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Delivering the Weather and Climate Science for Service Partnership (WCSSP) India in collaboration

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सार – 2017 में प्रारंभ की गई मौसम और जलवायु विज्ञान सेवा भागीदारी (Weather and Climate Science for Service Partnership–WCSSP) इंडिया, मौसम एवं जलवायु विज्ञान को सुदृढ़ करने के उद्देश्य से यूनाइटेड किंगडम और भारत के बीच दीर्घकालिक अनुसंधान साझेदारियों का निर्माण करती है। पूर्व में स्थापित सहयोग की परंपरा को आगे बढ़ाते हुए, यह कार्यक्रम वैज्ञानिक समझ, विधियों और उपकरणों में प्रगति के माध्यम से प्राकृतिक आपदाओं के जोखिम-आधारित पूर्वानुमान में सुधार पर केंद्रित है। ये सुधार जीवन और आजीविका की सुरक्षा करने वाली सेवाओं को बेहतर बनाने तथा भारत के पृथ्वी विज्ञान मंत्रालय (MoES) को कार्यवाही योग्य मौसम एवं मौसमी जलवायु संबंधी जानकारी प्रदान करने में सहायता करते हैं।

इस शोध-पत्र में WCSSP इंडिया के दृष्टिकोण का विवरण प्रस्तुत किया गया है तथा तीन उदाहरणात्मक क्षेत्रों में किए गए अनुसंधान का संक्षिप्त समेकित विवरण दिया गया है। इसमें मानसून प्रणालियों, चरम मौसम घटनाओं–विशेष रूप से कोहरे और कम दृश्यता–की समझ तथा जोखिम एवं प्रभाव-आधारित पूर्वानुमान विधियों के विकास में सहयोग के माध्यम से हुई हाल की प्रगति को रेखांकित किया गया है। WCSSP इंडिया की अनुसंधान उपलब्धियों का विस्तृत विवरण इस सारांश-पत्र में उद्धृत साहित्य में दिया गया है।

WCSSP इंडिया दीर्घकालिक प्रभाव प्राप्त करने के लिए गतिविधियों (Activities), निष्पादनों (Outputs) और परिणामों (Outcomes) के एक समेकित ढाँचे का उपयोग करता है। इसका अनुसंधान वैश्विक से क्षेत्रीय और नगरीय स्तरों तक तथा कुछ घंटों से लेकर ऋतुओं तक के विभिन्न समय-पैमाने पर किया जाता है। संयुक्त वैज्ञानिक कार्य में युग्मित पूर्वानुमान प्रणालियों का विकास एवं मूल्यांकन, प्रक्रियाओं की समझ और पूर्वानुमान के प्रारंभिक स्थिरीकरण में सुधार के लिए प्रेक्षणों का उपयोग तथा संयुक्त मॉडल अंतर-तुलना एवं प्रक्रिया-आधारित आकलन शामिल हैं। यह साझेदारी जोखिम-आकलन विधियों पर अनुसंधान तथा प्रोटोटाइप उपकरणों के विकास के माध्यम से भारत के प्रभाव-आधारित पूर्वानुमान एवं चेतावनी की दिशा में आगे बढ़ने में भी सहायता करती है। इस शोध-पत्र में भविष्य की जिन अनुसंधान दिशाओं पर चर्चा की गई है, वे कार्यक्रम की बदलती प्राथमिकताओं को प्रतिबिंबित करती हैं। WCSSP इंडिया का कार्यान्वयन विभिन्न सरकारी भागीदारों तथा संबद्ध शैक्षणिक परियोजनाओं द्वारा किया जाता है और कार्यशालाओं, अतिथि वैज्ञानिकों के आदान-प्रदान तथा नियमित सहकर्मि संवाद के माध्यम से सक्रिय सहयोग को सुदृढ़ किया जाता है। इसके निष्पादनों को बढ़ते हुए प्रकाशन-संग्रह के माध्यम से व्यापक रूप से साझा किया जाता है, जो सहयोगात्मक विज्ञान तथा बेहतर मौसम एवं जलवायु सेवाओं में WCSSP इंडिया के योगदान को रेखांकित करता है।

ABSTRACT. The Weather and Climate Science for Service Partnership (WCSSP) India, launched in 2017, builds long-term research partnerships between the UK and India to strengthen weather and climate science. Building on an established history of collaboration, the programme focuses on improving risk-based forecasting of natural hazards through advances in scientific understanding, methods, and tools. These improvements help enhance services that protect lives and livelihoods and support India's Ministry of Earth Sciences (MoES) in delivering actionable weather and seasonal climate information.

This paper outlines the WCSSP India approach and provides a synthesis of research in three example areas. This highlights recent progress through collaboration in understanding monsoon systems, extreme weather events, here focussing on fog and low visibility research, and in developing risk- and impact-based forecasting methods. More details on WCSSP India research achievements are documented in the literature cited in this summary paper.

WCSSP India uses a cross-cutting framework of Activities, Outputs and Outcomes to deliver long-term Impacts. Research spans across global, to regional, to urban scales and timescales from hours to seasons. Joint science focuses on developing and evaluating coupled prediction systems, using observations to improve process understanding and forecast initialisation, and conducting joint model intercomparisons and process-based assessments. The Partnership also supports India's move toward impact-based forecasting and warning through research on risk-assessment methods and development of prototype tools. Future research directions discussed in this paper reflect the programme's evolving priorities. WCSSP India is delivered by a range of governmental partners and linked academic projects, with interactions strengthened by active collaboration through workshops, visiting scientist exchanges and routine peer engagement. Outputs are shared widely through a growing publication record, highlighting WCSSP India's contribution to collaborative science and improved weather and climate services.

Key words – Partnership, Hazard prediction, Model development, Impact based forecasting.

1. Introduction

India needs to be resilient to a myriad of weather and climate hazards, with global-scale drivers such as the summer monsoon accounting for roughly 80% of annual rainfall underpinning national water resources, agriculture and food security (e.g. Rao *et al.*, 2019). Further, interactions between large-scale drivers and a diverse geography can result in a range of hazards that impact lives and livelihoods acting on varying timescales, including intense heatwaves, extreme rainfall, severe floods, landslides, cyclones, lightning, drought and cold waves. The Weather and Climate Science for Service Partnership (WCSSP) India was initiated between the UK and Indian governments in 2017 to support science that helps anticipate these risks more accurately (UK Government, 2021).

WCSSP India is focussed on collaborative research to enhance understanding, methods, and tools for improving risk-based forecasting of natural hazards.

Research is focussed on four core areas – development and evaluation of coupled modelling frameworks for improved prediction; improving understanding of monsoon processes and related high intensity weather hazards across timescales; utilising observations to improve process representation in models and their evaluation; development of methods to support risk-based hazard and impact forecasting. This science and development of related tools and prototypes provide pathways to improve India's operational weather and climate services. This includes transitioning from more traditional hazard-based meteorological warnings to early, impact-based warnings that can be more useful for communities and emergency responders.

This paper aims to provide an overview of WCSSP India. In addition to showcasing some highlights, reflections of the approach taken to encourage development of sustainable partnerships are discussed. Section 2 outlines the WCSSP India approach, with more specific research highlights illustrated in Section 3. Areas

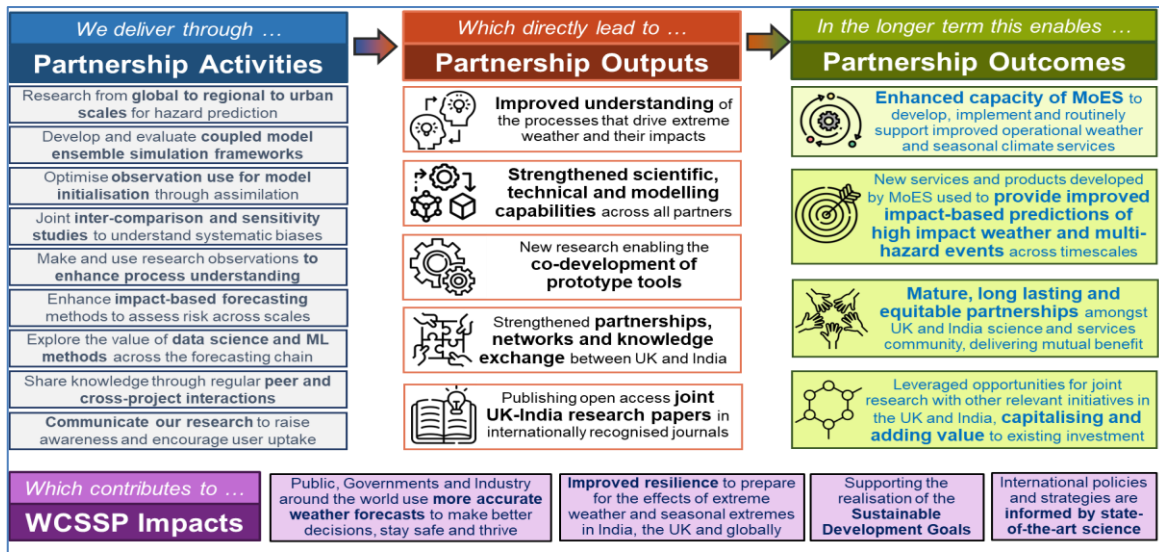


Fig. 1. Summary description of WCSSP India Activities, Outputs and Outcomes and of their long-term societal Impact

of ongoing and future focus are discussed in Section 4 along with summary conclusions.

2. Data and methodology

WCSSP India is a broad partnership engaging across 15 UK and India research organisations and the contributions of over 100 research scientists to date. The partnership is led on behalf of UK contributors by the Met Office, with targeted projects undertaken across WCSSP India themes by a range of UK academic contributors. The activity is delivered in support of the Ministry of Earth Sciences (MoES), with research delivered by its organisations represented by the National Centre for Medium Range Weather Forecasting (NCMRWF), India Meteorological Department (IMD), Indian Institute of Tropical Meteorology (IITM), Indian National Centre for Ocean Information Services (INCOIS), National Centre for Coastal Research (NCCR) and National Centre for Polar and Ocean Research (NCPOR).

Collaboration across WCSSP India is guided by a set of common *Outputs*, that are delivered by undertaking several *Activities*, and lead to delivery of *Outcomes* and wider societal *Impacts* (Fig. 1). The set of agreed Outcomes helps alignment across the wide range of WCSSP India activities and ensures ongoing focus to address the needs of MoES and its stakeholders. The Outputs provide a more measurable and tangible set of targets of direct relevance to all collaboration activities.

2.1. Joint UK-India science plan

To develop a sustainable and long-term collaborative research approach across a range of partners requires

several ingredients, briefly highlighted below. These are addressed through co-development of an evolving joint WCSSP India Science Plan to set out high-level plans and priorities

(i) Activities need to remain aligned to the science priorities across all partners to ensure relevance and longevity of contributions,

(ii) research needs to address pioneering scientific challenges, and ensure it remains at the cutting-edge of approaches to numerical weather prediction, coupled modelling, machine learning, and observational analysis,

(iii) by working in collaboration, activities need to strengthen both UK and India capabilities across the modelling and observational chain from improved understanding through to enhanced prediction systems from global to local hazard predictions,

(iv) to remain focussed while encouraging a breadth of input and application, a range of specific natural hazards of key importance have been identified, including extreme rainfall, flash floods, tropical cyclones, monsoon variability, heatwaves, and compound events,

(v) to remain relevant to delivering societal benefits, work needs to support a core aim of translating research to enable enhanced operational services, by underpinning the development of impact-based forecasting tools and prototype applications, ensuring that any forecasts are reliable, interpretable, and user focused,

(vi) activities should also be well aligned with national and international programmes to maximize efficiency,

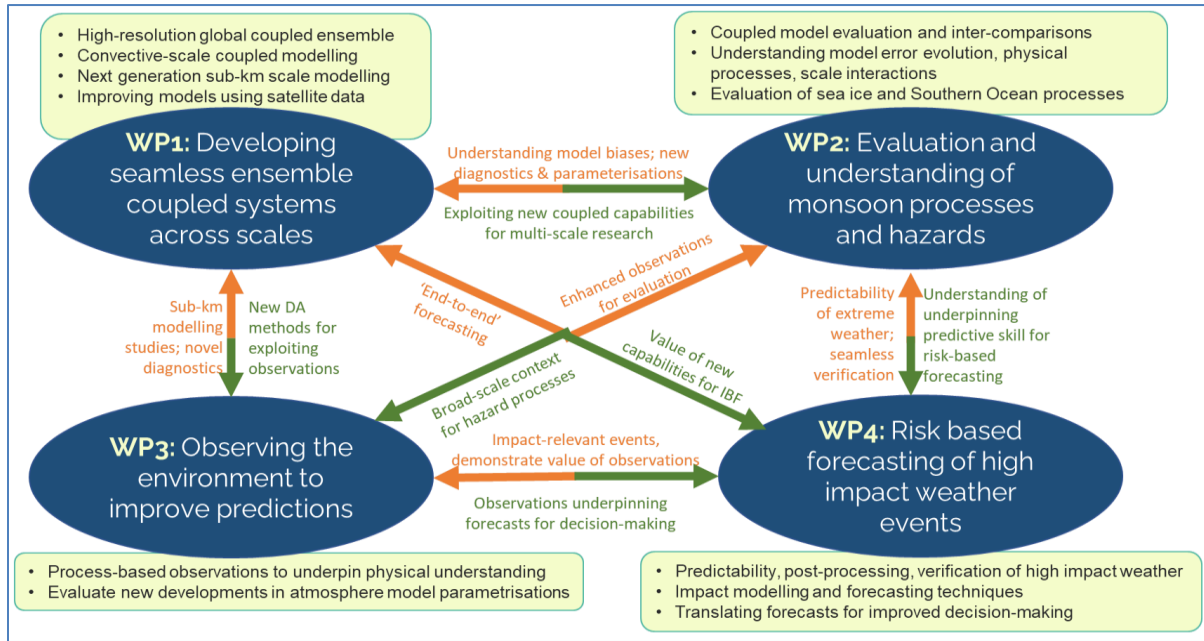


Fig. 2. Schematic summary of WCSSP India structure and research themes

share knowledge, and avoid duplication, creating a collaborative framework for impactful weather and climate services.

To coordinate delivery, WCSSP India is composed of four inter-dependent work packages (Fig. 2). Work packages 1 to 3 are more focused on underpinning research that will advance different areas of observation, process understanding and prediction of natural hazards, to improve the quality of the modelling systems that are used for predictions. Work package 4 is focused on developing methods and processes that build on that research to enhance impact-based forecasting capabilities and their effectiveness in India. The work packages and their activities are designed to meet the overall vision and objectives of WCSSP India, recognising many activities are conducted in collaboration across work package boundaries. To support delivery and further facilitate collaboration, a UK and India Work Package lead group has been tasked with supporting effective collaboration and enables this by meeting regularly on a work package specific and cross-theme basis to discuss coordination and alignment of activities.

2.2. Focussing academic research to deliver WCSSP India aims

UK contributions to WCSSP India are delivered by researchers working across the Met Office, together with aligned UK academic research. Since WCSSP India was initiated, 15 UK academic projects have been commissioned in response to directed research calls across

a range of topics. These have been further supplemented by more ad hoc short-term partner activities. Recent work has included exploring the use of machine learning for post-processing ensemble precipitation forecasts (e.g. Angus *et al.*, 2024), process understanding of the large-scale drivers and impacts of the Indian monsoon across timescales (e.g. Deoras *et al.*, 2025; Deoras *et al.*, 2026), development of a Flood Hazard Impact Model for India (FHIM-India), and exploration of approaches to improve the understanding of multi-risk assessment and its viability within delivery of Impact based Forecasting and Warning (IbFW; Lumbroso *et al.*, 2025).

Enabled by the initiation of Mission Mausam by the Government of India, implemented through MoES, a new call for Indian-based academic research proposals to deliver to WCSSP India aims was issued in spring 2025. Successful projects from this call will further boost the capacity of Indian research and provide a mechanism to directly integrate Indian academic work in support of the MoES mission and enhance UK-India research collaboration.

2.3. Core modelling systems

Alignment of research across a diverse network of partners in the UK and India is enabled through focus on a small core set of modelling infrastructure. These routinely deliver operational forecasts from hours to a season ahead at the Met Office or MoES partner organisations, enabling a pathway for effective translation from science to service (Fig. 3)

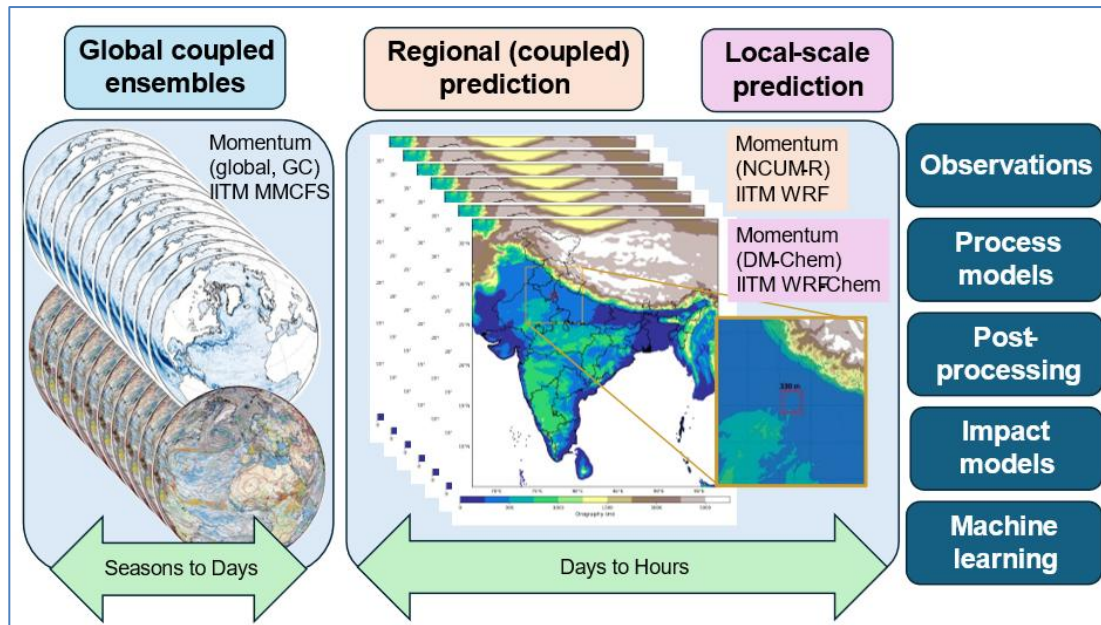


Fig. 3. Schematic illustration of modelling tools utilised and developed through WCSSP India research

Research on the global drivers of key hazards, such as the predictability of the summer monsoon, have supported the continuing development of two distinct global coupled prediction frameworks. The Momentum (Unified Model) Global Coupled (GC) configuration represents successive upgrades of the Met Office seamless atmosphere-ocean-land-ice system (e.g. Mignac *et al.*, 2025; Guivarc'h *et al.*, 2025; Lea *et al.*, 2022). This system is routinely used to generate operational ensemble seasonal and sub-seasonal forecasts by the Met Office in the UK (e.g. Kettleborough *et al.*, 2026; Kolusu *et al.*, 2023) and by NCMRWF in India (e.g. Rao *et al.*, 2025; Gupta *et al.*, 2024; Chakraborty *et al.*, 2023; Gera *et al.*, 2021). Collaborative studies have also utilised the development of the Monsoon Mission Climate Forecast System (MMCFS; Jain *et al.*, 2024) seasonal prediction framework and the Multi-Model Ensemble Prediction System (MMEPS; Pattanaik *et al.*, 2019) in use at IITM. This has enabled a number of detailed intercomparison studies through WCSSP India collaboration (e.g. Kalshetti *et al.*, 2025; Keane *et al.*, 2024; Niranjan Kumar *et al.*, 2024; Gautam *et al.*, 2024; Gautam *et al.*, 2023; Joseph *et al.*, 2023). Collaboration towards more strongly coupled atmosphere-ocean data assimilation has also been facilitated through WCSSP India activities (e.g. Wright *et al.*, 2024; Leung *et al.*, 2022). Examples of global coupled model research through WCSSP India are further highlighted in Section 3.1.

Research focussed on more local hazard processes and prediction have utilised km-scale configurations of the Unified Model, deployed operationally across India by NCMRWF (NCUM-R; e.g. Apsara *et al.*, 2025;

Mohandas *et al.*, 2025; Bhowmick *et al.*, 2024; Thota *et al.*, 2024; Barton *et al.*, 2023). Castillo *et al.* (2022) document the development and research application of a regional coupled framework using the Unified Model over India through WCSSP India collaboration, to better account for the role of air-sea interactions on hazard evolution and represent multi-hazard impacts. Niranjan Kumar *et al.* (2023) also illustrate the value of using regional model evaluation to inform global model development, particularly in the context of progress towards km-scale global prediction (e.g. Krishna *et al.*, 2025).

Pathways to higher resolution applications have been enabled through a focus on collaborative India-UK development of urban-scale or “hectometric” Unified Model applications, utilising models with grid spacing of order a few hundred metres (e.g. Jayakumar *et al.*, 2025; Anurose *et al.*, 2023; Jayakumar *et al.*, 2021). Example urban-scale WCSSP India developments are further discussed in Section 3.2.

A variety of approaches through WCSSP India to understand the use of weather and climate model outputs for impact-based forecasting are outlined in Section 3.3. The role of data-driven machine learning predictions in WCSSP India is discussed in Section 4.

3. Results and discussion

This section aims to showcase a few selected WCSSP India highlights. These aim to illustrate collaborative progress on key themes, rather than provide

an exhaustive overview of partnership achievements. These exemplify the delivery of several of the WCSSP India Outputs across each theme. Readers are encouraged to see cited publications that have arisen from a variety of WCSSP India collaborations for further details.

3.1. *Large-scale drivers and predictability of the Indian summer monsoon*

Prediction of the Indian summer monsoon, on timescales to support effective decision making, remains challenging. Many global circulation models have substantial systematic biases (*e.g.* Martin *et al.*, 2021). Collaborative WCSSP India research has considered a range of the large-scale factors that modulate Indian monsoon variability and predictability, including primary large-scale teleconnections such as to ENSO (El Niño Southern Oscillation), the IOD (Indian Ocean Dipole) and BSISO (Boreal Summer Intraseasonal Oscillation), ocean-atmosphere and land-atmosphere coupling, and extratropical or polar influences. This spans seasonal to sub-seasonal timescales, using coupled modelling, observations, sensitivity studies and development of process-based diagnostics to enhance understanding.

3.1.1. *Improved understanding*

ENSO remains the dominant large-scale driver of monsoon variability, but the teleconnection impact on India can be non-linear. For example, Srivastava *et al.* (2026) demonstrated the impact of a negative Indian Ocean Dipole (IOD) leading to more suppressed 2021 and 2022 monsoon seasons than typically associated with La Niña-like Pacific forcing. On sub-seasonal timescales, Keane *et al.* (2021; 2024) highlighted the strong influence of 10-60-day timescales of BSISO on active and break phases of the monsoon. It was shown that BSISO phase propagation was systematically delayed in sub-seasonal predictions, leading to phase-dependent rainfall biases. Understanding of the detailed processes by which the BSISO and soil moisture modulates movement and behaviour of monsoon depressions was also a focus of WCSSP India research delivered through the EUPHEMISMS (Exploring, Understanding and Predicting the Heterogeneity, Enhancement and Movement of Indian Summer Monsoon Storms) academic project led by University of Reading (Hunt and Turner, 2022; Deoras *et al.*, 2025).

The IMPROVE (Indian Monsoon PRecipitation over Orography: Verification and Enhancement of Understanding) project under WCSSP India included research to show how the BSISO (Hunt *et al.*, 2020) or stratification of the zonal winds (Phadtare *et al.*, 2022) help control the local behaviour of rainfall over the

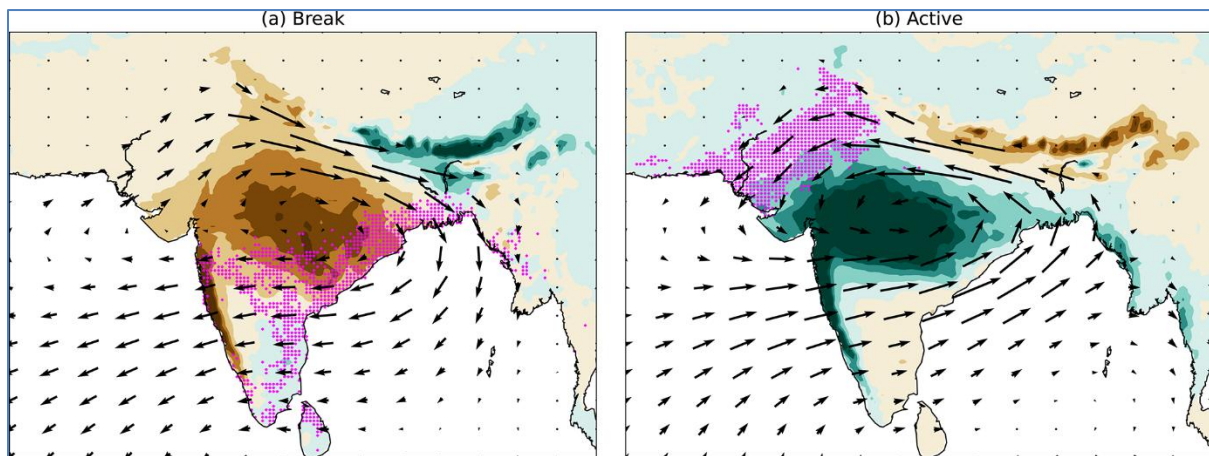
Western Ghats, as well as the essential processes that must be simulated in models at the convective scale to enhance prediction (Phadtare *et al.*, 2023). IMPROVE also supported research to assess the role of convective processes and orographic flows in impacting the representation of the precipitation diurnal cycle of the Central Himalaya (Hunt *et al.*, 2022).

More recently, targeted research under WCSSP India has sought to better understand the drivers and local-scale impacts of monsoon breaks. The OUTBREAK (On Understanding The Breaks in Rain, Exacerbating Air Quality) project, led by UK academic partners at the University of Reading, has shown that intrusions of dry air from arid regions to the west and northwest of India play a key role in triggering breaks (Deoras *et al.*, 2026a) and can also influence their duration.

Western disturbances shape pre-monsoon and winter rainfall, influencing soil moisture “memory” that later affects early monsoon dynamics. WCSSP India has contributed in part to a systematic review of western disturbances (Hunt *et al.*, 2025), while their interaction with monsoon depressions in bringing extreme rainfall to northern India and the Himalaya was discussed by Hunt *et al.* (2021).

3.1.2. *Strengthened modelling capabilities*

WCSSP India research has exploited collaborative analysis across complementary seasonal prediction systems developed in the UK (*e.g.* GloSea6; Met Office, Kettleborough *et al.*, 2026) and India (*e.g.* MMCFSv1; IITM, Saha *et al.*, 2014; Ramu *et al.*, 2016). For example, model intercomparison has highlighted that systematic model biases in the equatorial Indian Ocean (EIO) significantly influence monsoon prediction skill. In Met Office models, the development of warm-west / cool-east SST biases in the EIO tend to weaken the predicted monsoon circulation. Martin and Rodriguez (2024) used regional relaxation experiments to show that these biases arise from large-scale circulation errors over the Maritime Continent but are exacerbated by errors in representation of air-sea feedback more locally. In MMCFS configurations, a more widespread cold bias occurs over the EIO. Keane *et al.* (2024) analysed in detail how the biases develop in these two modelling systems, showing that there are differences in the SST-rainfall relationships that may be related to the different ocean model components and/or the way in which the atmosphere and ocean models are coupled. This remains an active area of research that is informing relevant coupled model development in India and UK (*e.g.* Lock *et al.*, 2024; Mohan *et al.*, in prep).



Figs. 4(a&b). Schematic diagram illustrating the preferred location of moist heatwaves (magenta dots) on the middle day of a breaks and b active events during June–September 1940–2023. Only those locations are shown where the relative occurrence of moist heatwave days exceeds 5% of 188 and 261 middle days of breaks and active events, respectively. Shading shows precipitation anomaly, with brown showing negative precipitation anomaly and green showing positive precipitation anomaly. Vectors show the 1000–700 hPa vertically integrated moisture flux during the same period. [Reproduced from Deoras et al., 2026 (Open Licence)]

3.1.3. Development of tools

Several diagnostic approaches have been developed through WCSSP India relating to understanding monsoon processes and their local impacts in India. Mohan *et al.* (2024) examined the relationship between small-scale convection and large-scale circulation patterns using a moist static energy (MSE) budget framework to assess NCMRWF operational forecasts associated with active/break spells. This highlighted overly weak sensitivity of relationships between rainfall and column water vapour, indicating areas for future model development. In a more applied context, Lekshmi *et al.* (2024) proposed an operational framework for predicting heat waves and heat stress based on principal component/empirical orthogonal function (PC/EOF) analysis of summer temperature variability. Complementing these process-based diagnostics, Niranjana Kumar *et al.* (2022) tested empirical and parametric quantile mapping bias-correction techniques using IMDAA precipitation to calibrate NCMRWF Unified Model operational forecasts, demonstrating improved rainfall distributions for coastal flood early-warning applications. Current work includes the development of a recipe for monitoring Indian Ocean biases, to be included in the open-source, community-driven ESMValTool package, which supports consistent comparisons across model versions and across major international global coupled climate models.

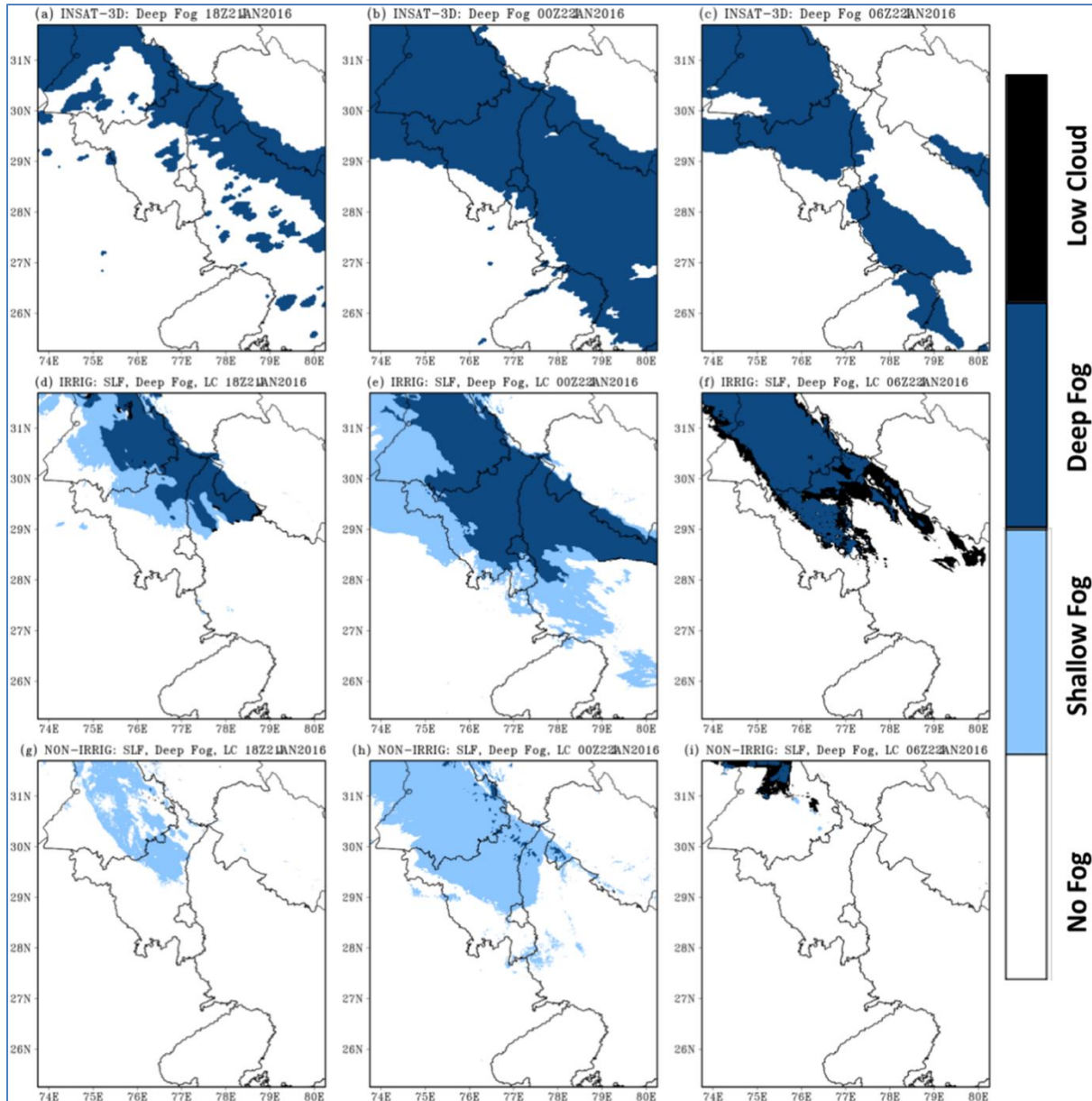
3.1.4. Strengthened partnerships

The impact of open collaboration is evident across the range of WCSSP India research directed to improving

understanding and prediction of the Indian summer monsoon to date. This has been enabled through focus on analysis of complementary seasonal and sub-seasonal coupled prediction systems between Indian and UK groups (*e.g.* Keane *et al.*, 2024; Joseph *et al.*, 2023; Gautam *et al.*, 2023). This activity has been enhanced by support for long-term directed UK academic research under WCSSP India through the EUPHEMISMS, IMPROVE and OUTBREAK projects linked to these themes. Direct links to UK academic research through WCSSP India has also facilitated a MoES scientist to undertake a visiting scientist stay at the University of Reading linked to this theme.

Illustrative of the potential for the evolving nature of successful partnership working, collaboration through WCSSP India in applying PC/EOF analysis to wet bulb temperature has identified new pathways for understanding potentially deadly moist heatwaves within the monsoon season (Deoras *et al.*, 2026b; Fig. 4)

The wide scope of UK and India research represented by Met Office and MoES organisations has also supported growth of new collaborations. For example, strengthened interactions between UK and Indian partners with interest in polar ocean and sea ice processes, facilitated through routine group discussions, have advanced research on polar – monsoon teleconnections. This has led to new joint research exploring the role of Arctic sea ice decline on the Indian summer, showing reduced sea ice in the Barents – Kara region correlating with strengthened monsoon circulation and relatively enhanced rainfall over north-west India (Chatterjee *et al.*, 2026). More recently, Saheed *et al.* (2026) led an assessment by researchers at IIT Delhi,



Figs. 5(a-i). Panels show shallow fog, deep fog and low cloud at the development stage 18Z 21 January (left), mature stage 00Z 22 January (centre) and dissipation stage 06Z 22 January 2016. The rows show observations from INSAT-3D (a–c); then irrigated (d–f) and non-irrigated (g–i) model output. [Reproduced from Smith *et al.*, 2024 (Open Licence)]

NCMRWF and the Met Office of extended range Antarctic sea ice forecasts in the NCMRWF seasonal forecasting system (based on the Met Office GloSea5-GC2 system).

3.2. New insights on fog processes and their prediction in India

Fog and low visibility are a major winter hazard across northern India, particularly in the Indo-Gangetic Plains (IGP). Poor visibility episodes cause substantial impacts to sectors such as transport, agriculture and

energy, and can exacerbate public health issues. Accurate prediction remains challenging due to the complex interactions of processes across different timescales and strong dependencies on local conditions that are responsible for its formation and evolution (Ghude *et al.*, 2023).

3.2.1. Improved understanding

WCSSP India research has included an assessment of the frequency of fog occurrence and types based on surface observations across India (Smith *et al.*, 2023). It

was found that fog in IGP has become more frequent through the period 2000 to 2020. The study considered if changes in the frequency of Western Disturbances (WD) over the IGP might account for observed increases but results suggested that increases were driven mainly by environmental changes associated with urban expansion and increased aerosol loading impacting on radiative and microphysical processes. Aerosol feedback was also illustrated to play a controlling role on fog evolution in linked modelling studies by Anurose *et al.* (2024), who demonstrated that fog ‘holes’ can develop due to delayed onset and early dissipation in rural areas associated with enhanced aerosol absorption. The simulation study by Bhowmik *et al.* (2024) also confirmed that aerosol chemistry, and thereby its representation in weather prediction models, strongly influences fog formation and visibility, with aerosol hygroscopicity a key regulating factor.

3.2.2. Strengthened modelling capabilities:

Maintaining a focus on the role of environmental factors, the role of irrigation, and its representation in weather prediction models, has also been assessed through WCSSP India collaboration. Smith *et al.* (2024) demonstrated that including irrigation in high resolution regional numerical weather prediction (NWP) models can correct a common dry bias. This led to much more realistic spatial extent and temporal evolution of fog when compared to INSAT satellite observations and surface measurements (Fig. 5).

3.2.3. Development of tools

Even with accurate prediction, the diagnosis of fog using numerical model outputs is non-trivial. VERA (Visibility Employing Realistic Aerosol; Claxton, 2025), developed through WCSSP India activities, offers a more comprehensive diagnostic visibility scheme than had previously been used for operational forecasting. Importantly, this includes scope to couple more directly to aerosol schemes utilised in the local prediction models employed for some Indian cities and developed by MoES partners (*e.g.* Jayakumar *et al.*, 2021; Parde *et al.*, 2022; Jayakumar *et al.*, 2025).

3.2.4. Strengthened partnerships

The range of WCSSP India research relating to fog and low visibility illustrates the value of three key aspects in approach for collaboration. First, studies have been underpinned by the availability and sharing of high-quality research observations from the Wintertime Fog Experiment (WiFEX; Ghude *et al.*, 2023) at Delhi airport. This was a key enabler to focussing cross-partner efforts

towards common case studies of interest. Second, modelling activities have been relatively agnostic to the choice of modelling tools, from idealised studies using the Met Office NERC Cloud Model (MONC; *e.g.* Poku *et al.*, 2021) to sub-km and km-scale grid regional modelling using either the Unified Model (*e.g.* DM-Chem, led by NCMRWF; Bhati *et al.*, 2026; Jayakumar *et al.*, 2025) and WRF-Chem applications for India led by IITM (*e.g.* Parde *et al.*, 2022). Finally, this research has benefitted from long-term participation from individuals working across organizations with common interests and goals. This includes targeted effort to motivate and initiate the Fog Over the Indo-Gangetic plains of India (FOGGI) project as part of WCSSP India, led by UK academic partners at the University of Leeds and University of East Anglia.

Practically, interactions have been enabled through routine (*e.g.* monthly) online discussions with more ad-hoc (*e.g.* annual) in-person project meetings. Progress has also been made through extended in-person visiting scientist stays, and remote access to common computing infrastructure to support model studies. More recently, interest from different organisations has evolved to co-working on a common microphysics scheme (CASIM; Field *et al.*, 2023). This has been enabled by alignment on common case studies of interest, exchange of model and development and sharing of new bespoke satellite-derived observation products from the Met Office to Indian partners.

3.3. Transition towards impact-based forecasting and warning (IbFW)

Since its inception, WCSSP India research across a range of hazard-related themes and from global to local-scale interests have a central goal to support enhanced impact-based forecasting and warning (IbFW). This supports India’s transition from hazard-based forecasts (“*what the weather will be*”) to impact-focussed early warnings (“*what the weather will do*”) (*e.g.* Mohapatra *et al.*, 2023).

3.3.1. Improved understanding

Impact-based forecasting increasingly requires assessment of interacting and cascading risks. The MIDAS (Multi-Risk Impact-Based Forecasting and Warning Systems) project, led by partners HR Wallingford in the UK, has provided the first comprehensive analysis of the scientific and operational feasibility of multi-risk IbFW. This begins to address compound and cascading hazards in the Indian context (*e.g.* Lumbroso *et al.*, 2025). Major challenges exist however, including limited availability of impact and vulnerability data.

Improved process understanding and prediction of natural hazards (*e.g.* see previous Sections) are necessary but not sufficient input for successful IbFW. For practical implementation, a Value Chain framework has been assessed in partnership to map decision pathways, information flow and stakeholder needs and gaps with reference to extreme rainfall events in India. This highlights the importance of adopting consistent risk language, of mapping user-decision contexts, and the need for improved visualisation and communication guidance for Operational Meteorologists. In addition to India-specific case studies, exploration of UK storm cases has offered transferable understanding and lessons for effective multi-hazard communication.

3.3.2. *Strengthened modelling capabilities*

The Flood Hazard Impact Model (FHIM-India) project under WCSSP India, led by the UK Centre for Ecology & Hydrology, adapted approaches first developed in a UK context to develop and demonstrate a prototype flood hazard impact model (Fig. 6). This uses the Grid-to-Grid hydrological model (Bell *et al.*, 2007) with grid spacing of 1km to compute probabilistic flood hazard over the selected region. Predictions can be generated using ensemble precipitation forecast inputs from either India-based or UK-based global and regional ensemble numerical weather prediction. A set of pre-calculated impact libraries, based on offline HiPIMS hydrodynamic inundation modelling with resolution of order 5 to 30 m, and maps of receptor information are then used to enable rapid translation from flood hazard to impact prediction for a range of specific sectors. The FHIM-India capability was initially developed for catchments in the Kerala region, with further development to extend to other regions and prepare for more real-time use. FHIM-India development included training and co-development with MoES partners to enable successful deployment to MoES supercomputer architectures.

3.3.3. *Development of tools*

A range of prototype tools have been developed through WCSSP India research. These have provided practical examples of applying IbFW concepts across sectors, and provide insight on requirements of data, models and user inputs for full operational IbFW.

One of the first WCSSP India activities delivered a set of probabilistic weather patterns for India (Neal *et al.*, 2022; Neal *et al.*, 2020). This offers a framework for providing medium-range forecast guidance and related weather pattern forecast applications (*e.g.* Neal *et al.*, 2024).

On operational timescales, the reliability of heavy-rain probabilities can be enhanced through exploiting

post-processing methods. The HEavy Precipitation forecast Post-Processing over India (HEPPI) project under WCSSP India, led by the University of Birmingham, has explored the use of quantile mapping (QM) and ensemble model output statistics (EMOS) to improve the reliability between forecast and observed rainfall distributions, and enhance the accuracy of location-specific rainfall probabilities (Angus *et al.*, 2024). EMOS was found to deliver the most robust skill gains for heavy rainfall, improving Brier Skill Scores and CRPS in many regions of India. Results have informed steps towards operational implementation of EMOS and NCMRWF for ensemble rainfall forecasting. More recently, the HEPPI-ML project has built on these methods by incorporating additional machine learning predictors using neural network methods, thereby extending aspects of optimisation and physical interpretability.

Beyond predictive aspects of impact-based forecasting, the Satellites for Impact and Vulnerability Assessment (SIVA) project, led by HR Wallingford, focussed on exploitation of Earth Observation to assess and quantify the impacts of severe weather in selected regions of India. This combined satellite imagery and machine-learning based classifiers to identify agricultural and infrastructure damage following floods, demonstrating the potential for decision-relevant dashboards to support further embedding of impact-based forecasting and response.

3.3.4. *Strengthened partnerships*

A UK-India working group on Impact-based Forecasting was initiated through WCSSP India in 2021 to support dialogue across the range of IbFW across organisations. This continues to routinely engage across Met Office, UK partners and MoES researchers, and has supported practical knowledge exchange on IbFW methods and joint evaluation of flood impact models. Ongoing dialogue supports common understanding and assessment of similarities and differences of vulnerabilities, exposures and multi-risk frameworks in UK and Indian contexts.

Beyond routine peer-to-peer and science workshop interactions, more specific training and extended visits have facilitated successful deployment of the FHIM-India capability on MoES supercomputing infrastructure, and greater understanding of user needs through dialogue with operational meteorologists at the Indian Meteorological Department (IMD). A recent exchange visit by IMD scientists to the UK illustrates continuing opportunities for knowledge exchange and career development related to IbFW, building on a long-established collaboration to ensure IbFW needs can be consistently understood and enhanced across all partners.

4. Conclusions

Improving hazard prediction and the effectiveness of IbFW remains a compelling and complex challenge for India given the interacting and cascading nature of hazards in the region, with myriad drivers embedded in an evolving climate system across a range of scales. Activities targeting these challenges therefore remain important foci for future WCSSP India research. This includes the need for:

- (i) Further improvement to physics-based global coupled ensembles, km-scale regional coupled systems and urban-scale environmental modelling, providing the foundations for process-related research, and serving a core requirement for enhancing operational services in the period ahead (Section 2.1),
- (ii) Continued effort in observing monsoon processes and extreme events, including rapid deployment of new observation sources with data assimilation frameworks, to support future improvements in forecast skill (Section 3.1),
- (iii) Characterising interactions between hazards, exposure and vulnerability in the Indian context, particularly in challenging environments such as the Himalaya, to support effective multi-hazard IbFW (Section 3.3). The increasing complexity of representing cascading risks requires ongoing research to advance process understanding, develop more coupled approaches to prediction systems across scales, and further improve the translation from hazard-based to impact-based warnings.

Beyond this, the WCSSP India approach (Fig. 1) offers a flexible partnership framework through which evolving user, scientific and organisational priorities continue to be reflected through an evolving science plan and new research directions.

4.1. Machine learning across WCSSP India

Consistent with the explosion in weather and climate model development activity exploiting data-driven methods, WCSSP India collaboration already includes elements of machine learning across a range of themes. For example, Hunt and Turner (2024) used a machine learning (ML) framework to advance understanding on the role of different dynamical drivers of low-pressure systems over India. The HEPPI-ML project continues to exploit a variety of machine learning approaches to advance post-processing of ensemble rainfall predictions over India.

In parallel, collaborative evaluation of the strengths and weaknesses of global data-driven models has begun

and is anticipated to grow in future WCSSP India research, with a focus on their ability to predict the South Asian monsoon on a variety of timescales out to a season ahead. The multi-scale nature of the South Asian monsoon and its impacts make it a particularly challenging problem for both physics-based and data-driven approaches. Initial assessments through WCSSP India indicate that, in general, ML models can simulate large-scale monsoon features and intraseasonal variability well but often develop biases consistent with those evident in physics-based models. This has included dry biases over the core monsoon zone beyond around 5–7 days lead time. Evaluation of ML and hybrid models will continue to be a rapidly growing research area through WCSSP India, building on the years of collaborative experience assessing physical model characteristics.

Building on WCSSP India research themes focussed on more local-scale prediction, machine learning is likely to unlock some of the computational cost limitations of running physical models for operational activities at sub-km resolutions (*e.g.* for urban-scale prediction; Blunn *et al.*, 2024) and is therefore a further strand for ongoing collaboration.

In such a rapidly evolving theme, however, identifying the relevant collaboration focus areas and priorities in the context of developing and evaluating machine learning for weather to seasonal prediction remains a challenge. Equally, the maturity and breadth of WCSSP India collaborations enables agility to respond and adjust to new approaches as they evolve.

4.2. Enhanced process understanding through exploiting research observations

Supported through Mission Mausam, the Atmospheric Research Testbed (ART) implemented by IITM provides a world-class research observational infrastructure in central India. This includes a growing array of high-quality meteorological instruments for long-term monitoring of the monsoon core zone. The WCSSP India partnership is well placed to apply these observations to address a range of research gaps in collaboration, from fundamental process understanding (*e.g.* Ghosh *et al.*, 2025) to routine evaluation of new physics-based and machine learning models from global to convective-scales (*e.g.* Bush *et al.*, 2025). The UNICon (Utilising emerging observation Networks in India for the evaluation of Convective-scale processes) academic project, led by University of Reading in the UK, has been initiated through WCSSP India to support this activity, including a focus on development of shared evaluation frameworks.

4.3. *Growing UK – India partnership through new expanded collaboration*

New research connections and frontiers will be explored through the period ahead with integration of new Indian academic partner projects within WCSSP India. MoES has actively invited proposals from Indian universities and research institutes to contribute to forecasting, monsoon studies, hazard prediction and risk-based early warnings under the WCSSP India. These new activities will further broaden scientific innovation, diversify methods, and strengthen national capabilities.

The continued success of WCSSP India remains critically dependent on being able to sustain effective and active peer-to-peer and group collaboration across organisational boundaries. This requires maintaining high-levels of joint activity, including exchange visits, workshops, collaboration on joint research publications and routine peer-to-peer interaction. These activities continue to be supported by access to shared workspace on the UK's JASMIN data analysis facility for environmental science provided by the Natural Environment Research Council. A further legacy of WCSSP India partnership development has been the initiation of UK-based PhD projects aligned with project themes, and in some cases with UK and India supervision. These all contribute to a growing WCSSP India publication record of over 90 published papers with 1200 citations, of which only a cross-section has been cited through this paper.

In summary, WCSSP India has been built on strong UK-India strategic alignment in weather and climate science, and on the recognition from both UK and India partners and stakeholders of the shared challenges and need for continuous innovation in weather and hazard forecasting for the benefit of society. These remain firm foundations through which operational and academic research partnerships will expand in the years ahead, enabling further impact and benefit from collaborative international research.

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References

- Angus, M., Widmann, M., Orr, A., Ashrit, R., Leckebusch, G.C. and Mitra, A., 2024, “A comparison of two statistical postprocessing methods for heavy-precipitation forecasts over India during the summer monsoon”, *Quarterly Journal of the Royal Meteorological Society*, **150**, 761, 1865–1883. doi: <https://doi.org/10.1002/qj.4677>.
- Anurose, T.J., Jayakumar, A., Sandhya, M., Gordon, H., Aryasree, S., Mohandas, S., Bhati, S. and Prasad, V.S., 2024, “Unraveling the mechanism of the holes in the blanket of fog over the Indo-Gangetic plains: Are they driven by urban heat islands or aerosol?”, *Geophysical Research Letters*, **51**, e2023GL107252. doi: <https://doi.org/10.1029/2023GL107252>.
- Anurose, T.J., Jayakumar, A., Gupta, K., Mohandas, S., Hendry, M.A., Smith, D.K.E., Francis, T., Bhati, S., Parde, A.N., Mohan, M., Mitra, A.K., Gupta, P.K., Chauhan, P., Jenamani, R.K. and Ghude, S., 2023, “Implementation of the urban parameterization scheme in the Delhi model with an improved urban morphology”, *Quarterly Journal of the Royal Meteorological Society*, **149**, 750, 40–60. doi: <https://doi.org/10.1002/qj.4382>.
- Apsara, K.S., Jayakumar, A., Anurose, T.J., Mohandas, S., Field, P.R., Prabhakaran, T., Konwar, M. and Prasad, V.S., 2025, “Analysis of raindrop size distribution from the double moment cloud microphysics scheme for monsoon over a tropical station”, *Atmospheric Chemistry and Physics*, **25**, 11423–11439. doi: <https://doi.org/10.5194/acp-25-11423-2025>.
- Barton, E.J., Taylor, C.M., Mitra, A.K. and Jayakumar, A., 2023, “Systematic daytime increases in atmospheric biases linked to dry soils in irrigated areas in Indian operational forecasts”, *Atmospheric Science Letters*, **24**, 9, e1172. doi: <https://doi.org/10.1002/asl.1172>.
- Bell, V.A., Kay, A.L., Jones, R.G. and Moore, R.J., 2007, “Development of a high resolution grid-based river flow model for use with regional climate model output”, *Hydrology and Earth System Sciences*, **11**, 532–549. doi: <https://doi.org/10.5194/hess-11-532-2007>.
- Bhati, S., Anurose, T.-J., Jayakumar, A., Gordon, H., Jones, A., Mohandas, S. and Prasad, V.S., 2026, “Impact of Aerosol Absorption and Scattering on Winter Fog Lifecycle: Insights from NWP Simulations over Indo-Gangetic Plains”, *Atmospheric Chemistry and Physics*, 2026. doi: <https://doi.org/10.5194/egusphere-2025-6088>.
- Bhowmik, M., Hazra, A., Ghude, S.D., Wagh, S., Chowdhury, R., Parde, A.N., Govardhan, G., Gultepe, I. and Rajeevan, M., 2024, “Is a more physical representation of aerosol chemistry needed for fog forecasting?”, *Quarterly Journal of the Royal Meteorological Society*, **150**, 762, 2690–2711. doi: <https://doi.org/10.1002/qj.4729>.
- Bhowmick, M., Jayakumar, A., Mohan, T.S., Anurose, T.J., Mohandas, S., Menon, A. and Prasad, V.S., 2024, “Role of midtropospheric heating and surface forcing on monsoon intraseasonal transitions”, *Quarterly Journal of the Royal Meteorological Society*, **150**, 765, 5249–5263. doi: <https://doi.org/10.1002/qj.4868>.
- Blunn, L.P., Ames, F., Croad, H.L., Gainford, A., Higgs, I., Lipson, M. and Lo, C.H.B., 2024, “Machine learning bias correction and downscaling of urban heatwave temperature predictions from kilometre to hectometre scale”, *Meteorological Applications*, **31**, 3, e2200. doi: <https://doi.org/10.1002/met.2200>.
- Bush, M., Flack, D.L.A., Lewis, H.W., Bohnenstengel, S.I., Short, C.J., Franklin, C., Lock, A.P., Best, M., Field, P., McCabe, A., Van Weverberg, K., Berthou, S., Boutle, I., Brooke, J.K., Cole, S., Cooper, S., Dow, G., Edwards, J., Finnenkoetter, A., Furtado, K., Halladay, K., Hanley, K., Hendry, M.A., Hill, A., Jayakumar, A., Jones, R.W., Lean, H., Lee, J.C.K., Malcolm, A., Mittermaier, M., Mohandas, S., Moore, S., Morcrette, C., North, R., Porson, A., Rennie, S., Roberts, N., Roux, B., Sanchez, C., Su, C.-H., Tucker, S., Vosper, S., Walters, D., Warner, J., Webster, S., Weeks, M., Wilkinson, J., Whitall, M., Williams, K.D. and Zhang, H., 2025, “The third Met Office Unified Model–JULES Regional Atmosphere and Land Configuration, RAL3”, *Geoscientific Model Development*, **18**, 3819–3855. doi: <https://doi.org/10.5194/gmd-18-3819-2025>.
- Castillo, J.M., Lewis, H.W., Mishra, A., Mitra, A., Polton, J., Brereton, A., Saulter, A., Arnold, A., Berthou, S., Clark, D., Crook, J., Das, A., Edwards, J., Feng, X., Gupta, A., Joseph, S., Klingaman, N., Momin, I., Pequignat, C., Sanchez, C., Saxby, J. and Valdivieso da Costa, M., 2022, “The Regional Coupled Suite (RCS-IND1): application of a flexible regional coupled modelling framework to the Indian region at kilometre scale”,

- Geoscientific Model Development, 15, 4193–4223. doi: <https://doi.org/10.5194/gmd-15-4193-2022>.
- Chakraborty, P., Dube, A. K., Sarkar, A., Pillai, P. A., Rao, S. A., Rajeevan, M., 2023, “How much does a high-resolution global ensemble forecast improve upon deterministic prediction skill for the Indian summer monsoon?”, *Meteorology and Atmospheric Physics*, 135, 33. doi: <https://doi.org/10.1007/s00703-023-00966-1>.
- Chatterjee, S., Smith, D.M., Murukesh, N. and Ravichandran, M., 2026, “Potential contribution of Barents–Kara Sea ice loss to the increased rainfall over northwest India through atmospheric teleconnection”, *Clim Dyn* 64, 252. doi: <https://doi.org/10.1007/s00382-026-08169-1>.
- Claxton, B., 2025, “Vera: A stochastic, polydisperse scheme for diagnosing fog and visibility”, *Quarterly Journal of the Royal Meteorological Society*, 151, 767, e4915. doi: <https://doi.org/10.1002/qj.4915>.
- Deoras, A., Hunt, K.M.R. and Turner, A.G., 2025, “The role of soil moisture in the inland penetration of Indian monsoon low-pressure systems”, *Quarterly Journal of the Royal Meteorological Society*, e70095. doi: <https://doi.org/10.1002/qj.70095>.
- Deoras, A., Turner, A.G., Volonté, A., Schiemann, R.K.H., Wilcox, L.J. and Menon, A., 2026a, “The role of dry intrusions in breaks of the Indian summer monsoon”, *Journal of Climate*, e250004. doi: <https://doi.org/10.1175/JCLI-D-25-0004.1>.
- Deoras, A., Turner, A.G., Lekshmi, S., Birch, C.E., Volonté, A., Menon, A., Schiemann, R.K.H., and Wilcox, L.J., 2026b, “Anatomy of moist heatwaves in India during the summer monsoon season”, *Climate Dynamics*, 64, 103. doi: <https://doi.org/10.1007/s00382-025-08023-w>.
- Field, P.R., Hill, A., Shipway, B., Furtado, K., Wilkinson, J., Miltenberger, A., Gordon, H., Grosvenor, D.P., Stevens, R. and Van Weverberg, K., 2023, “Implementation of a double moment cloud microphysics scheme in the UK Met Office regional numerical weather prediction model”, *Quarterly Journal of the Royal Meteorological Society*, 149, 752, 703–739. doi: <https://doi.org/10.1002/qj.4414>.
- Gautam, P., Chattopadhyay, R., Joseph, S., Martin, G.M. and Sahai, A.K., 2023, “Coupled model biases and extended-range prediction skill during the onset phase of the Indian summer monsoon with different initializations related to land surface and number of observations”, *Quarterly Journal of the Royal Meteorological Society*, 149, 754, 1650–1673. doi: <https://doi.org/10.1002/qj.4475>.
- Gautam, P., Chattopadhyay, R., Martin, G., Joseph, S. and Sahai, A.K., 2024, “Intraseasonal oscillation of land surface moisture and its role in the maintenance of CTCZ during the active phases of the Indian summer monsoon”, *Climate Dynamics*, 62, 5663–5679. doi: <https://doi.org/10.1007/s00382-023-07070-5>.
- Gera, A., Gupta, A., Mitra, A.K., Rao, D.N., Momin, I.M., Rajeevan, M.N., Milton, S.F., Martin, G. M., Martin, M.J., Waters, J., and Lea, D., 2021, “Skill of the extended range prediction (NERP) for Indian summer monsoon rainfall with NCMRWF global coupled modelling system”, *Quarterly Journal of the Royal Meteorological Society*, 148, 742, 480–498. doi: <https://doi.org/10.1002/qj.4216>.
- Ghosh, R., Bhowmik, M., Hazra, A., Pawar, S.D., Mohan, G.M., Domkaware, M.A., Gopalakrishnan, V., and Ghosh, R., 2025, “Exacerbation of lightning activity during Indian summer monsoon season over India: Estimation of cloud-to-ground lightning activity in wet and dry convective regimes”, *Quarterly Journal of the Royal Meteorological Society*, 151, 773, e70007. doi: <https://doi.org/10.1002/qj.70007>.
- Ghude, S.D., Jenamani, R.K., Kulkarni, R., Wagh, S., Dhangar, N.G., Parde, A.N., Acharja, P., Lonkar, P., Govardhan, G., Yadav, P., Vispute, A., Debnath, S., Lal, D.M., Bisht, D.S., Jena, C., Pawar, P.V., Dhankhar, S.S., Sinha, V., Chate, D.M., Safai, P.D., Nigam, N., Konwar, M., Hazra, A., Dharmaraj, T., Gopalakrishnan, V., Padmakumari, B., Gultepe, I., Biswas, M., Karipot, A.K., Prabhakaran, T., Nanjundiah, R.S. and Rajeevan, M., 2023, “WiFEX: Walk into the Warm Fog over Indo-Gangetic Plain Region”, *Bulletin of the American Meteorological Society*, 104, 5, E980–E1005. doi: <https://doi.org/10.1175/BAMS-D-21-0197.1>.
- Guiavarc’h, C., Storkey, D., Blaker, A.T., Blockley, E., Megann, A., Hewitt, H., Bell, M.J., Calvert, D., Copsey, D., Sinha, B., Moreton, S., Mathiot, P. and An, B., 2025, “GOSI9: UK Global Ocean and Sea Ice configurations”, *Geoscientific Model Development*, 18, 377–403. doi: <https://doi.org/10.5194/gmd-18-377-2025>.
- Gupta, A., Mitra, A.K. and Pandey, A.C., 2024, “Prospects and status of forecasting monthly mean subregional rainfall during the Indian summer monsoon using the coupled Unified Model”, *Quarterly Journal of the Royal Meteorological Society*, 150, 762, 2906–2919. doi: <https://doi.org/10.1002/qj.4741>.
- Hunt, K.M.R., Turner, A.G., Stein, T.H.M., Fletcher, J.K. and Schiemann, R.K.H., 2021, “Modes of coastal precipitation over southwest India and their relationship with intraseasonal variability”, *Quarterly Journal of the Royal Meteorological Society*, 147, 181–201. doi: <https://doi.org/10.1002/qj.3913>.
- Hunt, K.M.R., Turner, A.G. and Schiemann, R.K.H., 2021, “How Interactions between Tropical Depressions and Western Disturbances Affect Heavy Precipitation in South Asia”, *Monthly Weather Review*, 149, 6, 1801–1825. doi: <https://doi.org/10.1175/MWR-D-20-0373.1>.
- Hunt, K.M.R. and Turner, A.G., 2022, “Non-linear intensification of monsoon low-pressure systems by the BSISO”, *Weather and Climate Dynamics*, 3, 1341–1358. doi: <https://doi.org/10.5194/wcd-3-1341-2022>.
- Hunt, K.M.R., Turner, A.G. and Schiemann, R.K.H., 2022, “Katabatic and convective processes drive two preferred peaks in the precipitation diurnal cycle over the Central Himalaya”, *Quarterly Journal of the Royal Meteorological Society*, 148, 745, 1731–1751. doi: <https://doi.org/10.1002/qj.4275>.
- Hunt, K.M.R. and Turner, A.G., 2024, “Using interpretable gradient-boosted decision-tree ensembles to uncover novel dynamical relationships governing monsoon low-pressure systems”, *Quarterly Journal of the Royal Meteorological Society*, 150, 758, 1–24. doi: <https://doi.org/10.1002/qj.4582>.
- Hunt, K.M.R., Baudouin, J.-P., Turner, A.G., Dimri, A.P., Jeelani, G., Pooja, Chattopadhyay, R., Cannon, F., Arulalan, T., Shekhar, M.S., Sabin, T.P. and Palazzi, E., 2025, “Western disturbances and climate variability: a review of recent developments”, *Weather and Climate Dynamics*, 6, 43–112. doi: <https://doi.org/10.5194/wcd-6-43-2025>.
- Jain, D., Rao, S.A., Dandi, R.A., Pillai, P.A., Srivastava, A., Pradhan, M. and Gangadharan, K.V., 2024, “Monsoon Mission Coupled Forecast System version 2.0: model description and Indian monsoon simulations”, *Geoscientific Model Development*, 17, 709–729. doi: <https://doi.org/10.5194/gmd-17-709-2024>.
- Jayakumar, A., Gordon, H., Francis, T., Hill, A.A., Mohandas, S., Sandeeppan, B.S., Mitra, A.K. and Beig, G., 2021, “Delhi Model with Chemistry and aerosol framework (DM-Chem) for high-

- resolution fog forecasting”, *Quarterly Journal of the Royal Meteorological Society*, 147, 741, 3957–3978. doi: <https://doi.org/10.1002/qj.4163>.
- Jayakumar, A., Anurose, T.J., Bhati, S., Hendry, M.A., Hayman, G., Gordon, H., Field, P., Mohandas, S., Rumbold, H., Yadav, P., Dhangar, N.G., Parde, A., Wagh, S., Ghude, S., Ross, A.N., Smith, D., Dorling, S., George, J.P., Prasad, V.S. and Ravichandran, M., 2025, “Development of an Integrated Modeling Framework for Visibility and Air Quality Forecasting in Delhi”, *Bulletin of the American Meteorological Society*, 106, 2, E261–E274. doi: <https://doi.org/10.1175/BAMS-D-24-0194.1>.
- Joseph, S., Chattopadhyay, R., Sahai, A.K., Martin, G.M., Dey, A., Mandal, R. and Phani, R., 2023, “Evaluation and comparison of the subseasonal prediction skill of Indian summer monsoon in IITM CFSv2 and UKMO GloSea5”, *Climate Dynamics*, 61, 1683–1696. doi: <https://doi.org/10.1007/s00382-022-06650-1>.
- Kalshetti, M., Chattopadhyay, R., Turner, A.G., Phani, R., Joseph, S. and Sahai, A.K., 2025, “The Skill of Extended-Range ERPAS and GloSea5 Models in Capturing Extratropical–Tropical Interactions During the North Indian Summer Monsoon”, *International Journal of Climatology*, 45, e8834. doi: <https://doi.org/10.1002/joc.8834>.
- Keane, R.J., Parker, D.J. and Fletcher, J.K., 2021, “Biases in Indian summer monsoon precipitation forecasts in the Unified Model and their relationship with BSISO index”, *Geophysical Research Letters*, 48, e2020GL090529. doi: <https://doi.org/10.1029/2020GL090529>.
- Keane, R.J., Srivastava, A. and Martin, G.M., 2024, “Development of Indian summer monsoon precipitation biases in two seasonal forecasting systems and their response to large-scale drivers”, *Weather and Climate Dynamics*, 5, 671–702. doi: <https://doi.org/10.5194/wcd-5-671-2024>.
- Kettleborough, J.A., Davis, P.J., Comer, R.E., Martin, M.J., Barbosa Aguiar, A., Collier, T., Scaife, A.A., Clark, A., Mancell, J., Smout-Day, K.A. and Hardiman, S.C., 2026, “Global Seasonal Forecasting System 6 (GloSea6): A Large Ensemble Seasonal Forecasting System”, *Monthly Weather Review*, 154, 1, 39–57. doi: <https://doi.org/10.1175/MWR-D-25-0007.1>.
- Kolusu, S.R., Mittermaier, M., Robbins, J., Ashrit, R. and Mitra, A.K., 2023, “Novel evaluation of sub-seasonal precipitation ensemble forecasts for identifying high-impact weather events associated with the Indian monsoon”, *Meteorological Applications*, 30, 4, e2139. doi: <https://doi.org/10.1002/met.2139>.
- Krishna, R.P.M., Kumar, S., Prajeesh, A.G., Bechtold, P., Wedi, N., Roy, K., Ganai, M., Reddy, B.R., Tirkey, S., Goswami, T., Kanase, R., Sarkar, S., Deshpande, M. and Mukhopadhyay, P., 2025, “Indian Institute of Tropical Meteorology (IITM) High-Resolution Global Forecast Model version 1: an attempt to resolve monsoon prediction deadlock”, *Geoscientific Model Development*, 18, 1879–1894. doi: <https://doi.org/10.5194/gmd-18-1879-2025>.
- Lea, D.J., While, J., Martin, M.J., Weaver, A., Storto, A. and Chrut, M., 2022, “A new global ocean ensemble system at the Met Office: Assessing the impact of hybrid data assimilation and inflation settings”, *Quarterly Journal of the Royal Meteorological Society*, 148, 745, 1996–2030. doi: <https://doi.org/10.1002/qj.4292>.
- Lekshmi, S., Chattopadhyay, R. and Pai, D.S., 2024, “Attribution of subseasonal temperature modes as the drivers of dry and moist heat discomfort for the heat hazard monitoring over the Indian region”, *Climate Dynamics*, 62, 6779–6797. doi: <https://doi.org/10.1007/s00382-024-07236-9>.
- Leung, T.Y., Lawless, A.S., Nichols, N.K., Lea, D.J. and Martin, M.J., 2022, “The impact of hybrid oceanic data assimilation in a coupled model: A case study of a tropical cyclone”, *Quarterly Journal of the Royal Meteorological Society*, 148, 746, 2410–2430. doi: <https://doi.org/10.1002/qj.4309>.
- Lock, A.P., Whittall, M., Stirling, A.J., Williams, K.D., Lavender, S.L., Morcrette, C., Matsubayashi, K., Field, P.R., Martin, G., Willett, M. and Heming, J., 2024, “The performance of the CoMorph-A convection package in global simulations with the Met Office Unified Model”, *Quarterly Journal of the Royal Meteorological Society*, 150, 763, 3527–3543. doi: <https://doi.org/10.1002/qj.4781>.
- Lumbroso, D., White, C.J., Brown, E. and Kolusu, S.R., 2025, “Rethinking Impact-based Forecasts and Warnings (IbFW) for multi-risks”, *npj Natural Hazards*, 2, 105. doi: <https://doi.org/10.1038/s44304-025-00157-5>.
- Martin, G.M., Levine, R.C., Rodríguez, J.M. and Vellinga, M., 2021, “Understanding the development of systematic errors in the Asian summer monsoon”, *Geoscientific Model Development*, 14, 1007–1035. doi: <https://doi.org/10.5194/gmd-14-1007-2021>.
- Martin, G.M. and Rodríguez, J.M., 2024, “Using regional relaxation experiments to understand the development of errors in the Asian summer monsoon”, *Weather and Climate Dynamics*, 5, 711–731. doi: <https://doi.org/10.5194/wcd-5-711-2024>.
- Mohan, T.S., Lekshmi, S., Mohandas, S., Jayakumar, A. and Whittall, M., in draft, “Process-oriented evaluation of parameterized convection in the NCUM Global modelling system over the Indian Subcontinent”, for submission to *Quarterly Journal of the Royal Meteorological Society*.
- Mignac, D., Waters, J., Lea, D.J., Martin, M.J., While, J., Weaver, A.T., Vidard, A., Guiavarc’h, C., Storkey, D., Ford, D., Blockley, E.W., Baker, J., Haines, K., Price, M.R., Bell, M.J. and Renshaw, R., 2025, “Improvements to the Met Office’s global ocean–sea ice forecasting system including model and data assimilation changes”, *Geoscientific Model Development*, 18, 3405–3425. doi: <https://doi.org/10.5194/gmd-18-3405-2025>.
- Mohandas, S., Jayakumar, A., Field, P.R., Anurose, T.J., Van Weverberg, K., Wilkinson, J.M., Rani, S.I., Mamgain, A., Raphael, R., Apsara, K.S., Mitra, A.K. and Prasad, V.S., 2025, “Impact of cloud microphysical factors on the track prediction of recurved tropical cyclone Vayu (2019) in a convective-scale model”, *Quarterly Journal of the Royal Meteorological Society*, 151, 772, e5047. doi: <https://doi.org/10.1002/qj.5047>.
- Mohapatra, M., Chauhan, A., Varshney, A., Gurjar, S., Bushair, M.T., Sharma, M., Jenamani, R., Srivastava, K., Thakurta, G., Chattopadhyay, R., Yadav, M., Sharma, R., Mitra, A., Das, A., Nath, S., Kumar, N., Senroy, S., Thanigachalam, A., Bharadwaj, A. and Mausam-IMD, 2023, “Short to medium range impact based forecasting of heavy rainfall in India”, *Mausam*, 74, 311–344. doi: <https://doi.org/10.54302/mausam.v74i2.6180>.
- Neal, R., Robbins, J., Crocker, R., Cox, D., Fenwick, K., Millard, J. and Kelly, J., 2024, “A seamless blended multi-model ensemble approach to probabilistic medium-range weather pattern forecasts over the UK”, *Meteorological Applications*, 31, 1, e2179. doi: <https://doi.org/10.1002/met.2179>.
- Neal, R., Guentchev, G., Arulalan, T., Robbins, J., Crocker, R., Mitra, A. and Jayakumar, A., 2022, “The application of predefined weather patterns over India within probabilistic medium-range forecasting tools for high-impact weather”, *Meteorological*

- Applications, 29, 3, e2083. doi: <https://doi.org/10.1002/met.2083>.
- Neal, R., Robbins, J., Dankers, R., Mitra, A., Jayakumar, A., Rajagopal, E.N. and Adamson, G., 2020, "Deriving optimal weather pattern definitions for the representation of precipitation variability over India", *International Journal of Climatology*, 40, 1, 342–360. doi: <https://doi.org/10.1002/joc.6215>.
- Niranjan Kumar, K., Thota, M.S., Ashrit, R., Mitra, A.K. and Rajeevan, M.N., 2022, "Quantile mapping bias correction methods to IMDAA reanalysis for calibrating NCMRWF unified model operational forecasts", *Hydrological Sciences Journal*, 67, 6, 870–885. doi: <https://doi.org/10.1080/02626667.2022.2049272>.
- Niranjan Kumar, K., Ashrit, R., Sreevathsa, R., Kumar, S., Mishra, A.K., Thota, M.S., Jayakumar, A., Mohandas, S., and Mitra, A.K., 2023, "Atmospheric kinetic energy spectra from global and regional NCMRWF unified modelling system", *Quarterly Journal of the Royal Meteorological Society*, 149, 756, 2784–2799. doi: <https://doi.org/10.1002/qj.4531>.
- Niranjan Kumar, K., Gupta, A., Mohan, T.S., Mishra, A.K., Ashrit, R., Momin, I.M., Mahapatra, D.K., Nagarjuna Rao, D., Mitra, A.K., Prasad, V.S. and Rajeevan, M., 2024, "Unraveling Subseasonal Drought Dynamics in India: Insights from NCMRWF Extended Range Prediction System", *Journal of Hydrometeorology*, 25, 8, 1191–1207. doi: <https://doi.org/10.1175/JHM-D-23-0171.1>.
- Parde, A.N., Ghude, S.D., Dhangar, N.G., Lonkar, P., Wagh, S., Govardhan, G., Biswas, M. and Jenamani, R.K., 2022, "Operational Probabilistic Fog Prediction Based on Ensemble Forecast System: A Decision Support System for Fog", *Atmosphere*, 13, 10, 1608. doi: <https://doi.org/10.3390/atmos13101608>.
- Pattanaik, D.R., Sahai, A.K., Mandal, R., Phani Muralikrishna, R., Dey, A., Chattopadhyay, R., Joseph, S., Tiwari, A. D., and Mishra, V., 2019, "Evolution of operational extended range forecast system of IMD: Prospects of its applications in different sectors", *Mausam*, 70, 233–264. doi: <https://doi.org/10.54302/mausam.v70i2.170>.
- Phadtare, J.A., Fletcher, J.K., Ross, A.N., Turner, A.G. and Schiemann, R.K.H., 2022, "Froude-number-based rainfall regimes over the Western Ghats mountains of India", *Quarterly Journal of the Royal Meteorological Society*, 148, 748, 3388–3405. doi: <https://doi.org/10.1002/qj.4367>.
- Phadtare, J.A., Fletcher, J.K., Ross, A.N., Turner, A.G., Schiemann, R.K.H. and Burns, H.L., 2023, "Unravelling the mechanism of summer monsoon rainfall modes over the west coast of India using model simulations", *Quarterly Journal of the Royal Meteorological Society*, 149, 757, 3164–3182. doi: <https://doi.org/10.1002/qj.4550>.
- Poku, C., Ross, A.N., Hill, A.A., Blyth, A.M. and Shipway, B., 2021, "Is a more physical representation of aerosol activation needed for simulations of fog?", *Atmospheric Chemistry and Physics*, 21, 7271–7292. doi: <https://doi.org/10.5194/acp-21-7271-2021>.
- Ramu, D.A., Sabeerali, C.T., Chattopadhyay, R., Rao, D.N., George, G., Dhakate, A.R., Salunke, K., Srivastava, A. and Rao, S.A., 2016, "Indian summer monsoon rainfall simulation and prediction skill in the CFSv2 coupled model: Impact of atmospheric horizontal resolution", *Journal of Geophysical Research: Atmospheres*, 121, 2205–2221. doi: <https://doi.org/10.1002/2015JD024629>.
- Rao, D.N., Mohan, T.S., Gupta, A., Mitra, A. K., Dube, A. K., Martin, G. M., Martin, M. J., and Lea, D. J., 2025, "Fidelity of coupled hindcast simulations in representing intraseasonal biases over South Asia", *Climate Dynamics*, 63, 218. doi: <https://doi.org/10.1007/s00382-025-07686-9>.
- Rao, S.A., Goswami, B.N., Sahai, A.K., Rajagopal, E.N., Mukhopadhyay, P., Rajeevan, M., Nayak, S., Rathore, L.S., Shenoi, S.S.C., Ramesh, K.J., Nanjundiah, R.S., Ravichandran, M., Mitra, A.K., Pai, D.S., Bhowmik, S.K.R., Hazra, A., Mahapatra, S., Saha, S.K., Chaudhari, H.S., Joseph, S., Sreenivas, P., Pokhrel, S., Pillai, P.A., Chattopadhyay, R., Deshpande, M., Krishna, R.P.M., Das, R.S., Prasad, V.S., Abhilash, S., Panickal, S., Krishnan, R., Kumar, S., Ramu, D.A., Reddy, S.S., Arora, A., Goswami, T., Rai, A., Srivastava, A., Pradhan, M., Tirkey, S., Ganai, M., Mandal, R., Dey, A., Sarkar, S., Malviya, S., Dhakate, A., Salunke, K. and Maini, P., 2019, "Monsoon Mission: A Targeted Activity to Improve Monsoon Prediction across Scales", *Bulletin of the American Meteorological Society*, 100, 12, 2509–2532. doi: <https://doi.org/10.1175/BAMS-D-17-0330.1>.
- Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M.P., van den Dool, H., Zhang, Q., Wang, W., Chen, M. and Becker, E., 2014, "The NCEP Climate Forecast System Version 2", *Journal of Climate*, 27, 6, 2185–2208. doi: <https://doi.org/10.1175/JCLI-D-12-00823.1>.
- Saheed, P.P., Gupta, A., Pant, V., Mitra, A.K. and Blockley, E., 2026, "Evaluation of Extended Range Hindcasts of Antarctic Sea-ice Using a Coupled Model", *submitted to Journal of Operational Oceanography*.
- Smith, D.K.E., Dorling, S.R., Renfrew, I.A., Ross, A.N. and Poku, C., 2023, "Fog trends in India: Relationships to fog type and western disturbances", *International Journal of Climatology*, 43, 2, 818–836. doi: <https://doi.org/10.1002/joc.7832>.
- Smith, D.K.E., Reka, S., Dorling, S.R., Ross, A.N., Renfrew, I.A., Jayakumar, A., Anurose, T.J., Parde, A.N., Ghude, S.D. and Rumbold, H., 2024, "Forecasts of fog events in northern India dramatically improve when weather prediction models include irrigation effects", *Communications Earth & Environment*, 5, 141. doi: <https://doi.org/10.1038/s43247-024-01314-w>.
- Srivastava, A., Martin, G.M., Pradhan, M., Rao, S.A. and Ineson, S., 2026, "The multi-year negative Indian Ocean Dipole of 2021–2022", *Weather and Climate Dynamics*, 7, 1–15. doi: <https://doi.org/10.5194/wcd-7-1-2026>.
- Thota, M.S., Ashrit, R., Niranjan Kumar, K., Saha, U., Rao, D.N., Jayakumar, A., Mohandas, S. and Prasad, V.S., 2024, "Assessment of extreme rainfall events for iFLOWS Mumbai in NCUM regional forecasting system", *Natural Hazards*, 120, 10785–10805. doi: <https://doi.org/10.1007/s11069-024-06628-8>.
- UK Government, 2021, "2030 Roadmap for India-UK future relations". Available from: <https://www.gov.uk/government/publications/india-uk-virtual-summit-may-2021-roadmap-2030-for-a-comprehensive-strategic-partnership/2030-roadmap-for-india-uk-future-relations>.
- Wright, A., Lawless, A.S., Nichols, N.K., Lea, D.J. and Martin, M.J., 2024, "Assessment of short-range forecast error atmosphere–ocean cross-correlations from the Met Office coupled numerical weather prediction system", *Quarterly Journal of the Royal Meteorological Society*, 150, 762, 2783–2797. doi: <https://doi.org/10.1002/qj.4735>.