

**QUANTIFYING AND CONSTRAINING THE MODEL
UNCERTAINTY IN FUTURE SUB-DAILY
PRECIPITATION PROJECTIONS**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2023**

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by

ARCHANA MAJHI

DEPARTMENT OF CIVIL ENGINEERING

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

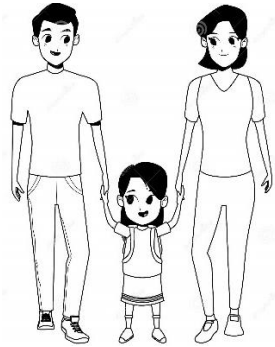
to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2023

I DEDICATE THIS DISSERTATION
TO MY PARENTS



CERTIFICATE

This is certified that the thesis entitled “**Quantifying and Constraining the Model Uncertainty in Future Sub-Daily Precipitation Projections**” being submitted by **Miss. Archana Majhi** to the **Indian Institute of Technology Delhi, India** for the award of the **degree of Doctor of Philosophy** is a record of the original bonafide research work carried by her under our guidance and supervision. The thesis work, in our opinion, has reached the requisite standards fulfilling the requirement for the **Degree of Doctor of Philosophy**.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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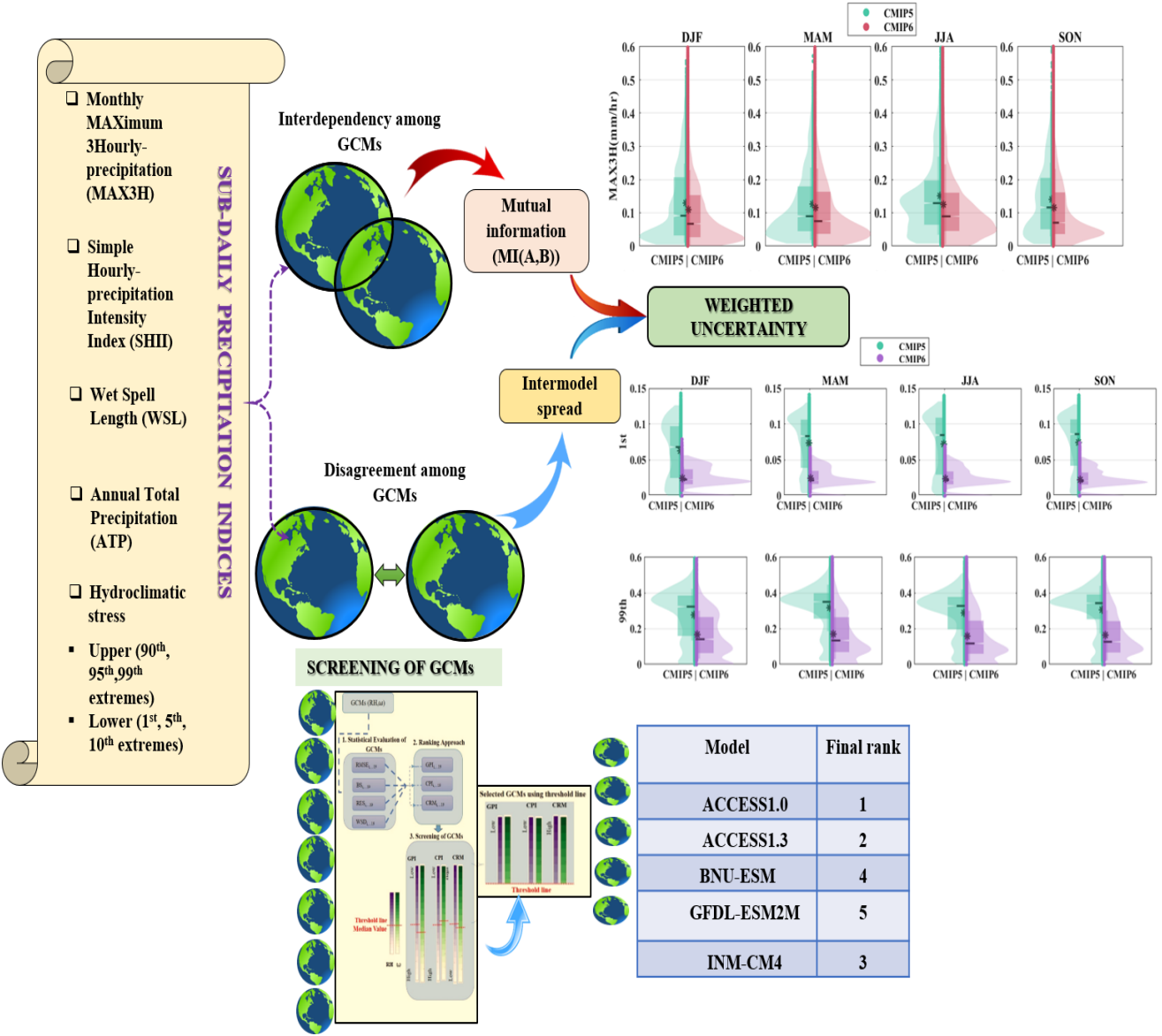
I owe and respectfully offer my thanks to my beloved parents, my mother Mrs. Bandana Majhi, my father Mr. Gagan Majhi, who made their significant contribution to achieve all the goals of my life. Their mellifluous affection, constant support and blessings made my journey smooth and successful. I also extend my special thanks to my sisters – Prangya, Suryasmita, brothers-in-laws – Rabindra and Tripathi, Anshu and Trisha for their light-heartedness during this time consuming efforts of mine.

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Archana Majhi

Archana Majhi

ABSTRACT



Changes in climate as a result of rising greenhouse gas emissions, is one of the major concerns for earth's ecosystem, as it has induced frequent occurrences of extreme precipitation events all across the globe. More importantly, sub-daily precipitation is projected to intensify more rapidly with global warming, that in turn may lead to frequent disasters such as flash floods, landslides, etc. However, the precipitation projections from Global Climate Model (GCMs) are known to be highly uncertain, with an increasing magnitude at finer spatio-temporal scales. Given the fact that GCMs are ill equipped to represent extreme precipitation events as compared to convection permitting models, as the simulation of these fine-resolution phenomena are computationally expensive, it is unclear to what extent the results from such experiments can be applied globally. At the same time, it is known that due to warming climate, short intense spells will increase in the future over many parts of the world. Considering these two factors, GCMs remain the only option for obtaining a global perspective on the future intensification of sub-daily precipitation events. However, the associated uncertainty in GCM projections hinder their application in analysing the climate change impact on global scale. Therefore, the current study attempts for realistic quantification of the inherent uncertainty to improve the confidence in these projections, for the mitigation/adaptation applications. Given the availability of global sub-daily precipitation projections, uncertainty is quantified in the extreme indices proposed by INTENSE (INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes) project. It will help in assessing the confidence to be put in different mitigation/adaptation measures pertaining to various water resources management activities such as drainage infrastructure systems, deriving future water management practices, risk management etc.

In the present study, the model uncertainty in sub-daily (3-hourly) precipitation extremes is estimated, by considering Coupled Model Intercomparison Project Phase (CMIP5/6) GCMs,

during four different seasons for the near (2026-45) and far-future (2081-99) periods. While quantifying the uncertainty, often the possible dependency between the GCMs due to their shared common model code, literature, ideas of representation processes, parameterization schemes, evaluation datasets etc., are ignored. As this will lead to wrong conclusions, the inter-model dependency and the respective independence weights need to be considered, for a realistic quantification of uncertainty. Here, we present the detailed step-wise methodology of a “mutual information based independence weight” framework, that accounts for the linear and nonlinear dependence between GCMs and the equitability property. A brief illustration of the utility of this method is provided by applying it to the multi-model ensemble of CMIP GCMs. The weighted variance approach seemingly reduces the uncertainty about one GCM given the knowledge of another. Analysis of the heterogeneity in seasonal model uncertainty with various spatial domain-related aspects confirms the spatio-temporal variability of uncertainty. The model uncertainty on a particular region is found to be most sensitive to the observed magnitude of different precipitation characteristics of that location. Among the geophysical factors, elevation has more effect than land cover, on the uncertainty range.

The model uncertainty is found to be more dominant over tropical regions for precipitation projection. Therefore, there is need for selecting a reduced set of models having least biases so that effective decision on climate change mitigation and adaptation strategies can be taken based on the minimum possible outcomes of the future events. In this study, we tried to select the models based on their performance in relative humidity and vertical velocity since these variables plays an important role in precipitation simulation and hence contribute towards the intermodel spread. The models are evaluated by using various statistical performance measures and also ranked using multiple approaches such as global performance indicator (GPI), compromise programming index

(CPI) and comprehensive rating metric (CRM). The variability in the ranking is observed among the approaches. After selecting the better performing GCMs from the whole ensemble, the best possible subset of GCMs is chosen using Jenks natural breaks optimization algorithm.

Moreover, the quantification should be based on the newly released updated projections available from CMIP6 to enhance the effectiveness. The recently released CMIP6 includes a number of advances relative to its predecessor (CMIP5), in terms of horizontal resolution, physical parameterization schemes and concept of specifying shared socioeconomic pathways (SSPs). The question, however, is do these modifications indeed reduce the uncertainty in the projected sub-daily precipitation at global scales? The question is addressed by using CMIP5 and CMIP6 models for quantifying the uncertainty in sub-daily extreme precipitation indices for near and far-future period. The results indicate a noticeable reduction in the uncertainty in CMIP6 precipitation relative to CMIP5. It indicates the improved simulation of extreme indices in CMIP6 models relative to its predecessor (CMIP5). The study provides information about the regions, seasons and indices where model agreement is improved for CMIP6 models. Despite, uncertainty in models is inherent and this calls for further research on the sources of persistent systematic biases and a prerequisite for identifying GCMs with robust features that can accurately simulate observed sub-daily precipitation for future usage. Overall, the current study of uncertainty will be useful to understand the reliability that can be placed in the sub-daily precipitation projections. Such uncertainty quantification can do the needful in the field of risk assessment, by providing better interpretation of climate change impacts as well as for informed policies to mitigate the associated consequences.

शोध प्रबंध का शीर्षक: भविष्य के उप-दैनिक वर्षा अनुमानों में मॉडल अनिश्चितता की मात्रा का निर्धारण एवं परिसीमन

छात्र का नाम: अर्चना माझी

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सारांश

बढ़ते ग्रीनहाउस गैस उत्सर्जन के परिणामस्वरूप जलवायु में परिवर्तन प्रमुख चिंताओं में से एक है पृथ्वी का पारिस्थितिकी तंत्र, क्योंकि इसने हर जगह अत्यधिक वर्षा की घटनाओं को बार-बार प्रेरित किया है। इससे भी महत्वपूर्ण बात यह है कि उप-दैनिक वर्षा और अधिक तेजी से बढ़ने का अनुमान है ग्लोबल वार्मिंग, जिसके परिणामस्वरूप अचानक बाढ़, भूस्खलन आदि जैसी लगातार आपदाएँ हो सकती हैं। हालाँकि, वैश्विक जलवायु मॉडल (जीसीएम) से वर्षा के अनुमान बेहतर स्थानिक-लौकिक पैमानों पर बढ़ते परिमाण के साथ अत्यधिक अनिश्चित हैं। तथ्य यह है कि जीसीएम संवहन की तुलना में अत्यधिक वर्षा की घटनाओं का प्रतिनिधित्व करने के लिए अनुमति देने वाले मॉडल सुसज्जित नहीं हैं, क्योंकि इन बारीक-रिज़ॉल्यूशन वाली घटनाओं का अनुकरण कम्प्यूटेशनल रूप से किया जाता है, यह स्पष्ट नहीं है कि ऐसे प्रयोगों के परिणामों को विश्व स्तर पर किस हद तक लागू किया जा सकता है। साथ ही, यह ज्ञात है कि गर्म जलवायु के कारण, दुनिया के कई हिस्सों में भविष्य छोटी तीव्र अवधि में वृद्धि होगी। इन दो कारकों को ध्यान में रखते हुए, उप-दैनिक वर्षा की घटनाओं की भविष्य की तीव्रता पर वैश्विक परिप्रेक्ष्य प्राप्त करने के लिए जीसीएम ही एकमात्र विकल्प है। हालाँकि, जीसीएम अनुमानों में संबंधित अनिश्चितता वैश्विक स्तर पर जलवायु परिवर्तन का प्रभाव विश्लेषण में उनके अनुप्रयोग में बाधा डालती है। इसलिए, वर्तमान अध्ययन प्रयास करता है इन अनुमानों में विश्वास को बेहतर बनाने के लिए अंतर्निहित अनिश्चितता की मात्रा और शमन/अनुकूलन अनुप्रयोग का निर्धारण करता है। वैश्विक उप-दैनिक वर्षा की उपलब्धता को देखते हुए अनुमानों, अनिश्चितता को *INTENSE* (बुद्धिमान गैर-स्थिर हाइड्रोलॉजिकल चरम सीमाओं के अनुकूलन के लिए जलवायु मॉडल का उपयोग) परियोजना द्वारा प्रस्तावित चरम सूचकांकों में परिमाणित किया गया है। इससे विभिन्न शमन/अनुकूलन उपायों से संबंधित आत्मविश्वास का आकलन करने में विभिन्न जल संसाधन प्रबंधन गतिविधियाँ जैसे जल

निकासी बुनियादी ढाँचा प्रणालियाँ, व्युत्पन्न भविष्य के जल प्रबंधन अभ्यास, जोखिम प्रबंधन आदि में मदद मिलेगी ।

वर्तमान अध्ययन में, उप-दैनिक (3-घंटे) वर्षा चरम सीमा में मॉडल अनिश्चितता का निकट (2026-45) और दूर-भविष्य (2081-99) अवधियों के लिए चार अलग-अलग मौसमों के दौरान है युग्मित मॉडल अंतरतुलना परियोजना चरण (CMIP6) जीसीएम पर विचार करके अनुमान लगाया गया है । जबकि अनिश्चितता को मापना, अक्सर जीसीएम के बीच उनके साझा होने के कारण संभावित निर्भरता सामान्य मॉडल कोड, साहित्य, प्रतिनिधित्व प्रक्रियाओं के विचार, मानकीकरण योजनाएं, मूल्यांकन डेटासेट आदि को नजरअंदाज कर दिया जाता है। चूँकि इससे ग़लत निष्कर्ष निकलेंगे, अंतर-मॉडल वास्तविकता के लिए निर्भरता और संबंधित स्वतंत्रता भार पर विचार करने की आवश्यकता है अनिश्चितता की मात्रा का निर्धारण. यहां, हम "आपसी" की विस्तृत चरण-वार पद्धति प्रस्तुत करते हैं सूचना आधारित स्वतंत्रता भार" ढाँचा, जो रैखिक और गैर-रेखीय के लिए जिम्मेदार है, जीसीएम और समानता संपत्ति के बीच निर्भरता। इसकी उपयोगिता का एक संक्षिप्त उदाहरण विधि को सीएमआईपी जीसीएम के मल्टी-मॉडल समूह में लागू करके प्रदान किया जाता है। भारित विचरण दृष्टिकोण प्रतीत होता है कि ज्ञान दिए जाने पर एक जीसीएम के बारे में एक और अनिश्चितता कम हो जाती है । विभिन्न स्थानिक डोमेन-संबंधित पहलुओं के साथ मौसमी मॉडल अनिश्चितता में विविधता का विश्लेषण अनिश्चितता की स्थानिक-लौकिक परिवर्तनशीलता की पुष्टि करता है। मॉडल पर अनिश्चितता एक विशेष क्षेत्र, उस स्थान की विशेषताएँ विभिन्न वर्षा के प्रेक्षित परिमाण के प्रति सबसे अधिक संवेदनशील पाया जाता है। अनिश्चितता सीमा पर भूभौतिकीय कारकों में भूमि की तुलना में ऊँचाई का अधिक प्रभाव पड़ता है ।

वर्षा के लिए उष्णकटिबंधीय क्षेत्रों पर प्रक्षेपण मॉडल अनिश्चितता अधिक प्रभावी पाई गई है । इसलिए, कम से कम पूर्वाग्रह वाले मॉडलों के एक कम सेट का चयन करने की आवश्यकता है जिसके आधार पर भविष्य की घटनाओं के न्यूनतम संभावित परिणाम, जलवायु परिवर्तन शमन और अनुकूलन रणनीतियों पर प्रभावी निर्णय लिया जा सकता है । इस अध्ययन में, हमने मॉडलों का चयन सापेक्ष आर्द्रता और ऊर्ध्वाधर वेग में उनके प्रदर्शन के आधार पर करने का प्रयास किया क्योंकि वर्षा सिमुलेशन में एक महत्वपूर्ण भूमिका और इसलिए इंटरमॉडल प्रसार में योगदान देता है । मॉडलों का मूल्यांकन विभिन्न सांख्यिकीय प्रदर्शन उपायों का उपयोग करके किया जाता है और उनका उपयोग करके रैंकिंग वैश्विक प्रदर्शन संकेतक (जीपीआई), समझौता प्रोग्रामिंग इंडेक्स जैसे कई दृष्टिकोण (सीपीआई) और व्यापक रेटिंग मीट्रिक (सीआरएम) भी की

जाती है। रैंकिंग दृष्टिकोण में परिवर्तनशीलता देखी गई है। जीसीएम के संभावित उपसमुच्चय को जेनक्स नेचुरल ब्रेक ऑप्टिमाइज़ेशन एल्गोरिदम का उपयोग करके पूरे समूह में से बेहतर प्रदर्शन करने वाले जीसीएम का चयन करने के बाद, सर्वश्रेष्ठ का चयन किया जाता है।

इसके अलावा, प्रभावशीलता बढ़ाने के लिए *CMIP6* से परिमाणीकरण उपलब्ध नए जारी किए गए अद्यतन अनुमानों पर आधारित होना चाहिए। हाल ही में जारी *CMIP6* में क्षेत्रीय रिज़ॉल्यूशन, भौतिक के संदर्भ में, अपने पूर्ववर्ती (*CMIP5*) के सापेक्ष मानकीकरण योजनाएं और साझा सामाजिक आर्थिक रास्ते (एसएसपी) निर्दिष्ट करने की कई अवधारणा शामिल हैं। हालाँकि, सवाल यह है कि क्या ये संशोधन वास्तव में वैश्विक स्तर पर अनुमानित उप-दैनिक वर्षा में अनिश्चितता को कम करते हैं? प्रश्न का समाधान *CMIP5* और *CMIP6* मॉडल का उपयोग निकट और दूर भविष्य के उप-दैनिक अत्यधिक वर्षा सूचकांकों में अनिश्चितता की मात्रा निर्धारित करके किया गया है। परिणाम *CMIP5* के सापेक्ष, *CMIP6* वर्षा में अनिश्चितता में उल्लेखनीय कमी का संकेत देते हैं। यह *CMIP6* मॉडल अपने पूर्ववर्ती (*CMIP5*) के सापेक्ष, चरम सूचकांकों के बेहतर सिमुलेशन को इंगित करता है। अध्ययन क्षेत्रों, मौसमों आदि के बारे में जानकारी प्रदान करता है सूचकांक जहां *CMIP6* मॉडल के लिए मॉडल समझौते में सुधार किया गया है। इसके बावजूद, मॉडलों में अनिश्चितता है, अंतर्निहित और इसके लिए लगातार व्यवस्थित पूर्वाग्रहों के स्रोतों पर और अधिक शोध की आवश्यकता है, मजबूत विशेषताओं वाले जीसीएम की पहचान करने के लिए पूर्वापेक्षा जो भविष्य में उपयोग के लिए देखी गई उप-दैनिक वर्षा का सटीक अनुकरण कर सकती है। कुल मिलाकर, अनिश्चितता का वर्तमान अध्ययन उपयोगी होगा जिसे उप-दैनिक वर्षा अनुमानों में रखा जा सकता है। ऐसा अनिश्चितता परिमाणीकरण, जोखिम मूल्यांकन के क्षेत्र में आवश्यक कार्य कर सकता है और जलवायु परिवर्तन के प्रभावों की व्याख्या के साथ-साथ संबंधित को कम करने के लिए सूचित नीतियों की व्याख्या बेहतर प्रदान कर सकता है।

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LIST OF ABBREVIATIONS

Acronyms

Expanded form

CMIP	Couple Model Intercomparison Project
GCM	General Circulation Models
SHII	Simple Hourly-precipitation Intensity Index
WSL	Wet Spell Length
MAX3H	MAXimum 3Hourly-Precipitation
ATP	Annual Total Precipitation
NDVI	Normalized Difference Vegetation Index
IQR	Interquartile Range
HY-INT	Hydroclimatic Intensity
PI	Precipitation Intensity
RH	Relative Humidity
RMSE	Root Mean Square Error
RES	Relative Error In Standard Deviation
BS	Bias Skill
WD	Wasserstein Distance
GPI	Global Performance Indicator
CPI	Compromise Programming Index
CRM	Comprehensive Rating Metrics
JOM	Jenks Optimization Method
GVF	Goodness of Variance Fit
CHIRPS	Climate Hazards Group Infrared Precipitation With Station Data
SSPs	Shared Socioeconomic Pathways
RCPs	Representative Concentration Pathways