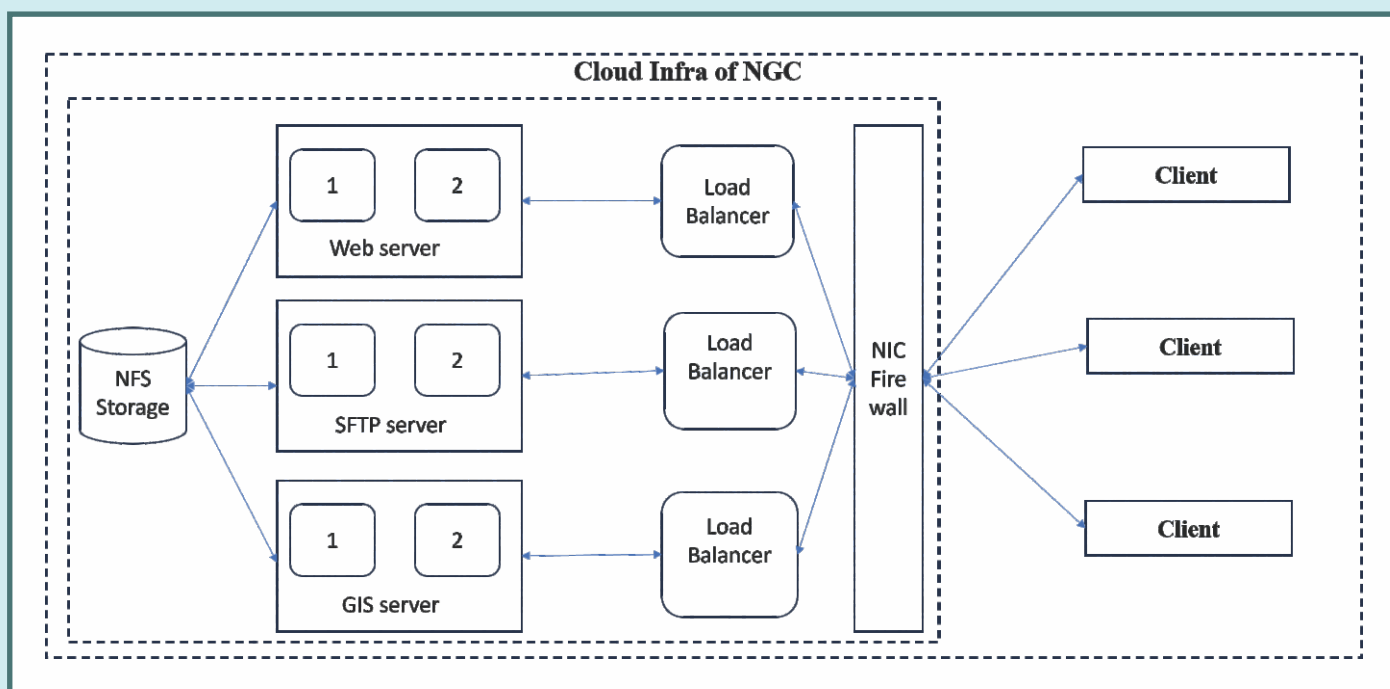


b. New Cloud Services at NCMRWF

As part of its ongoing infrastructure upgrades, NCMRWF has integrated National Government Cloud (NGC) Cloud Services, a robust and scalable platform designed to enhance the operational efficiency of its weather and climate data services. The NGC, under the authority of National Informatics Centre (NIC), offers a secure, flexible, and cost-efficient cloud environment for government projects, providing critical services such as compute, storage, Kubernetes, databases, and networking through a unified portal. The NGC Cloud infrastructure at NCMRWF features six dedicated servers, categorized as Web Servers, SFTP Servers, and GIS Servers, with a load balancer ensuring optimal performance and redundancy. The servers operate on Ubuntu 22.04 and are equipped with 13 TB of total NAS storage distributed across applications. Specialized GIS servers, supported by GeoServer, process spatial data, offering advanced geospatial analytics and mapping capabilities. Integrated handling of NetCDF files and Web Map Services (WMS) further enables dynamic data visualization for end users.

These cloud services augment NCMRWF's ability to deliver secure, efficient, and remote access to critical weather and climate datasets, ensuring reliability and scalability for future expansions. The inclusion of cloud-based geospatial functionality emphasizes the center's commitment to leveraging advanced technologies for enhanced data accessibility and analytics.

SCHEMATIC REPRESENTING THE NGC CLOUD SERVER ARCHITECTURE



CELEBRATION OF 30 YEARS OF OPERATIONAL NWP IN INDIA

NCMRWF proudly hosted a workshop on November 19, 2024, to commemorate 30 years of operational numerical weather prediction (NWP) in India and the 150th anniversary of the India Meteorological Department (IMD). The event showcased NCMRWF's pioneering contributions to medium-range global forecasting since 1994 and highlighted significant advancements in NWP over the years. As part of the 30-year celebrations, an invited talk by Prof. Jagadish Shukla, titled 'NCMRWF and the Dawn of Weather Forecasting with Global Models and Supercomputers in India,' was held on November 5, 2024.



The workshop began with an inaugural session attended by over 300 national and international delegates. The Honourable Secretary, Ministry of Earth Sciences (MoES), Dr. M. Ravichandran, inaugurated the event. Distinguished participants included:

- Dr. M. Mohapatra, Director General of Meteorology, IMD
- Dr. Michael R. Farrar, Director, NCEP-NOAA, USA
- Dr. David Walters, Associate Director, UK Met Office
- Dr. V. S. Prasad, Head, NCMRWF
- Dr. Parvinder Maini, Scientific Secretary, Office of the Principal Scientific Adviser to the Govt of India
- Dr. Ashish Routray, Scientist-F, NCMRWF



Dr. V. S. Prasad extended a warm welcome to the dignitaries and delegates, setting the tone for an inspiring day of knowledge exchange. Keynote addresses by Dr. Ravichandran, Dr. Mohapatra, Dr. Farrar, Dr. Walters, and Dr. Maini reflected on NCMRWF's trajectory of growth and excellence in operational weather prediction, emphasizing its role in national and international meteorological advancements.



• **Launches and Felicitations**

During the inaugural session:

- A state-of-the-art cloud server was launched to enhance computational and data storage capabilities for NWP.



- An E-book souvenir and a commemorative book documenting 30 years of NCMRWF's achievements were unveiled.



Former directors, heads, and key contributors were honoured by the Secretary, MoES, and the Head, NCMRWF, recognizing their pivotal roles in shaping the center's legacy.



• Presentations by Experts

The technical presentations began with a detailed overview of NCMRWF's advancements by Dr. V. S. Prasad. This was followed by insightful talks by:

- Dr. Michael R. Farrar, highlighting innovations at NCEP-NOAA and collaborative opportunities.
- Dr. David Walters, presenting the UK Met Office's contributions to global NWP.
- Dr. M. Mohapatra, emphasizing IMD's efforts in operational weather services.
- Mr. Karma Dupchu, representing BIMSTEC, showcasing regional hydrology and meteorology advancements.

The presentations offered a comprehensive view of global and regional NWP developments, fostering discussions on future strategies.



- **Panel Discussions**

The second half of the workshop featured four expert-led panel discussions:

1. Emerging Trends in Observation and Data Assimilation

Panelists: Dr. Vijay Thallapragada, Dr. S. P. Aggrawal, Dr. Randir Singh, Dr. Sudheer Joseph, Dr. Ananda Kumar Das, Dr. Ashish Routray

Moderator: Dr. Indira Rani | Rapporteur: Dr. Upal Saha

Focus: Advances in observation technologies, data quality, and assimilation techniques to improve model accuracy.

2. Future Roadmap for Modelling

Panelists: Prof. U.C. Mohanty, Dr. R. Krishnan, Prof. A. Chandrasekhar, Dr. Huw Lewis, Prof. D.V. Bhaskara Rao, and Dr. Saji Mohandas

Moderator: Dr. A. Jayakumar | Rapporteur: Dr. Anurose T. J.

Focus: Innovations in modelling frameworks, parameterization schemes, and computational advancements.

3. NWP Products for Evolving User Requirements

Panelist: Prof Balaji Ramakrishnan, Air Commodore S K Thakur, Dr Kamaljit Ray, Dr Raghavendra Ashrit, Prof. Rajiv Bhatla

Moderator: Dr. V. K. Soni | Rapporteur: Dr. Mohana S. Thota

Focus: Development of tailored NWP products to meet diverse user needs across sectors like agriculture, disaster management, and aviation.

4. Scope of Hybrid Methods in Data Assimilation and Weather Forecasting

Panelists: Dr. K J Ramesh, Dr. John P George, Dr KC Gouda, Mr. Raghavendra Sreevathsa

Moderator: Dr. K. Amar Jyothi | Rapporteur: Dr. Kondapalli Niranjan Kumar

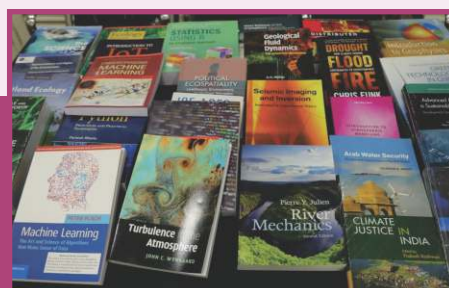
Focus: Integration of hybrid methods combining machine learning, traditional techniques, and big data analytics to enhance prediction accuracy.



• Value-Added Activities

To further enrich the event:

- A plantation drive was organized, emphasizing environmental sustainability and aligning with global climate goals.
- A book fair by Cambridge University Press provided attendees with access to advanced meteorological literature.



- **Closing Ceremony**

The workshop concluded with a vote of thanks by Dr. Ashish Routray, who acknowledged the contributions of all attendees, organizers, and dignitaries. The National Anthem and a group photograph symbolized the unity and collective vision of the meteorological community.



- **Significance and Future Directions**

The workshop highlighted NCMRWF's commitment to advancing meteorological science through innovation, collaboration, and capacity-building. With a strong focus on addressing uncertainties in weather prediction, NCMRWF is prepared to achieve global leadership in NWP. The event underscored the importance of sustained efforts, cutting-edge research, and international partnerships in driving the next generation of meteorological breakthroughs.



COLLABORATIONS AND OUTREACH

a. National and International Meteorological Agencies

The 5th Annual Science Meeting of the Weather and Climate Science for Service Partnership India (WCSSP-India) took place from July 2-5, 2024, at the UK Met Office in Exeter. A 10-member Indian delegation, led by Dr. V. S. Prasad (NCMRWF), included Dr. John P. George, Dr. Akhilesh Mishra, Dr. Kamaljit Ray (MoES), Dr. Shiekha Elizabeth John (MoES), Dr. Anupam Hazra (IITM), Dr. Vinu K. Valsala (IITM), Dr. Prashanth A. Pillai (IITM), Dr. R. K. Jenamani (IMD), and Dr. Shobhit Katiyar (IMD). The meeting focused on scientific advancements in coupled modeling, data assimilation, monsoon predictability, and impact-based forecasting. Delegates engaged in presentations, discussions, and side meetings with UK scientists, including Dr. Matt Martin, Dr. Huw Lewis, and Dr. Arathy Menon. They also met UK Met Office Chief Executive Prof. Penny Endersby and visited key Met Office facilities, strengthening Indo-UK collaboration and contributing to improved weather forecasting capabilities for India.



- The Seychelles Meteorological Authority (SMA) visited NCMRWF to explore our NWP facilities and strengthening international collaborations for enhanced weather forecasting capabilities.
- Delegates from Tamil Nadu Disaster Risk Reduction Agency (TNDRRA) visited NCMRWF on 27th August 2024, for a familiarization of ongoing research works at NCMRWF.
- The delegation of UKRI and NERC visited NCMRWF to discuss the potential areas of collaboration.



WCSSP-India Work Package Meeting (November 20–21, 2024)

The WCSSP-India initiative promotes UK-India collaboration to advance weather and climate science for societal benefits. Held at NCMRWF, the meeting reviewed progress on ongoing projects and explored academic partnerships. Key participants included researchers from the UK Met Office, MoES, and representatives from Indian academia.



6th Momentum Partnership Convective Scale Workshop & LFRic Training, BoM, Australia (September 9–20, 2024)

A delegation of four scientists from NCMRWF, led by Dr. A. Jayakumar, participated in the 6th Momentum Partnership Convective Scale Workshop and Joint Annual R&D Workshop in Melbourne, Australia, from September 9–13, 2024.

Dr. Jayakumar delivered a talk on “Evaluation of CASIM Microphysics Using DSD Bulk Parameters and Its Improvement for Monsoon Weather Extremes.”

Dr. Akhilesh Kumar Mishra presented “Indian Monsoon 2023 & 2024 in a Partially Coupled Regional Suite.”

Dr. Gibies George and Dr. Mohan S. Thota actively participated in the workshop discussions.

As part of convection-permitting model development, Dr. Jayakumar also presented on “The Role of Advanced Cloud Microphysics in the Prediction of Extreme Precipitation,” highlighting improvements in warm rain microphysics for cloud-to-rain mass conversion during monsoon cases.



Colloquium and Training Workshop on HAFS at NCMRWF (November 20–22, 2024)

The Hurricane Analysis and Forecasting System (HAFS), NOAA's advanced high-resolution coupled atmosphere-ocean-wave model for tropical cyclone (TC) forecasting across global tropical ocean basins, represents a milestone in TC prediction, enhancing accuracy and lead times for disaster preparedness. To foster capacity building among scientists and young researchers in TC studies, NCMRWF, in collaboration with IMD and NOAA's Environmental Modeling Center (EMC), hosted a Colloquium and Training Workshop on HAFS from November 20–22, 2024.

The event was led by Dr. Michael R. Farrar, Director of NCEP, and Dr. Vijay Tallapragada, Senior Scientist at NOAA's EMC. Five esteemed scientists from NOAA delivered lectures and facilitated hands-on training sessions, ensuring an immersive learning experience.

The workshop brought together 40 participants, including researchers and professionals from organizations, universities, IITs, and IISERs. It served as a platform for technical discussions, knowledge sharing, and practical training on the HAFS framework, emphasizing its role in advancing tropical cyclone forecasting capabilities.



Dr. Preveen Kumar D and Dr. B. Athiyaman represented NCMRWF at SC24, the International Conference for High-Performance Computing, held from Nov 17-22, 2024, in Atlanta, GA, USA. Engaging discussions with different HPC OEMs on HPC innovations and future road map.



b. Stakeholders Engagement

NCMRWF hosted NWP Data User workshop for Grid-India, highlighting sectoral applications crucial to Renewable Energy. The interactions during the workshop helped develop synergy for collaborative work and data exchange.



Dr. R. Ashrit, Sc-G and Sushant Kumar, NCMRWF participated in the "Stakeholder Consultation Workshop on Modelling of Solar/Wind Power Plants and Forecasting of VRE Generation" organized by GRID-India & CIGRE. Dr. Ashrit delivered an invited lecture on Numerical Weather Prediction

Dr. V. S. Prasad, Head of NCMRWF, had a productive discussion with Cochin University of Science & Technology Vice-Chancellor, Prof. (Dr.) M. Junaid Bushiri, and the Director of the Advanced Centre for Atmospheric Radar Research, Prof. Abhilash, on ways to enhance collaboration.

c. Memorandum of Understanding

Dr. V.S. Prasad, Head, NCMRWF, and Dr. P.K. Satyawali, Director, DGRE, DRDO, signed an MoU on 20 May 2024, at the office of DGRE, Chandigarh. Present were scientists Dr. Ashish Routray and Dr. Surya K Dutta from NCMRWF, along with Dr. M. S. Shekhar and others from DGRE.

As a part of the NCMRWF-IIST MoU, the first meeting was held on 30th October 2024, to discuss the plan of action to enhance the MoU activities. The discussion was led by Dr. V. S. Prasad, Head, NCMRWF, and Prof. Dipankar Banerjee, Director, IIST.



d. Training Programs, Workshops, & Knowledge-sharing sessions

A 2-day training on "Data Driven Decision Making" was held at NCMRWF on May 21-22, 2024. Expert faculty from Wadhvani Center for Government Digital Transformation trained NCMRWF staff on the latest tools to make data-driven decisions



NCMRWF scientists presented the research work in the 8th WMO Workshop on the "Impact of Various Observing Systems on Numerical Weather Prediction and Earth System Prediction," being held during 27-30 May 2024, in Norrköping, Sweden (online/in-person), shared valuable insights.

Dr. Akhilesh Mishra, Sc.E, shared insights on "NCMRWF Sub-seasonal & Seasonal (S2S) Products" at SASCOF-28 for the Summer Monsoon Season and CSUF held at Pune, India (29 April - 01 May, 2024). Dr. Ankur Gupta, Sc.D, also attended the meeting.

Dr. Amar Jyothi, Scientist-E, gave a talk on "Application of NWP - An AI/ML Perspective" at the workshop titled "AI/ML Methods in Weather Modelling" organized by the Centre for Data, Learning and Decision Sciences at Ashoka University, Sonipat, on 7th September 2024.

Mr. Harvir Singh, Proj.Sc-III, NCMRWF delivered 2 talks in the "9th International Verification Methods Workshop (9IVMW)", 20-22 May 2023, Cape Town, South Africa.

Mr. Harvir Singh delivered a virtual talk on "Improving Heatwave Predictions with Machine Learning: Insights from India's Rising Temperature Trends" at the 2024 NOAA Subseasonal and Seasonal Applications Workshop, held on 4-6, September, 2024.

Dr. Anumeha Dube, Sc-E of NCMRWF, participated in the Brainstorming Workshop on "Strengthening Regional Capability for Effective Utilization of Meteorological Services in Agriculture and Allied Sectors," held on 31 May - 1 June 2024.

Dr. A. Jayakumar, Sc-E of NCMRWF participated in STIPMEX Conference at IITM Pune and Chaired a Session on Extreme Weather Prediction.

Dr. Jayakumar, Dr. Kondapalli Niranjan Kumar, and Dr. Ankur Gupta presented NCMRWF research activities at the 9th

Global Energy and Water Exchanges (GEWEX) Open Science Conference, 7-12 July 2024, Sapporo, Japan.

Dr. Mohana S. Thota, Scientist-E, attended a one-day workshop on "Monsoon Variability and Its Impact on India's Hazardscape" held at India Habitat Center (IHC), New Delhi on 12th August 2024.

Dr. Hashmi Fatima presented her work on soil moisture analysis for landslide warnings during heavy rainfall at the #JULES Annual Science Meeting 2024 (4-5 Sept), important research contributing to disaster preparedness.

On National Space Day (23 Aug 2024), Dr. Kondapalli Niranjan Kumar (Sc-'E') delivered a guest lecture at SRM Institute, Delhi/NCR campus on 'The Rising Dominance of Space-Based Observations in Numerical Weather Prediction.

Dr. A. Jayakumar and Dr. Anurose presented the "Dust forecast from NCMRWF Unified model" in the International Workshop on Dust and Aerosols (September 24) at Ministry of Earth Sciences, New Delhi.

Dr. Raghavendra Ashrit, Dr. S. Indira Rani, & Mr. Ashutosh Srivastava participated in the 36th Edition of the Four-Day Capacity Building Program on 'Advance Procurement & Strategic Sourcing' by the Indian Institute of Corporate Affairs, held from 24-27 September 2024 in Goa.

Dr. Kondapalli Niranjan Kumar, Sc-E, NCMRWF, delivered a plenary talk on "Forecasting Extreme Rainfall in the Indian Himalayan Region: Progress & Perspectives" at the Natural-hazard Symposium for the Indian Himalayas 2024 (NSIH 2024) hosted by Department of Hydrology, IIT Roorkee.

Dr. V S Prasad, Head, NCMRWF, delivered an insightful talk on "Predicting Monsoon Extremes and Early Warning Systems" at the SURE-ALERT training program at IISER Mohali. This one-week training program focuses on developing skills for landslide early warning techniques.

Dr. Preveen Kumar, Dr. B. Athiyaman, Dr. K. Amar Jyothi, Dr. Kondapalli Niranjan Kumar, Mr. Deepak Singh Bisht, and Mr. Sanjiban Roy from NCMRWF participated in the NVIDIA AI Summit India 2024 at the Jio World Convention Centre, Mumbai.

Dr. Indira Rani, Sc-F, NCMRWF, contributed as a Member of the International Programme Committee at the 6th WCRP International Conference on Reanalysis (ICR6) in Tokyo, Japan (28 Oct-1 Nov 2024). She delivered a keynote speech on "Renewable Energy Applications of Reanalysis".

Dr. Ashish Routray delivered an insightful talk on 'High Resolution Rapid Refresh Modelling System at NCMRWF' during TROPMET 2024 at NIT Rourkela. The session highlighted advanced capabilities in weather forecasting.

Dr. Sujata Pattanayak presented 'Analysis and Assimilation of INSAT-3DR Satellite Radiance in NCMRWF Global Forecast System' during TROPMET 2024 at NIT Rourkela. An insightful session on advancements in satellite data assimilation.

Dr. Mohan S. Thota, Scientist E, delivered a talk on "Medium Range Weather Forecasting and Related Services" during the brainstorming workshop on "Mission Mausam: Forecast to Field (Techniques and Targets for Amrit Kaal)" at IARI, New Delhi

Students from Calcutta University visited NCMRWF for the NWP Familiarization Course (4-11 Dec 2024). The program offered insights into atmospheric & ocean observation systems, fostering an enriched learning experience in weather prediction and modeling.

Dr Anitha Gera, Scientist-F, delivered an Invited talk on "Hydrodynamics and Biogeochemistry of the Public at Lake" at the Symposium on "BIODIVERSITY & WETLAND CONSERVATION" on the occasion of the Flamingo Festival at Pulicat Lake-2025 during 18th & 19 January 2025 at KREA UNIVERSITY, SiriCity, Tirupathi, AP organized by the AP state Govt.



A two-week BCWC training workshop (15-26 July 2024) jointly organized by NCMRWF and BCWC was inaugurated by Sh. Vishvajit Sahay, AS & FA, DST/DBT, and MoES at NCMRWF, Noida, in the presence of senior officials from MoES and NCMRWF.



Head, NCMRWF, Dr. V. S. Prasad, gave an invited talk at the international conference "Sustainable Agricultural Development with Climate Smart Systems (SADCSS-2024)" during 18-20 July 2024 at SOA University, Bhubaneswar, Odisha.

Dr. V.S. Prasad, Head, NCMRWF, delivered a talk titled "Advancement in NWP Modelling" at the National Symposium on "Seventy-Five Years of Accomplishment of Mausam: Quarterly Journal of Meteorology, Hydrology, and Geophysics" on 13th January 2025.

NCMRWF was excited to host Dr. Keiran Hunt from Univ. of Reading for his insightful seminar on 'Using explainable AI to better understand Indian weather'. He shared insights on AI frameworks for South Asian palaeomonsoons, low-pressure systems, and energy demand models.

Dr M Ravichandran, Secretary, MoES, Dr Mrutyunjay Mohapatra, DG, IMD and Dr VS Prasad, Head, NCMRWF held a press briefing on Mission Mausam, where they provided valuable insights into the initiative's goals and impact on India. The session concluded with an engaging Q&A, where they addressed questions from the media.

Dr V.S. Prasad, Head, NCMRWF, graciously presided as the chief guest at the National Seminar on "Current Trends in Atmospheric and Oceanic Processes Related to Climate Change Studies," organized by the Dept of Meteorology & Oceanography, Andhra University, from 18-20 Sep 2024.

Dr. V. S. Prasad, Head, NCMRWF & Dr. Raghavendra Ashrit, Sc-F, gave invited talks at the National Seminar on "Current Trends in Atmospheric & Oceanic Processes Related to Climate Change Studies," organized by Dept. of Meteorology & Oceanography AU, from 18-20 Sep 2024.



In the sixth webinar of the "Digital Earths Webinar Series," scientists from NCMRWF discussed the organization's exploration of the grey zone. This series is co-convened by Huw Lewis (Met Office, UK) and Rosimar Rios-Berrios (NCAR, USA). <https://youtu.be/z1WsV2rFpow>



NCMRWF organized a one-day open house and curtain raiser event for the 10th India International Science Festival (IISF)-2024 on 6th November 2024. Students from nearby colleges and universities visited the high-performance computing (HPC) facility and attended insightful presentations showcasing the organization's work. During the Climate Change and Disaster Management Summit at IISF-24, held at IIT Guwahati, Dr. V.S. Prasad, Head of NCMRWF, delivered a compelling talk on "Climate Change." The session emphasized shaping the future of climate adaptation and enhancing disaster resilience.



Air Warriors of the Indian Air Force and personnel from the Indian Navy visited NCMRWF, Noida for a one-day familiarization visit on 24th October 2024.

10 Indian Navy officers visited NCMRWF for a basic training program on Numerical Weather Prediction (NWP) and Data Assimilation (DA) from 10-12 Feb 2025. They engaged in insightful interactions with scientists during the training.

Air Warriors of IAF and personnel from the Indian Navy", led by Wg Cdr Pranjal Deka, visited NCMRWF, Noida on 20th Feb 2025 for basic training on Numerical Weather Prediction (NWP) and Data Assimilation (DA)



e. Internal Activities at NCMRWF

NCMRWF, Noida hosted a wonderful event on 21.06.2024, where all officers and staff participated in a one-hour yoga session. Special thanks to Yoga Instructors Sh. Nilesh Mourya and Ms Radhika from Morarji Desai National Institute of Yoga, Ministry of AYUSH, for guiding us.



NCMRWF organized a Walkathon from Prithvi Vihar (NCMRWF Residential Complex) to the NCMWRF office premises as a part of "Swachhata Hi Seva" Campaign. All officials enthusiastically participated in the event on 21 September 2024



Flag hoisting on the 78th Independence Day by Dr. V.S. Prasad, Head, NCMRWF at NCMRWF, Noida.



NCMRWF organized a cleanliness drive at the NCMRWF residential complex as part of the "Achievement of Special Campaign 4.0" in the first week of October 2024. The NCMRWF staff enthusiastically participated in this initiative.

Vigilance Awareness Week 2024 is being observed at NCMRWF from 28.10.2024 to 02.11.2024. Sh. H.K. Sharma, former Dy DG (Procurement), Ministry of Home Affairs, delivered an insightful talk on vigilance awareness on 29.10.2024.

On National Unity Day 2024, NCMRWF scientists and staff took the Rashtriya Ekta Diwas pledge to uphold the unity, integrity, and security of the nation, honoring the birth anniversary of Sardar Vallabhbhai Patel.

NCMRWF proudly celebrate the 74th Constitution Day. All NCMRWF officials gathered to recite the Preamble, honoring the values of Justice, Equality, Liberty, and Fraternity that define our nation.

NCMRWF-ICC organized a session for "Sexual Harassment at Workplace Prevention Week," with active participation from all staff, promoting awareness and discussions on building a safe and inclusive workplace.

On the International Day of Women and Girls in Science (11 Feb 2025), NCMRWF celebrates and applauds the contributions of women scientists and researchers. Wishing all women in STEM continued success and recognition.



f. Awards & Recognitions

Dr. V.S. Prasad, Head of NCMRWF, was honored with the prestigious IMS Fellow Award during TROPMET 2024, held at NIT Rourkela. As part of the event, Dr. Prasad also contributed to a panel discussion on "Agro-Meteorological Applications," where he emphasized innovative strategies for leveraging weather forecasting to support agriculture.

Dr. Kondapalli Niranjan Kumar, Scientist E, joined a panel discussion at the "Natural-Hazard Symposium for the Indian Himalayas 2024 (NSIH 2024)" hosted by the Department of Hydrology, IIT Roorkee. The symposium focused on addressing challenges and advancements in understanding and mitigating natural hazards in the Indian Himalayan region, providing a collaborative platform for experts and researchers to share insights and solutions.

Dr. Jayakumar, Scientist-E, NCMRWF, joined the panel discussion on "Weather and Climate Services for Air Quality and Health Sectors" at the 150th Foundation Day of the India Meteorological Department.

Dr. Kondapalli Niranjan Kumar, Scientist E, invited as a panelist in the workshop on 'Co-producing Risk-informed, Gender-responsive Actions & Adaptation Pathways at Local Level (CRITICAL). He contributed to the session 'Opportunities for Climate Information Downscaling at Local-Level,' organized by CoEDMM, IIT Roorkee, & GIZ India's CAFRI II project on Jan 30, 2025.

Dr. Saji Mohandas, Scientist G, invited as a keynote speaker for the National Conference on "Mitigating Lightning Hazards: Advancing Monitoring, Forecasting, Protection, and Community Resilience" at Fakir Mohan University, Odisha, from February 13–15, 2025.



WMO Secretary-General Prof. Celeste Saulo visited NCMRWF. Dr. V.S. Prasad welcomed her and showcased the center's activities. She appreciated the ongoing modelling and data assimilation work at NCMRWF.



Prof Petteri Taalas, Director General, Finnish Meteorological Institute leading 3-member delegation visited NCMRWF. Head NCMRWF, Dr Prasad & other senior scientists had a discussion with the delegation on ongoing research activities at NCMWRF & possible collaborations



BIMSTEC CENTRE FOR WEATHER AND CLIMATE (BCWC)

The Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC), established on 6 June 1997, promotes economic growth and social progress in the Bay of Bengal region. Initially called BIST-EC, it was renamed BIMSTEC after Myanmar joined in 1997, followed by Bhutan and Nepal in 2004. Its seven Member States are Bangladesh, Bhutan, India, Myanmar, Nepal, Sri Lanka, and Thailand. The goal of BIMSTEC is to promote economic and technical cooperation among these countries. The following flow chart (Figure 45) provides the seven sectors of cooperation among the BIMSTEC member countries.

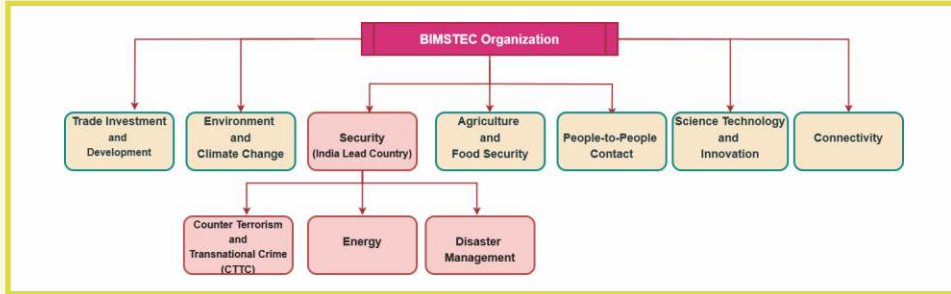


Figure 45: Schematic indicating the seven sectors of cooperation among the BIMSTEC member countries with India leading the "Security" sector

BIMSTEC focuses on collaboration across various sectors with India leading the "Security" sector, including Counterterrorism, Disaster Management, and Energy. Under Disaster Management, BIMSTEC Centre for Weather and Climate (BCWC) was established as a virtual centre at NCMRWF following the inaugural BIMSTEC Summit held on July 31, 2004, in Bangkok where India proposed to set up a BCWC in India to enable all BIMSTEC countries to pool their scientific resources for providing weather and climate-related information and services to the society at large taking advantage of the existing weather forecasting system in India.

A Memorandum of Association (MoA) was signed by all the member countries on 04 March 2014 during the 3rd BIMSTEC Summit in Myanmar to establish the BCWC in India. Thus, NCMRWF has been doubling up as BCWC with the following objectives

- To promote and encourage cooperation between BIMSTEC member countries in identified areas of fundamental and applied scientific research in weather prediction and climate modelling
- To promote scientific capacity building in weather and climate research
- To encourage and assist the publication of important research results obtained within the BIMSTEC cooperation framework on weather and climate.

BCWC facilitates real-time forecast sharing, organizes workshops, and holds weekly discussions among forecasters and scientists from member states. BCWC also drives collaborative research to support disaster management and risk reduction in the region.

BIMSTEC Day" Celebrated at BCWC & NCMRWF, Noida on 6th June 2024

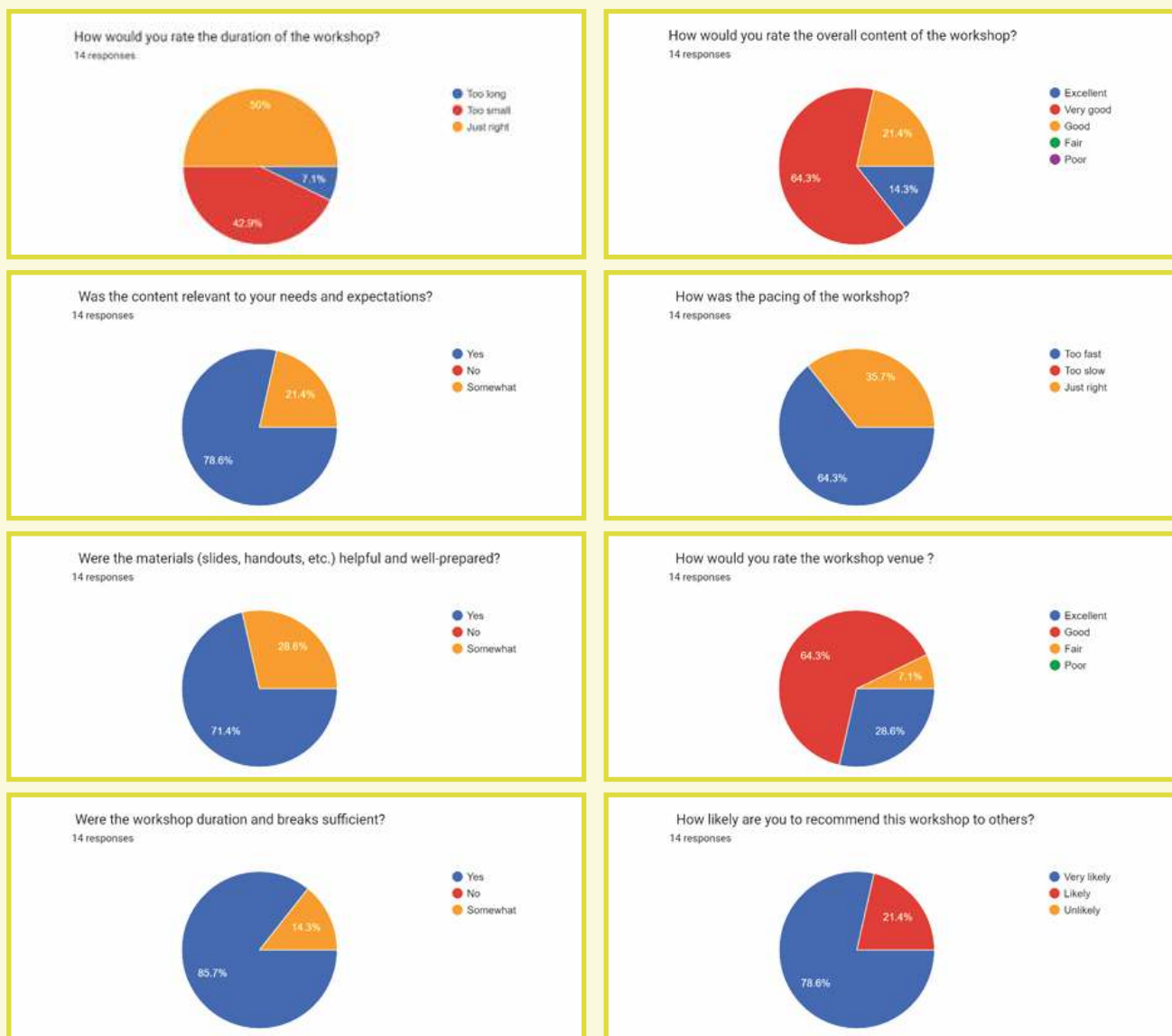


• **BCWC Training Workshop 15-26 July 2024**

BCWC & NCMRWF hosted a training workshop for the students and young researchers belonging to the BIMSTEC member countries. The Training Workshop was planned during the third GB & SAC meeting held in Dec 2023 at BCWC, Noida. All the members of the SAC took a keen interest in identifying scientific themes for the training workshop. During the following months, special online meetings of BCWC-SAC were held to crystalize the training content and format. It was finally agreed that the training should include lectures and hands-on practical sessions. It was also decided that the lecture sessions would be conducted in hybrid mode, enabling other forecasters/scientists from the member countries to attend online.

Accordingly, the two-week training from 15-26 July 2024 was organized at BCWC/NCMRWF Noida. The training workshop was attended by 18 participants from the six BIMSTEC member countries. All the participants were from the National Hydro-Met Services (NHMS). The participation had a healthy mix of young & experienced forecasters/scientists. They also belonged to diverse areas of work experience like cyclone forecasting, operational meteorology, etc.

Feedback from participants



The two-week training schedule was prepared to provide broad exposure and an in-depth understanding of the various topics. The workshop was inaugurated by the Additional secretary of MoES, Shri. Vishvajit Sahay on 15th Jul 2024. In the first week from 15-19 Jul 2024, the training covered some introductory topics and advanced NWP concepts to get the participants started. Subsequently, the training focused on high-resolution WRF modelling and data assimilation. All participants could work on the NCMRWF HPC for hands-on practical sessions. They could carry out model simulations

for the respective countries. The lecture sessions were accompanied by hands-on practical sessions involving running the WRF modelling system and data assimilation exercises. NCMRWF HPC was used for the hands-on practical sessions. Each BIMSTEC member country was given a separate user ID for working on HPC. The participants had the opportunity to design the experiments that were configured to their respective country geographies and select simulations of weather disturbances specific to their respective countries. The participants gained useful experience while using the HPC for hands-on practical exercises. For all the technical difficulties, help and assistance were provided by project scientists and NCMRWF volunteers.

During the training course, there were lectures from 16 speakers. Three speakers were invited from IMD. It provided an opportunity for exciting discussions on the operational practices/challenges in India and other BIMSTEC member countries. All the faculty and volunteers pitched extra to engage with the participants. The hands-on sessions are often extended until 6 PM in the evening. The training also included a tour of NCMRWF HPC and a session on using HPCs in weather and climate. On the final day today, we had no lectures. Participants and faculty were both engaged in clearing doubts or additional hands-on exercises or planning projects using the NCMRWF Data, etc.



Workshop participants during hands-on practical sessions



Workshop participants visiting NCMRWF HPC (top) and India Meteorological Department (bottom)

Workshop participants visiting NCMRWF HPC (top) and India Meteorological Department (bottom)

•4th GB Meeting of BCWC on 18th Nov 2024

The 4th Governing Board (GB) Meeting of the BIMSTEC Centre for Weather and Climate (BCWC) was held at BCWC/NCMRWF on the 18th Nov 2024. The Governing Board (GB) of the BCWC meets annually to monitor and review the activities and future plans of the BCWC to make suitable recommendations. The members of GB are the Director General (DGs) of the NHMS of each of the member countries or their nominated representatives. The members from Bhutan, Bangladesh, Myanmar, Thailand along with ex-officio member from BIMSTEC Secretariate attended the meeting in person. The representatives from Sri Lanka and Nepal attended the meeting online. India (Dr. V. S. Prasad) is elected as the Chair of the GB for the year 2024-25.



BIMSTEC "Youth-Led Action on Climate Change"

The NCMRWF and BCWC hosted participants of the BIMSTEC Youth-Led Action on Climate Change program, organized by Bharat Scouts and Guides (BSG). The event was inaugurated by Dr. M. Ravichandran, Secretary, MoES, at NCMRWF. During their visit, the young participants attended insightful sessions on weather and climate forecasting and engaged in interactive discussions with NCMRWF scientists. They also toured the high-performance computing (HPC) facility and learned about research and collaboration opportunities available for students from BIMSTEC member countries.



BCWC Vision

Climate Change and its regional impacts are going to significantly alter and affect the lives and economies in densely populated South Asia. The effects of the regional impacts in short, medium and long term are all expected to exceed the thresholds of local weather and climate for which communities have adapted over decades and centuries. With increasing extreme weather conditions evidenced during recent decades and their devastating impacts as testimony. India's vision and plan towards advancing the weather and climate Science by 2047 will be strongly linked with the regional cooperation and impacting the regional economies. BCWC and NCMRWF will be in the forefront of technological adaptation and innovation to help and enable the operational agencies in the BIMSTEC member countries in providing early warning services by the operational agencies. Providing regional leadership, BCWC through regional and global collaborations envisages to use state of the art technologies and provide capacity building for the BIMSTEC member countries. This involves, Data Collection from all the member countries, enhancing the observational network with conventional and non-conventional platforms, use of crowd sourced data, IoT, advanced AI/ML techniques. The program envisages enabling and empowering the end-user/individual user or communities to make better adaptive or mitigative decisions to minimize the adverse effects due to disasters.

FUTURE INITIATIVES

This section outlines NCMRWF's strategic roadmap for advancing its capabilities in high-resolution Earth System Modelling (ESM), data assimilation, and forecasting. Leveraging the state-of-the-art HPC system, Arunika, and its robust data management infrastructure, these initiatives aim to address emerging challenges in weather and climate prediction. By integrating advanced technologies such as AI/ML, hybrid modelling, and high-resolution urban-scale systems, NCMRWF is prepared to deliver actionable insights and support societal resilience against extreme weather events. These efforts align with national priorities and global advancements in Earth system sciences.

a. Strategic plans for upcoming years

The evolving complexity of Earth System Models (ESMs) demands a robust and high-quality observational network to improve data assimilation (DA) and forecasting capabilities. NCMRWF plays a critical role in efficiently utilizing the enhancements to the observational network under the initiative of "Mission Mausam" to advance its DA systems. By integrating observations from dense sensor networks, weather radars, UAVs, and radiosonde descent profiles, NCMRWF aims to refine forecast accuracy and uncertainty quantification. The establishment of Direct Broadcast Network (DBNet) and GeoNetCast stations will further enable real-time data ingestion and processing. International collaborations, such as the Joint Effort for Data Assimilation Integration (JEDI), will facilitate the development of modular DA systems and seamless integration of diverse observations, including data from advanced satellite platforms, to enhance Earth system modeling and prediction capabilities.

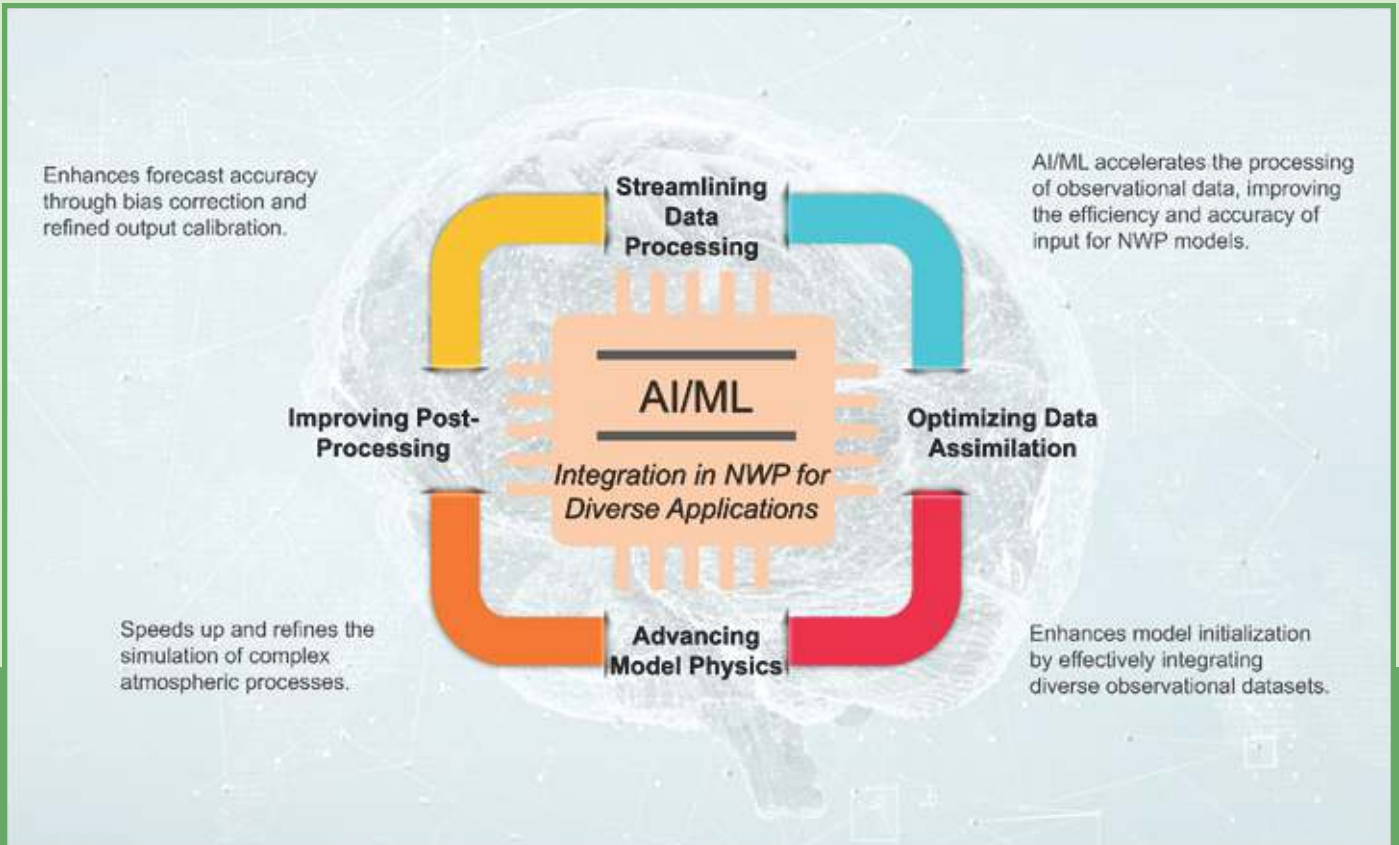
NCMRWF is committed to advancing seamless ESM to deliver accurate and actionable forecasts at various spatial and temporal scales. In alignment with IMD's initiative "Har Har Mausam, Har Ghar Mausam," the centre aims to upgrade its current unified model to the Atmanirbhar Unified Earth System Model (AUESM). This upgraded model will feature an advanced dynamical core on an unstructured cubed sphere mesh, improving the representation of critical physical processes such as boundary layer dynamics, convection, microphysics, and aerosol-cloud interactions. With a resolution of 3–6 km, AUESM will provide skillful medium-range forecasts and identify extreme weather events up to 3–4 weeks in advance. Enhanced regional systems, updated with high-resolution terrain and land-use data, will refine predictions of tropical rainfall intensity and timing. Further upgrades to ensemble prediction systems, incorporating multiple inflation schemes, will address uncertainties and improve forecast reliability. NCMRWF envisions developing kilometre-scale ESMs capable of resolving deep convection and sub-grid processes, ultimately contributing to a seamless predictive framework for high-impact weather and urban-scale modelling.

NCMRWF's future initiatives will leverage the advanced computational capabilities of its next-generation supercomputing system, Arunika, with 8.24 petaflops of peak performance and 24 petabytes of storage, to drive breakthroughs in ESM and data assimilation. The centre aims to operationalize the Atmanirbhar Unified Earth System Model (AUESM) with kilometre-scale resolution, improving forecasts of high-impact weather events and resolving sub-grid scale processes. Ensemble Prediction Systems (EPS) will be expanded, offering adaptive ensemble sizes for disaster-prone areas. Advanced data assimilation systems, such as the JEDI, will process extensive observational datasets, including those from satellites and dense sensor networks. Urban-scale modelling will be enhanced to metre-scale resolutions, focusing on megacities and localized weather phenomena. A robust 10 PB High-Performance Storage System (HPSS) will manage growing data volumes, while the Closed User Group (CUG) network and National Knowledge Network (NKN) will ensure secure and efficient data sharing. These initiatives position NCMRWF to advance scientific research and deliver actionable insights for societal benefit.

b. Focus areas for Research and Operations, emphasizing AI/ML

NCMRWF aims to integrate AI/ML techniques across key stages of the NWP workflow to enhance forecast accuracy and operational efficiency. Efforts will focus on developing a radar and satellite data-based nowcasting system for precise short-term forecasting. AI/ML applications will include hybrid data assimilation methods, improved quality control of observational data, and optimized model physics calculations. Machine learning-based parameterizations will be introduced to better represent complex atmospheric processes, while AI-driven diagnostic tools will help identify and address systematic errors in model processes. Additionally, personalized weather alerts through smartphones, tailored to real-time data and user preferences, will be developed to empower better decision-making. These initiatives will lay the

foundation for a comprehensive AI/ML-enhanced NWP framework, bridging the gap between traditional models and innovative technologies for improved weather-based risk reduction.



राजभाषा कार्यान्वयन

राजभाषा निरीक्षण

- दिनांक 15.04.2024 को क्षेत्रीय कार्यान्वयन कार्यालय (उत्तर-2) गाजियाबाद, राजभाषा विभाग, गृह मंत्रालय द्वारा राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र का निरीक्षण किया गया। उक्त निरीक्षण में कार्यालय की विभागीय राजभाषा कार्यान्वयन तथा निष्पादन समिति के सदस्यों ने भाग लिया।



राजभाषा कार्यशाला

- राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र, नोएडा में दिनांक 20.06.2024 को एक दिवसीय हिन्दी कार्यशाला का आयोजन किया गया। जिसमें श्री स्वामी चिद्रूपानंद, निदेशक, अखिल भारतीय चिन्मय युवा केंद्र द्वारा व्याख्यान दिया गया। कार्यालय के सभी अधिकारियों ने कार्यशाला में भाग लिया।
- रा. म. अ. मौ. पू. के. कार्यालय में दिनांक 24.09.2024 को हिन्दी कार्यशाला का आयोजन किया गया। डॉ. के अमर ज्योति, वैज्ञानिक-ई और श्री दीपक सिंह बिष्ट, परियोजना वैज्ञानिक II, रा. म. अ. मौ. पू. के. द्वारा "राजभाषा हिन्दी में कृत्रिम बुद्धिमत्ता का योगदान" विषय पर व्याख्यान दिया गया, जिसमें सभी अधिकारियों एवं कर्मचारियों ने भाग लिया।
- राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र, नोएडा में दिनांक 06.12.2024 को एक दिवसीय हिन्दी कार्यशाला का आयोजन किया गया। जिसमें श्री ललित भूषण, सदस्य सचिव, नराकास (उपक्रम), गाजियाबाद द्वारा व्याख्यान दिया गया। कार्यालय के सभी अधिकारियों ने कार्यशाला में भाग लिया।



प्रारम्भिक अनुवाद प्रशिक्षण में प्रतिभागिता

- राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र, नोएडा की कनिष्ठ अनुवाद अधिकारी सुश्री रुचिका ने दिनांक 01.07.2024 से 12.08.2024 तक केंद्रीय अनुवाद ब्यूरो, गृह मंत्रालय द्वारा आयोजित '30 कार्य दिवसीय प्रारम्भिक अनुवाद प्रशिक्षण कार्यक्रम' में भाग लिया।



नराकास, नोएडा की छमाही बैठक में प्रतिभागिता

- रा.म.अ.मौ.पू.के., नोएडा से श्री विश्वजीत गुहा, उप सचिव, डॉ हाशमी फातिमा, वैज्ञानिक-डी व हिन्दी प्रभारी तथा सुश्री रुचिका, कनिष्ठ अनुवाद अधिकारी ने दिनांक 23.08.2024 को राष्ट्रीय होटल प्रबंध एवं केंटरिंग टेकनालॉजी परिषद में आयोजित नराकास, नोएडा की 47वीं बैठक में भाग लिया।



हिन्दी पखवाड़ा-2024

- राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र, नोएडा में हिन्दी पखवाड़ा (01.09.2024 से 14.09.2024) का उद्घाटन मुख्य अतिथि डॉ प्रमोद कुमार सत्यवली, वैज्ञानिक-एच व निदेशक, डी. जी. आर. ई द्वारा दिनांक 02.09.2024 को किया गया। मुख्य अतिथि ने राजभाषा हिन्दी के महत्व का उल्लेख किया तथा हिन्दी में कार्य करने को बढ़ावा देने के लिए किए जाने वाले विभिन्न प्रयासों के बारे में बताया। उद्घाटन समारोह में कार्यालय के सभी अधिकारियों तथा कर्मचारियों ने भाग लिया।
- हिन्दी पखवाड़ा-2024 के दौरान विभिन्न प्रतियोगिताओं का आयोजन करवाया गया। प्रतियोगिताओं में कार्यालय के सभी अधिकारियों / कर्मचारियों ने बढ़-चढ़कर भाग लिया
- रा. म. अ. मौ. पू. के. कार्यालय में हिन्दी पखवाड़ा 2024 के समापन समारोह का आयोजन किया गया। मुख्य अतिथि डॉ. अजीत त्यागी, पूर्व महानिदेशक, भारत मौसम विज्ञान विभाग तथा सहायक प्रमुख, वायुसेना द्वारा विजेता अधिकारियों / कर्मचारियों को प्रमाण पत्र दिए तथा 'मेघदूत' अर्द्धवार्षिक पत्रिका का विमोचन किया गया। समारोह में कार्यालय के सभी अधिकारियों एवं कर्मचारियों ने भाग लिया।



पारंगत योजना (जनवरी-मई, 2024)

- राजभाषाविभाग, गृह मंत्रालय द्वारा आयोजित हिन्दी शिक्षण योजना के अंतर्गत "पारंगत योजना (जनवरी-मई, 2024)" में राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र, नोएडा के 10 अधिकारियों/कर्मचारियों ने भाग लिया तथा सभी अधिकारियों/कर्मचारियों ने अच्छे अंकों से परीक्षा उत्तीर्ण की।

पारंगत परीक्षा निम्नलिखित अधिकारियों/कर्मचारियों द्वारा उत्तीर्ण की गई:-

क्रम सं	नाम	पदनाम
1.	डॉ मोहन सत्यनारायण थोटा	वैज्ञानिक दृ ई
2.	डॉ कोंडापल्ली निरंजन कुमार	वैज्ञानिक दृ ई
3.	डॉ बी आरआर हरी प्रसाद कोट्टु	वैज्ञानिक दृ डी
4.	डॉ देसम्सेट्टी श्रीनिवास	वैज्ञानिक दृ डी
5.	डॉ सुजाता पट्टनायक	वैज्ञानिक दृ ड
6.	श्री आशुतोष श्रीवास्तव	अनुभाग अधिकारी
7.	सुश्री रुचिका कनिष्ठ	अनुवाद अधिकारी
8.	श्रीमती रचना पाल	बहुकार्य कर्मचारी
9.	श्रीमती आयुषी शर्मा	बहुकार्य कर्मचारी
10.	श्री मोहित शर्मा	कनिष्ठ सहायक

- राष्ट्रीय मध्यम अवधि मौसम पूर्वानुमान केंद्र, नोएडा से डॉ हाशमी फातिमा, वैज्ञानिक- डी व हिन्दी प्रभारी तथा सुश्री रुचिका, कनिष्ठ अनुवाद अधिकारी ने दिनांक 14.09.2024 को भारत मंडपम, नई दिल्ली में आयोजित चतुर्थ अखिल राजभाषा सम्मेलन (राजभाषा हीरक जयंती वर्ष) में भाग लिया।
- हिन्दी कार्यशाला (06.12.2024) में उप सचिव तथा मुख्य व्याख्यता द्वारा सुश्री रुचिका, कनिष्ठ अनुवाद अधिकारी तथा श्री मोहित शर्मा, कनिष्ठ सहायक को पारंगत परीक्षा, 2024 उत्तीर्ण करने पर कार्यालय की ओर से स्मृति चिह्न प्रदान किया गया।



- रा. म. अ. मौ. पू. के., नोएडा से डॉ. वी. एस. प्रसाद, कार्यालय प्रमुख, डॉ. हाशमी फातिमा, वैज्ञानिक-डी व हिन्दी प्रभारी तथा सुश्री रुचिका, कनिष्ठ अनुवाद अधिकारी ने दिनांक 29.01.2025 को राष्ट्रीय मुक्त विद्यालयी शिक्षा संस्थान में आयोजित नराकास, नोएडा की 48वीं बैठक में भाग लिया।
- दिनांक 17.02.2025 को रा. म. अ. मौ. पू. के. से श्री अंकुर गुप्ता, डॉ. हरि प्रसाद कोट्टू, डॉ. देवानील चौधरी एवं डॉ. ग्रीष्माएम. मोहन ने जयपुर, राजस्थान में आयोजित मध्य, पश्चिम, उत्तरी क्षेत्रों के संयुक्त क्षेत्रीय राजभाषा सम्मेलन एवं पुरस्कार वितरण समारोह में भाग लिया।
- दिनांक 17.02.2025 को रा. म. अ. मौ. पू. के. से श्री अंकुर गुप्ता, डॉ. हरि प्रसाद कोट्टू, डॉ. देवानील चौधरी एवं डॉ. ग्रीष्माएम. मोहन ने जयपुर, राजस्थान में आयोजित मध्य, पश्चिम, उत्तरी क्षेत्रों के संयुक्त क्षेत्रीय राजभाषा सम्मेलन एवं पुरस्कार वितरण समारोह में भाग लिया।
- रा. म. अ. मौ. पू. के. कार्यालय में दिनांक 05.03.2025 को "व्याकरणिक भूलें एवं निराकरण" नामक विषय पर कार्यशाला का आयोजन करवाया गया। जिसमें श्रीमती सुनीता यादव, सहायक निदेशक, राजभाषा विभाग द्वारा व्याख्यान दिया गया। कार्यशाला में कार्यालय के सभी अधिकारियों/कर्मचारियों ने भाग लिया।



HUMAN RESOURCES

a. Details of Officers & Staff (Regular)

Name	Designation
Dr. V.S. Prasad	Scientist – G & Head
Dr. John P. George	Scientist - G
Dr. Preveen Kumar D	Scientist - G
Dr. Saji Mohandas	Scientist - G
Dr. Raghavendra Ashrit	Scientist - G
Dr. B. Athiyaman	Scientist - F
Dr. Ashish Routray	Scientist - F
Dr. Indira Rani	Scientist - F
Sh. M.N. Raghavendra Sreevathsa	Scientist - F
Dr. Anitha Gera	Scientist - F
Dr. Aditi	Scientist - E
Dr. D.K.Mahapatra	Scientist - E
Dr. A.Jayakumar	Scientist - E
Dr. Anumeha Dube	Scientist - E
Sh. Imranali M. Momin	Scientist - E
Dr. K. Amar Jyothi	Scientist - E
Dr. Sumit Kumar	Scientist - E
Dr. Gibies George	Scientist - E
Dr. Ashu Mangain	Scientist - E
Dr. Suryakanti Dutta	Scientist - E
Dr. Mohana Satyanarayana Thota	Scientist - E
Dr. Hashmi Fatima	Scientist – D
Dr. Sujata Pattanayak	Scientist – D
Sh. Ankur Gupta	Scientist – D
Dr. Devajyoti Dutta	Scientist – D
Dr. D Srinivas	Scientist – D
Dr. BRR Hari Prasad Kottu	Scientist – D
Dr. Deepeshkumar Maheshkumar Jain	Scientist – D
Dr. Gaurav Rajabhau Goverdhan	Scientist – D
Sh. Basant Sharma	Scientist – C
Dr. Upal Saha	Scientist - C
Dr. M. V.S. Ramarao	Scientist – C
Dr. DevaniilChouhaury	Scientist - C
Ms. Pragya Joshi	SFO
Sh. A.K. Majumder	Junior Analyst
Ms. Ruchika	Jr. Translator
Sh. Arun Kumar	M.T.S
Sh. Rajkumar -II	M.T.S
Sh. V.K. Meena	M.T.S
Sh. Sonu	M.T.S
Ms. Rachna Pal	M.T.S
Ms. Suman Devi	M.T.S
Ms. Ayushi Sharma	M.T.S
Sh. Rajkumar- I (Senior)	M.T.S

MoES Staff working in NCMRWF

Dr. Akhilesh Kumar Mishra	Scientist - E
Dr. Anurose TJ	Scientist - E
Dr. Kondapalli Niranjan Kumar	Scientist – E
Sh. Biswajit Guha	DS
Sh. Ashutosh Srivastava	SO
Sh. Ashok Ranga	SSA
Sh. Shiv Kumar	MTS
Sh. Dinesh Kumar	MTS

b. Details of Project Scientists& Research Fellows

Name	Designation
Greeshma M. Mohan	Project Scientist III
Mansi Bhowmick	Project Scientist III
Shweta Bhati	Project Scientist III
Durgesh N. Piyush	Project Scientist III
S Kiran Prasad	Project Scientist III
Sandhya M	Project Scientist III
Dinesh Kr Sankhala	Project Scientist III
M Venkatarami Reddy	Project Scientist III
Rahul Raghudhas	Project Scientist II
Rehan Hossain	Project Scientist II
Jivesh Dixit	Project Scientist II
Smrutishree Lenka	Project Scientist II
Radharani Sen	Project Scientist II
Ezhilarasi S, Pro	Project Scientist II
Sanjiban Roy	Project Scientist II
Bibhuti Sharan Keshav	Project Scientist II
Ashutosh Sinha	Project Scientist II
Kumarjit Saha	Project Scientist II
Navin Chandra	Project Scientist II
Abhijit V	Project Scientist II
Sushant Kumar	Project Scientist II
Harvir Singh	Project Scientist II
Neha Rajput	Project Scientist II
Shivali Gangwar	Project Scientist II
Lokesh Pandey	Project Scientist II
Shenoy Meenakshi	Project Scientist II
Chollangi Sridevi	Project Scientist II
Suraj Ravindran	Project Scientist II
Nishtha Agrawal	Project Scientist II
Deepak Singh Bisht	Project Scientist II
Shubha Singh	Project Scientist II
Nagarjuna Rao	Project Scientist II
Sukhwinder Kaur	Project Scientist II
GopinadhRongali	Project Scientist II
Jisha CR	Project Scientist II
Donali Gogoi	Project Scientist II
Smrati Purwar	Project Scientist II
Gauri Shanker	Project Scientist II
Joydeb Saha	Project Scientist II
Sanjeeb Kumar Sahoo	Project Scientist II
Azad Singh Rajpoot	Project Scientist II
Aman Fatima	Pro Sci I
Md Amjad Ali	Pro Sci I
Jibi G Thannikkal	Tech. Ofc.

Research Fellows

Shivaji Singh Patel	JRF
Arpita Dhamija	JRF
Arunima	JRF
Vidushi Chauhan	JRF
Deepmala Vishwakarma	JRF
Pundarikaksha Nath	JRF
Akash Singh Rajput	JRF
Pundarikaksha Nath	JRF

11. Appendices

a. Internal Reports

- Bhowmick M., Jayakumar A., Mohandas S. and Anurose T.J. (2024). A utility for the vertical interpolation of UM sigma level fields to height above ground. Technical Report No. NMRF/TR/07/2024, https://www.ncmrwf.gov.in/Technical_report_August2024.php
- Indira Rani, S., Srinivas, D., Saha, U., Prasad, V.S., and John P. George (2024) NCMRWF Observation Reception, Processing and Monitoring (NCObsProM) System, Research Report No. NMRF/TR/09/2024, https://www.ncmrwf.gov.in/NCObsProM_Report_Dec_2024.php
- Lenka, S., Mohan T. S., Mohandas, S., and Prasad, V. S. (2024) An advanced process-oriented diagnostic for the representation of tropical convection, Research Report No. NMRF/RR/12/2024, https://www.ncmrwf.gov.in/GDI_report_20Dec2024_Final_SMMS.php
- Pandey, L., Gupta, A., and Mishra, A. K. (2024) Study of Indian Ocean features during 2023 summer monsoon using NCMRWF coupled model, Research Report No. NMRF/RR/06/2024. https://www.ncmrwf.gov.in/Lokesh_RR2024_IndianOceanFeature_in_CoupledModel.php
- Rajput, N., Amarjyothi K, Reddy, V., Kumar, D.P. (2024) Development of Near Real-time Blended Rainfall Product. Technical Report No. NMRF/TR/06/2024, https://www.ncmrwf.gov.in/Modified_Blended_NRT_product_report.php
- Saha, U., Indira Rani, S., Srinivas, D., Prasad, V. S. (2024) Real-time Monitoring of GTS Data Reception at NCMRWF, Research Report No. NMRF/TR/08/2024 https://www.ncmrwf.gov.in/Technical_Report_GTS_Data_Monitoring.php
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- Singh, P., Ashrit, R. and Kumar, S. (2024) NWP Model Wind Speed Forecast Evolution for Optimized Wind Farm Operation. Research Report No. NMRF/RR/11/2024 https://www.ncmrwf.gov.in/Wind_Farm_Research_REPORT_FINAL.php
- Singh, P., Kumar, S and Ashrit, R. (2024). Assessment of Wind Forecasts from NWP Model for Indian NPP Sites, Research Report No. NMRF/RR/07/2024 https://www.ncmrwf.gov.in/Wind_NPCIL_REPORT_FINAL.php
- Singh, S., Kumar, K. N., Dube, A., Mohan T. S., John P. George, Mohandas, S., and Prasad, V. S. (2025) Assessing Upper Tropospheric Humidity During Monsoon Depression Using NCMRWF Unified Model Forecasts, Research Report No. NMRF/RR/01/2025, https://www.ncmrwf.gov.in/shubha_JBB_report.php
- Niranjana Kumar, K., Sukhwinder Kaur, Mohana S. Thota, M. Venkatarami Reddy, Harvir Singh, Sushant Kumar, Anumeha Dube, and Raghavendra Ashrit, "NCUM Global Model Verification: Pre-monsoon (MAM) 2024". NMRF/VR/03/2024. https://www.ncmrwf.gov.in/NCUMG_MAM2024.php
- Niranjana Kumar, K., Sukhwinder Kaur, Mohana S. Thota, M. Venkatarami Reddy, Harvir Singh, Sushant Kumar, Anumeha Dube, Sumit Kumar, Raghavendra Ashrit, Saji Mohandas, and V.S. Prasad, "NCUM Global Model Verification: Monsoon (JJAS) 2024". NMRF/VR/04/2024. https://www.ncmrwf.gov.in/NCMRWF_MonsoonReport_JJAS2024.php
- Niranjana Kumar, K., Sukhwinder Kaur, Mohana S. Thota, M. Venkatarami Reddy, Harvir Singh, Sushant Kumar, Anumeha Dube, Sumit Kumar, Raghavendra Ashrit, Saji Mohandas, and V.S. Prasad, "NCUM Global Model Verification: October-November 2024". NMRF/VR/05/2024. https://www.ncmrwf.gov.in/NCUM_Vx_ON2024_final.php

b. Publications

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For more details on the past achievements of NCMRWF, readers are encouraged to refer to our publication "30 Years of Excellence in Operational Numerical Weather Prediction" and the Annual Reports. These publications provide a comprehensive overview of our progress and milestones. All reports are available at www.ncmrwf.gov.in/publications





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