

**Assessing the Impact of Climate Change and
Modeling Uncertainties on Rice Production of a
Major Rice Belt in Central India**

Shoobhangi Tyagi



**CENTRE FOR ATMOSPHERIC SCIENCES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
SEPTEMBER 2024**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2024

**Assessing the Impact of Climate Change and
Modeling Uncertainties on Rice Production of a
Major Rice Belt in Central India**

by

Shoobhangi Tyagi

Centre for Atmospheric Sciences

Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER 2024

Dedicated to my parents & brother
For their patience, belief, and support

Certificate

This is to certify that the thesis titled “*Assessing the Impact of Climate Change and Modeling Uncertainties on Rice Production of a Major Rice Belt in Central India*” being submitted by **Ms. Shoobhangi Tyagi** to the Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is a record of original bonafide research work carried out by her. She has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis.

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



Dr. SAROJ KANTA MISHRA
Professor, Centre for Atmospheric Sciences
Indian Institute of Technology Delhi



Dr. SANDEEP SAHANY
Deputy Principal Research Scientist,
Department of Climate Research
Centre for Climate Research Singapore



Dr. AMLENDU DUBEY
Associate Professor, Department of Management Studies
Indian Institute of Technology Delhi

Acknowledgments

I am deeply grateful to my supervisors, Dr. Sandeep Sahany, Dr. Saroj Kanta Mishra, and Dr. Amlendu Dubey, for their unwavering guidance and support. Their mentorship has been crucial to my growth as a research professional. I am sincerely indebted to Dr. Sandeep Sahany for his generosity with time and remarkable patience. His approach to exploring the intricacies of a research question and finding the most viable solution has been pivotal in shaping this thesis. I wish to express my sincere appreciation to my collaborators, Dr. Hansoo Lee, Dr. Dharmendra Saraswat, and Dr. Dev Niyogi, whose contributions have enhanced my ability to work within a diverse research group. Their critical feedbacks have been beneficial in refining my skills to articulate research findings to a broader audience effectively.

I am highly thankful to SRC members - Dr. Sagnik Dey, Dr. Vimlesh Pant, Dr. Anupam Dewan, Dr. Dharmendra Saraswat, and Head CAS Dr. Somnath Baidya Roy for their feedback and advice. I also acknowledge the valuable inputs from other faculty members and express my thanks to the administrative staff at CAS, especially Narender sir and Nisha madam, for their unwavering support. I am thankful for the support IITD administrative and accounts staff provided throughout my PhD work.

I am grateful to the Indian Institute of Technology Delhi (IITD), DST Centre for Excellence (DST-CoE) in Climate Modeling, and IITD Super Computing Facility for providing the essential resources during my PhD. I thank the University Grants Commission (UGC) and the DST- Science and Engineering Research Board (SERB) for providing fellowship support. Acknowledgment is due to the ILDP program and DST-SERB Overseas Visiting Doctoral program for providing me the opportunity to conduct parts of my PhD research at Hiroshima University, Japan, and Purdue University, USA. I also appreciate the travel support from IITD and CSIR for conferences and workshops during my PhD I extend my thanks to the India Meteorological Department and the Indira Gandhi Agricultural University, Chhattisgarh, for providing the regional crop management data.

In my PhD program, I have had the privilege of engaging and interacting with exceptional individuals who have made my PhD journey both enjoyable and meaningful. My gratitude extends to Jyoti Singh, Ankur Dixit, Kamal Tewari, Gaurav Dogra, Popat Salunke, Prabhakar Namdev, Pankaj Upadhyaya, Debi Prasad Bhuyan, Ashish Dwivedi, Sundeep Kumar Baraik, Akhil, Shushovan Ghosh, Ekta Chaudhary, and Deepshikha Dhadhwal for

several insightful and encouraging discussions. Thanks to Dhruv, Taruna, Vasu, Shreya, Arzoo, and Vineetha for the tea breaks and get-togethers.

A special thanks to Shubham and Vivek for their exceptional support in my thesis work. I express my gratitude to Nidhi Madam and Pramit sir for their continuous guidance in my research endeavours. Thanks to Pooja, Varun, Aanis, Sajad, and several others for being a wonderful support system at Purdue University. My appreciation extends to all friends and extended family members for being a listening ear throughout my PhD journey and for showing trust in me when it was most needed.

My most profound appreciation goes to my parents, brother, sister-in-law, Nani, and late Nana for their unconditional love, patience, and encouragement. Last but not least, I express my heartfelt gratitude to my late Amma and Baba, for nurturing the dream of pursuing a PhD within my five-year-old self.

Abstract

Over the last decade, the global greenhouse gas emissions have reached record highs. Unless immediate and substantial measures are taken to reduce emissions, there is a significant threat to water, food, and energy security. The increase in temperature, uncertain precipitation patterns, and increased frequency of extreme events pose a great threat to water availability and food productivity. The projected increase in global population (~9.7 billion by 2050) exacerbates food security risks. The 2015 Paris Agreement proposed an ambitious target of limiting the rise in global mean surface temperature to well below 2°C, and preferably to 1.5°C, compared to the pre-industrial era. To support this, the participating nations need to understand the regional implications of climate change, recognizing that responses vary based on regional climatic, ecological, and social characteristics. Particularly vulnerable are the developing regions like India and Africa, due to high population, high dependency on climate-sensitive sectors, and low adaptive capacity. Beside the inter country variation, within country response to climate change is also heterogeneous. For instance, the vulnerability to climate change-induced losses is higher for Central India as compared to other Indian regions.

The Mahanadi basin of Chhattisgarh is a major rice belt in Central India and a global rice exporter. However, the region faces susceptibility to climate change due to its heavy reliance (80% of the population) on rainfed agriculture and lack of irrigation infrastructure. Understanding the regional impacts of climate change is crucial for ensuring food security in economically and socially significant areas. Therefore, to ensure food security in such a socio-economically relevant region, it is imperative to understand the regional impacts of climate change on water availability, food productivity, and associated economic losses.

The majority of impact studies available in the literature utilized process-based simulations, feeding General Circulation Model (GCM) climate variables into process-based models. However, the approach is associated with several challenges and is highly uncertain. This is because most of the studies are based on limited and low-resolution regional information, earlier Coupled Model Inter-comparison Project Phase (CMIP) versions, and inappropriate selection of GCMs that fail to represent the physical processes and lead to large uncertainties. Additionally, the standard uncertainty reducing approaches, such as bias adjustment and historically constrained inputs, are based on the assumption of stationarity, which may not hold true for non-stationary climatic conditions, especially for highly climate

sensitive CMIP6 models. Under invalid assumption of stationarity, the existing uncertainty-reducing approaches may lead to implausible hydrological projections. Recent studies have suggested that specific global warming-based assessments (e.g., 1.5°C) may help in reducing the regional projection uncertainties. However, the regional response to specific global warming levels is unknown and is expected to vary across different climate models and regions. To the best of our knowledge none of the previous studies have focused on a comprehensive assessment of the regional response of critical agricultural systems at a specific global warming level.

The research in this thesis focuses on 1) understanding the challenges and associated uncertainties with such regional impact studies, and 2) providing a comprehensive understanding of the regional-scale climate-hydrology-agriculture-economic response to specific global warming level (1.5°C) over the Mahanadi Basin of Chhattisgarh. To begin with, firstly, the input climate variables from 29 CMIP6 models were evaluated for their ability to represent regional monsoon characteristics and extreme climate indices, which are critical for rice productivity. The aim was to discard the highly biased models that may hamper the reliability of regional projections. Later, the process-based SWAT model was set up using multisource and multi-scale datasets and was evaluated for historical simulations by calibrating and validating the model against discharge and rice yield observations. It was found that eight out of 29 CMIP6 models showed extremely high biases (> 80%) in seasonal total precipitation, mean minimum, and mean maximum temperature. Accordingly, these eight CMIP6 models were discarded at this stage. The SWAT model calibration and validation results were found to be satisfactory (NSE > 0.7) for surface runoff and rice yield simulations. Based on the findings of this analysis, the 21 CMIP6 models and the calibrated and validated SWAT model were used for further analysis in the subsequent chapters.

Next, the sub-selected 21 models and calibrated and validated SWAT model were used to understand the uncertainty associated with regional hydrological projections. Firstly, the propagation of climate biases while translating from global-scale climate variables to regional hydrological simulations was evaluated. Later, the stationarity of these climate biases and the feasibility of commonly adopted uncertainty-reducing approaches were tested across the modeling chain – Climate Models (CM), Pre-Processing Approach (PP), and Climate Change Scenario (CCS). Additionally, the impact of high equilibrium climate sensitivity in some of the CMIP6 models on hydrological projections was also estimated. The results suggest that the climate biases increase/dampen while translating from global climate variables to regional

hydrological simulations. Notably, results highlight that the climate biases are not stationary and vary depending on the choice of modeling components. It was found that under non-stationary conditions, direct sub-selection of CMIP6 models or utilization of multi-model mean may not provide reliable hydrological projections. Additionally, the commonly adopted uncertainty-reducing approaches were found to be inefficient for mid-term and long-term projections, especially under extreme scenarios. Therefore, the specific global warming levels (e.g., 1.5°C) based impact assessments, which are expected to be independent of the choice of above-mentioned modeling components, must be analyzed to provide reliable regional projections.

Therefore, in the fourth chapter, the 1.5°C global warming level was estimated across 21 CMIP6 models and two emission scenarios — SSP2-4.5 and SSP5-8.5. Later, the regional response of critical climate variables and hydrological components — seasonal total precipitation, mean temperature and surface runoff to 1.5°C global warming level was evaluated based on SWAT simulations. The implications of 1.5°C global warming level, on critical agricultural components such as green water (essential for rainfed agriculture) and blue water (essential for irrigated agriculture) were also evaluated. Results highlight that even at a 1.5°C global warming level, substantial uncertainties are associated with the regional response to global warming. The critical components such as precipitation, surface runoff, green water, and blue water are projected to decrease by 5-15%, 10-35%, 12-1%, and 40-10%, respectively. Moreover, the projected decrease in blue water was greater than green water, suggesting that the region needs to improve its rainfed rice productivity. However, due to the projected decrease in green water, the demand for improving the irrigation efficiency of the region will increase. Therefore, there is a need to manage both green and blue water under global warming.

Next, the implications of 1.5°C global warming level on the regional rice yield were estimated for SSP2-4.5 and SSP5-8.5 scenarios. The SWAT model-based rice yield simulations for both rainfed and irrigated conditions were used in this study. This was done to understand the implications of transforming rainfed to irrigation conditions on climate-induced shocks. Later, the economic impacts of rice yield changes at 1.5°C global warming level were estimated using Autoregressive Integrated Moving Average (ARIMA) model-based rice price forecasts. Finally, the role of different climate variables, hydrological variables, and associated short-term Flash Drought (FD; rapidly developing and highly destructive) events on the projected rice yield changes was analyzed. It was found that under

rained conditions, rice yield is projected to change by ~ -15% to -2% (SSP2-4.5 scenario) and by ~ -15% to +2% (SSP5-8.5 scenarios). However, under irrigated conditions, rice yield is projected to change by ~ 1% to 9% (SSP2-4.5 scenario) and by ~ -2% to 8% (SSP5-8.5 scenario). A similar pattern is also visible in the case of economic loss estimation. The assessment of different climate variables suggests that for SSP2-4.5, water stresses, and associated FD events, are the major limiting factors for rice yield, such that sufficient irrigation may help in improving rice yield. However, for SSP5-8.5, a rise in night temperature dominates rice yield, such that the positive impact of irrigation is slightly compensated by the prevailing heat stress conditions. Overall, this study highlights 1) water scarcity and rice productivity losses in the region at the 1.5°C global warming level, 2) the narrow timeframe available for the region to develop the adaptive strategies, and 3) the uncertainty associated with regional-scale impact studies. More importantly, this study provides a framework to understand the intricate climate-hydrology-agriculture-economic nexus in a 1.5°C warmer world.

सार

पिछले दशक में, वैश्विक ग्रीनहाउस गैस उत्सर्जन रिकॉर्ड ऊंचाई पर पहुंच गया है। तत्काल और पर्याप्त उत्सर्जन में कटौती के बिना, पानी, भोजन और ऊर्जा सुरक्षा गंभीर खतरे में है। तापमान में वृद्धि, अनिश्चित वर्षा पैटर्न और चरम घटनाओं की बढ़ती आवृत्ति पानी की उपलब्धता और खाद्य उत्पादकता के लिए एक बड़ा खतरा पैदा करती है। वैश्विक जनसंख्या में अनुमानित वृद्धि (2050 तक ~9.7 बिलियन) खाद्य सुरक्षा जोखिमों को बढ़ा देती है। 2015 के पेरिस समझौते ने पूर्व-औद्योगिक युग की तुलना में वैश्विक औसत सतह तापमान में वृद्धि को 2°C से नीचे और अधिमानत 1.5°C तक सीमित करने का एक महत्वाकांक्षी लक्ष्य प्रस्तावित किया। इसका समर्थन करने के लिए, भाग लेने वाले देशों को जलवायु परिवर्तन के क्षेत्रीय प्रभावों को समझने की आवश्यकता है, यह पहचानते हुए कि प्रतिक्रियाएं क्षेत्रीय जलवायु, पारिस्थितिक और सामाजिक विशेषताओं के आधार पर भिन्न होती हैं। उच्च जनसंख्या, जलवायु-संवेदनशील क्षेत्रों पर बड़ी निर्भरता और कम अनुकूली क्षमता (स्कोल्स, 2020) के कारण भारत और अफ्रीका जैसे विकासशील देश विशेष रूप से असुरक्षित हैं। जलवायु परिवर्तन के प्रति संवेदनशीलता में अंतरदेशीय भिन्नता के अलावा, जलवायु परिवर्तन के प्रति देश के भीतर की प्रतिक्रिया भी विषम है। उदाहरण के लिए, भारत का मध्य भाग अन्य क्षेत्रों की तुलना में जलवायु परिवर्तन से होने वाले नुकसान के प्रति अत्यधिक संवेदनशील है।

छत्तीसगढ़ का महानदी बेसिन मध्य भारत में एक प्रमुख चावल बेल्ट और वैश्विक चावल निर्यातक है। हालाँकि, वर्षा आधारित कृषि पर भारी निर्भरता (जनसंख्या का 80%) और सिंचाई के बुनियादी ढांचे की कमी के कारण इस क्षेत्र को जलवायु परिवर्तन के प्रति संवेदनशीलता का सामना करना पड़ता है। आर्थिक और सामाजिक रूप से महत्वपूर्ण क्षेत्रों में खाद्य सुरक्षा सुनिश्चित करने के लिए जलवायु परिवर्तन के क्षेत्रीय प्रभावों को समझना महत्वपूर्ण है। इसलिए, ऐसे आर्थिक और सामाजिक रूप से प्रासंगिक क्षेत्र में खाद्य सुरक्षा सुनिश्चित करने के लिए, पानी की उपलब्धता, खाद्य उत्पादकता और संबंधित आर्थिक नुकसान पर जलवायु परिवर्तन के क्षेत्रीय प्रभावों को समझना जरूरी है।

साहित्य में उपलब्ध अधिकांश प्रभाव अध्ययनों ने प्रक्रिया-आधारित सिमुलेशन का उपयोग किया, जनरल सर्कुलेशन मॉडल (GCM) जलवायु चर को प्रक्रिया-आधारित मॉडल में फीड किया। हालाँकि, यह दृष्टिकोण कई चुनौतियों से जुड़ा है और अत्यधिक अनिश्चित है। ऐसा इसलिए है क्योंकि अधिकांश अध्ययन सीमित और कम-रिज़ॉल्यूशन वाली क्षेत्रीय जानकारी, पहले के CMIP6 संस्करणों और GCM के अनुचित चयन पर आधारित हैं जो भौतिक प्रक्रियाओं का प्रतिनिधित्व करने में विफल रहते हैं और बड़ी अनिश्चितताओं को जन्म देते हैं। इसके अतिरिक्त, मानक अनिश्चितता बाधा दृष्टिकोण,

जैसे पूर्वाग्रह समायोजन और ऐतिहासिक रूप से बाधित इनपुट, स्थिरता की धारणा पर आधारित हैं, जो गैर-स्थिर जलवायु स्थितियों के लिए सच नहीं हो सकता है, खासकर अत्यधिक जलवायु-संवेदनशील CMIP6 मॉडल के लिए। स्थिरता की अमान्य धारणा के तहत, मौजूदा अनिश्चितता-बाधक दृष्टिकोण अकल्पनीय जल विज्ञान संबंधी अनुमानों को जन्म दे सकते हैं। हाल के अध्ययनों ने सुझाव दिया है कि विशिष्ट ग्लोबल वार्मिंग-आधारित आकलन (उदाहरण के लिए, 1.5°C) क्षेत्रीय प्रक्षेपण अनिश्चितताओं को कम करने में मदद कर सकते हैं। हालाँकि, विशिष्ट ग्लोबल वार्मिंग स्तरों पर क्षेत्रीय प्रतिक्रिया अज्ञात है और विभिन्न जलवायु मॉडल और क्षेत्रों में भिन्न होने की उम्मीद है। हमारी सर्वोत्तम जानकारी के अनुसार पिछले किसी भी अध्ययन ने विशिष्ट ग्लोबल वार्मिंग स्तर पर महत्वपूर्ण कृषि प्रणालियों की क्षेत्रीय प्रतिक्रिया के व्यापक मूल्यांकन पर ध्यान केंद्रित नहीं किया है।

इस थीसिस में अनुसंधान इस पर केंद्रित है 1) ऐसे क्षेत्रीय प्रभाव अध्ययनों के साथ चुनौतियों और संबंधित अनिश्चितताओं को समझना और 2) विशिष्ट ग्लोबल वार्मिंग स्तर (1.5°C) के लिए क्षेत्रीय स्तर की जलवायु-जल विज्ञान-कृषि-आर्थिक प्रतिक्रिया की व्यापक समझ प्रदान करना। छत्तीसगढ़ के महानदी बेसिन पर। शुरुआत करने के लिए, सबसे पहले, 29 CMIP6 मॉडल से इनपुट जलवायु चर का मूल्यांकन क्षेत्रीय मानसून विशेषताओं और चरम जलवायु सूचकांकों का प्रतिनिधित्व करने की उनकी क्षमता के लिए किया गया था, जो चावल उत्पादकता के लिए महत्वपूर्ण हैं। इसका उद्देश्य अत्यधिक पक्षपाती मॉडलों को त्यागना था जो क्षेत्रीय अनुमानों की सटीकता में बाधा डाल सकते हैं। बाद में, प्रक्रिया-आधारित SWAT मॉडल को मल्टीसोर्स और मल्टी-स्केल डेटासेट का उपयोग करके स्थापित किया गया था और डिस्चार्ज और चावल की उपज टिप्पणियों के खिलाफ मॉडल को कैलिब्रेट और मान्य करके ऐतिहासिक सिमुलेशन के लिए मूल्यांकन किया गया था। यह पाया गया कि 29 CMIP6 मॉडलों में से आठ ने मौसमी कुल वर्षा, औसत न्यूनतम और औसत अधिकतम तापमान में अत्यधिक उच्च पूर्वाग्रह (> 80%) दिखाया। तदनुसार, इन आठ सीएमआईपी6 मॉडलों को इस स्तर पर खारिज कर दिया गया। सतही अपवाह और चावल की उपज सिमुलेशन के लिए SWAT मॉडल अंशांकन और सत्यापन परिणाम संतोषजनक (NSE > 0.7) पाए गए। इस विश्लेषण के निष्कर्षों के आधार पर 21 CMIP6 मॉडल और कैलिब्रेटेड और मान्य SWAT मॉडल का उपयोग बाद के अध्यायों में आगे के विश्लेषण के लिए किया गया था।

इसके बाद, क्षेत्रीय हाइड्रोलॉजिकल अनुमानों से जुड़ी अनिश्चितता को समझने के लिए उप-चयनित 21 मॉडल और कैलिब्रेटेड और मान्य SWAT मॉडल का उपयोग किया गया। सबसे पहले, वैश्विक स्तर के जलवायु चर से क्षेत्रीय जल विज्ञान सिमुलेशन में अनुवाद करते समय जलवायु पूर्वाग्रहों के

प्रसार का मूल्यांकन किया गया था। बाद में, इन जलवायु पूर्वाग्रहों की स्थिरता और आमतौर पर अपनाई जाने वाली अनिश्चितता-बाधित दृष्टिकोण की व्यवहार्यता का परीक्षण मॉडलिंग श्रृंखला - जलवायु मॉडल (CM), प्री-प्रोसेसिंग दृष्टिकोण (PP), और जलवायु परिवर्तन परिदृश्य (CS) में किया गया। इसके अतिरिक्त, हाइड्रोलॉजिकल प्रक्षेपण अनिश्चितता पर कुछ CMIP6 मॉडल में उच्च संतुलन जलवायु संवेदनशीलता (ECS) के प्रभाव का भी अनुमान लगाया गया था। नतीजे बताते हैं कि वैश्विक जलवायु चर से क्षेत्रीय जल विज्ञान सिमुलेशन में अनुवाद करते समय जलवायु पूर्वाग्रह बढ़ते/कम होते हैं। उल्लेखनीय रूप से, परिणाम इस बात पर प्रकाश डालते हैं कि जलवायु संबंधी पूर्वाग्रह स्थिर नहीं हैं और मॉडलिंग घटकों की पसंद के आधार पर भिन्न होते हैं। यह पाया गया कि गैर-स्थिर परिस्थितियों में, CMIP6 मॉडल का प्रत्यक्ष उप-चयन या मल्टी-मॉडल माध्य (MMM) का उपयोग विश्वसनीय हाइड्रोलॉजिकल अनुमान प्रदान नहीं कर सकता है। इसके अतिरिक्त, आम तौर पर अपनाए गए अनिश्चितता-बाधित दृष्टिकोण मध्यावधि और दीर्घकालिक अनुमानों के लिए अक्षम पाए गए, खासकर चरम परिदृश्यों में। इसलिए, विशिष्ट ग्लोबल वार्मिंग स्तरों (उदाहरण के लिए, 1.5°C) पर विश्लेषण को आधार बनाकर, जो कि मॉडलिंग घटकों की पसंद से स्वतंत्र होने की उम्मीद है, विश्वसनीय क्षेत्रीय अनुमान प्रदान करने के लिए विश्लेषण किया जाना चाहिए।

इसलिए, चौथे अध्याय में, 21 CMIP6 मॉडल और दो उत्सर्जन परिदृश्यों - SSP2-4.5 और SSP5-8.5 में 1.5°C ग्लोबल वार्मिंग स्तर का अनुमान लगाया गया था। बाद में, SWAT सिमुलेशन के आधार पर महत्वपूर्ण जलवायु चर और हाइड्रोलॉजिकल घटकों - सतही अपवाह, नीला पानी हरे पानी का 1.5°C ग्लोबल वार्मिंग स्तर पर क्षेत्रीय प्रतिक्रिया का मूल्यांकन किया गया। परिणाम इस बात पर प्रकाश डालते हैं कि 1.5°C ग्लोबल वार्मिंग स्तर पर क्षेत्रीय जलवायु अनुमानों से संबंधित पर्याप्त अनिश्चितता अभी भी है। वर्षा, सतही अपवाह, हरा पानी और नीला पानी जैसे महत्वपूर्ण घटक क्रमशः 5-15%, 10-35%, 12-1% और 40-10% की कमी होने का अनुमान है। इसके अलावा, नीले पानी में अनुमानित कमी हरे पानी की तुलना में अधिक थी, जिससे पता चलता है कि इस क्षेत्र को अपनी वर्षा आधारित चावल उत्पादकता में सुधार करने की आवश्यकता है। हालाँकि, हरे पानी में अनुमानित कमी के कारण, क्षेत्र की सिंचाई दक्षता में सुधार की माँग बढ़ेगी। इसलिए ग्लोबल वार्मिंग के तहत हरे और नीले दोनों प्रकार के पानी का प्रबंधन करने की आवश्यकता है।

इसके बाद, SSP2-4.5 और SSP5-8.5 परिदृश्यों के लिए क्षेत्रीय चावल पर 1.5°C ग्लोबल वार्मिंग स्तर के प्रभाव का अनुमान लगाया गया। इस अध्ययन में वर्षा आधारित और सिंचित दोनों स्थितियों के लिए SWAT मॉडल-आधारित चावल उपज सिमुलेशन का उपयोग किया गया था। ऐसा जलवायु-प्रेरित

झटकों पर वर्षा आधारित स्थितियों को सिंचाई में बदलने के निहितार्थ को समझने के लिए किया गया था। बाद में, 1.5°C ग्लोबल वार्मिंग स्तर पर चावल की उपज में बदलाव के आर्थिक प्रभावों का अनुमान ARIMA मॉडल-आधारित चावल मूल्य पूर्वानुमानों का उपयोग करके लगाया गया। अंत में, अनुमानित चावल की उपज में बदलाव पर विभिन्न जलवायु चर, जल विज्ञान संबंधी चर और संबंधित अल्पकालिक अचानक सूखा (FD; तेजी से विकसित होने वाला और अत्यधिक विनाशकारी) घटनाओं की भूमिका का विश्लेषण किया गया। यह पाया गया कि वर्षा आधारित परिस्थितियों में, चावल की उपज ~ -15% से -2% (SSP2-4.5 परिदृश्य) और ~ -15% से +2% (SSP5-8.5 परिदृश्य) तक बदलने का अनुमान है। हालाँकि, सिंचित परिस्थितियों में, चावल की उपज में ~ 1% से 9% (SSP2-4.5 परिदृश्य) और ~ -2% से 8% (SSP5-8.5 परिदृश्य) तक परिवर्तन का अनुमान है। ऐसा ही पैटर्न आर्थिक नुकसान के आकलन के मामले में भी दिखता है। विभिन्न जलवायु चरों के मूल्यांकन से पता चलता है कि SSP2-4.5 परिदृश्य के लिए, जल तनाव और संबंधित FD घटनाएँ चावल की उपज के लिए प्रमुख सीमित कारक हैं, जैसे कि पर्याप्त सिंचाई चावल की उपज में सुधार करने में मदद कर सकती है। हालाँकि, SSP5-8.5 के लिए, रात के तापमान में वृद्धि चावल की पैदावार पर हावी हो जाती है, जिससे कि सिंचाई के सकारात्मक प्रभाव की भरपाई मौजूदा गर्मी के तनाव की स्थिति से थोड़ी हो जाती है। कुल मिलाकर, यह अध्ययन 1.5°C सेल्सियस ग्लोबल वार्मिंग स्तर पर क्षेत्र में पानी की कमी और चावल उत्पादकता के नुकसान पर प्रकाश डालता है, 2) अनुकूली रणनीतियों को विकसित करने के लिए क्षेत्र के लिए उपलब्ध संकीर्ण समय सीमा, और 3) क्षेत्रीय पैमाने से जुड़ी अनिश्चितता प्रभाव अध्ययन। इससे भी महत्वपूर्ण बात यह है कि यह अध्ययन 1.5°C गर्म दुनिया में जटिल जलवायु-जल विज्ञान-कृषि-आर्थिक संबंध को समझने के लिए एक रूपरेखा प्रदान करता है।

Table of Contents

CERTIFICATE	I
ACKNOWLEDGMENTS	II
ABSTRACT	IV
सार	VIII
TABLE OF CONTENTS	XII
LIST OF FIGURES.....	XV
LIST OF TABLES.....	XX
LIST OF ACRONYMS.....	XXI
CHAPTER 1. INTRODUCTION	1
1.1 IMPACT OF CLIMATE CHANGE ON HYDROLOGY	2
1.2 IMPACT OF CLIMATE CHANGE ON AGRICULTURE	5
1.2.1 <i>Climate-induced stresses and Crop growth process</i>	5
1.2.2 <i>Impact of climate change on rice yield</i>	6
1.3 CHALLENGES AND UNCERTAINTIES ASSOCIATED WITH REGIONAL IMPACT ASSESSMENT	9
1.4 SPECIFIC WARMING-BASED ASSESSMENT OF CLIMATE CHANGE	12
1.5 STUDY AREA.....	14
1.6 RESEARCH PROBLEM AND OBJECTIVES	16
CHAPTER 2. EVALUATION OF CMIP6 MODEL OUTPUTS AND THE CALIBRATION AND VALIDATION OF THE SOIL AND WATER ASSESSMENT TOOL (SWAT) OVER THE MAHANADI BASIN OF CHHATTISGARH	19
2.1 INTRODUCTION	19
2.2 DATASETS.....	21
2.2.1 <i>Meteorological Data</i>	21
2.2.2 <i>Spatial and Hydrological Data</i>	23
2.3 METHODOLOGY	24
2.3.1 <i>Bias evaluation of CMIP6 models</i>	24
2.3.2 <i>Hydrological Modeling</i>	25
2.4 RESULTS AND DISCUSSION	31
2.4.1 <i>Mean biases in minimum temperature, maximum temperature, and precipitation</i>	31
2.4.2 <i>Performance of Models for precipitation Indices</i>	36
2.4.3 <i>Calibration and Validation of SWAT model</i>	37
2.5 SUMMARY	39

CHAPTER 3. UNCERTAINTY ASSESSMENT OF FUTURE HYDROLOGICAL PROJECTIONS OVER THE MAHANADI BASIN OF CHHATTISGARH BASED ON SWAT SIMULATIONS	42
3.1 INTRODUCTION	42
3.2 DATASETS.....	45
3.2.1 Meteorological Datasets	45
3.2.2 CMIP6 models	45
3.3 METHODOLOGY	45
3.3.1 Statistical Downscaling and Bias-Adjustment of CMIP6 models (Pre-Processing)	46
3.3.2 Propagation of precipitation biases and precipitation sensitivity of runoff	48
3.3.3 Uncertainty Analysis	49
3.4 RESULTS AND DISCUSSION	52
3.4.1 Propagation of climate biases and runoff sensitivity across CMIP6 models	52
3.4.2 Future runoff sensitivity for different CMIP6 models	55
3.4.3 Projected runoff variability under non-stationary climate biases	57
3.4.4 Variance decomposition of future runoff projection uncertainties	60
3.5 SUMMARY	63
CHAPTER 4. THE REGIONAL IMPLICATIONS OF 1.5°C GLOBAL WARMING ON THE BLUE WATER AND GREEN WATER FLOW OVER THE MAHANADI BASIN OF CHHATTISGARH	67
4.1 INTRODUCTION	67
4.2 DATASETS.....	69
4.2.1 Global Mean Temperature Data	69
4.2.2 Regional Climatological CMIP6 Data	69
4.2.3 Regional Daily CMIP6 Data	70
4.3 METHODOLOGY	70
4.3.1 Estimation of 1.5°C warming period for CMIP6 models	70
4.3.2 Estimation of changes in region climate variables at 1.5°C global warming level	70
4.3.3 Estimation of changes in hydrological components at 1.5°C global warming level	71
4.4 RESULTS AND DISCUSSION	72
4.4.1 Estimation of 1.5°C global warming period for CMIP6 models	72
4.4.2 Projected changes in regional-scale temperature and precipitation	74
4.4.3 Projected changes in surface runoff under a 1.5°C global warming level	76
4.4.4 Changes in green water and blue water under 1.5°C global warming level	77
4.5 SUMMARY	79
CHAPTER 5. ASSESSMENT OF RICE YIELD CHANGES AND ASSOCIATED ECONOMIC LOSSES AT 1.5°C GLOBAL WARMING LEVEL OVER THE MAHANADI BASIN OF CHHATTISGARH	84
5.1 INTRODUCTION	84

5.2 DATASETS.....	87
5.2.1 Rice Price Datasets.....	87
5.2.2 Meteorological Datasets.....	87
5.3 METHODOLOGY	88
5.3.1 Rice Price Forecast	88
5.3.2 Rice Yield Simulation	91
5.3.3 Estimation of Rice Yield Associated Economic Impacts.....	92
5.3.4 Changes in Regional Climate Variables at 1.5°C Global Warming Level.....	93
5.3.5 Occurrence of Flash Drought.....	94
5.4 RESULTS AND DISCUSSION	96
5.4.1 Changes in Rice Yield at 1.5°C Global Warming Level.....	96
5.4.2 Economic impacts of rice yield changes at 1.5°C global warming level.....	97
5.4.3 Changes in Regional Climate Variables at 1.5°C Global Warming Level	98
5.4.4 Changes in Blue Water and Green Water at 1.5°C Global Warming Level.	100
5.4.5 Projected occurrence of FD events at 1.5°C global warming level.....	101
5.5 SUMMARY	103
CHAPTER 6. CONCLUSIONS AND FUTURE WORK	106
6.1 CONCLUSIONS.....	106
6.2 FUTURE WORK	111
PUBLICATIONS AND CONFERENCES.....	113
CHAPTER 7. REFERENCES	114
APPENDIX	132
CURRICULUM - VITAE.....	140

List of Figures

FIGURE 1-1: STEPS INVOLVED IN PROCESS MODEL BASED REGIONAL IMPACT ASSESSMENT..... 11

FIGURE 1-2: LOCATION MAP OF THE STUDY AREA (SHADED REGION). THE DIGITAL ELEVATION MODEL (DEM) AND THE CATCHMENT OUTLET FOR THE SUBBASIN ARE SHOWN IN THE INSET..... 15

FIGURE 2-1: SPATIAL PATTERN OF BIASES (%) IN TOTAL PRECIPITATION IN CMIP6 MODELS AS COMPARED TO IMD OBSERVATIONS FOR JJAS FROM 1985-2014. IMD JJAS-TOTAL PRECIPITATION FOR THE HISTORICAL PERIOD (1985-2014) IS SHOWN AT THE TOP PANEL. 33

FIGURE 2-2: SPATIAL PATTERN OF BIASES (°C) IN SEASONAL MEAN OF THE DAILY MAXIMUM TEMPERATURE OF CMIP6 MODELS COMPARED TO IMD OBSERVATIONS FOR JJAS FROM 1985-2014. IMD JJAS-MEAN MAXIMUM TEMPERATURE PRECIPITATION FOR THE HISTORICAL PERIOD (1985-2014) IS SHOWN AT THE TOP PANEL..... 34

FIGURE 2-3: SPATIAL PATTERN OF BIASES (°C) IN SEASONAL MEAN OF THE DAILY MINIMUM TEMPERATURE OF CMIP6 MODELS FOR JJAS AS COMPARED TO IMD OBSERVATIONS FROM 1985-2014. IMD JJAS-MEAN MINIMUM TEMPERATURE PRECIPITATION FOR THE HISTORICAL PERIOD (1985-2014) IS SHOWN AT THE TOP PANEL..... 35

FIGURE 2-4: BIAS (%) IN PRECIPITATION INDICES FOR CMIP6 MODELS RELATIVE TO IMD FOR JJAS FROM 1985-2014. NOTE: FOR CONSISTENCY OF THE RESULTS THE COLOR CODE HAS BEEN REVERSED FOR CDD SUCH THAT RED REPRESENTS POSITIVE BIAS (DRIER MODELS), AND BLUE REPRESENTS NEGATIVE BIAS (WETTER MODEL). 36

FIGURE 2-5: THE HYDROGRAPH FOR CALIBRATION (1988-1998) AND VALIDATION (1999-2009) OF MEAN MONTHLY DISCHARGE (M³/S) BY SWAT MODEL AT THE CATCHMENT OUTLET (BASANTPUR STATION). 37

FIGURE 2-6: BIAS (%) IN PRECIPITATION INDICES (TOP PANEL) AND BIAS (°C; BOTTOM PANEL) IN MAXIMUM TEMPERATURE (TMAX) AND MINIMUM TEMPERATURE (TMIN) FOR RAW 29 CMIP6 MODELS RELATIVE TO IMD OBSERVATIONS FOR JJAS SEASON FROM 1985-2014. EIGHT DISCARDED MODELS ARE HIGHLIGHTED WITH THE DASHED BLACK BOX. 40

FIGURE 3-1: FLOWCHART SHOWING THE METHODOLOGY ADOPTED FOR THE PRESENT STUDY. 46

FIGURE 3-2: MODELING CHAIN COMBINATION FOR VARIANCE DECOMPOSITION APPROACH. 51

FIGURE 3-3: CIRCULAR PLOT TO REPRESENT THE ABSOLUTE BIAS PROPAGATION AND RUNOFF SENSITIVITY FOR TWO SCENARIOS: 1) USING DIFFERENT PRECIPITATION INPUT (A-B) AND 2) USING DIFFERENT TEMPERATURE AND PRECIPITATION INPUT (C-D). HERE RAW REPRESENT NON-ADJUSTED CLIMATE MODEL INPUTS AND BIASAD. REPRESENT BIAS-ADJUSTED CLIMATE MODEL INPUTS. THE DASHED RED LINE REPRESENTS THE RUNOFF SENSITIVITY FOR IMD OBSERVATIONS. 54

FIGURE 3-4: RELATIVE CHANGES IN RUNOFF SENSITIVITIES TO PRECIPITATION UNDER SSP2-4.5 SCENARIO AS COMPARED TO HISTORICAL PERIOD (1985-2014) FOR A) NON-ADJUSTED CMIP6 MODELS B) BIAS-ADJUSTED CMIP6 MODELS, AT 3-TIME SLICES - THE 2030S (2015-2040), 2060S (2041-2070), 2090S (2071-2100) AND C-D, SAME AS A-B, BUT FOR THE SSP5-8.5 SCENARIO. DW- DRY WARM, WW- WET WARM, DC- DRY COLD, AND WC- WET COLD..... 56

FIGURE 3-5: PDF OF JJAS-TOTAL SURFACE RUNOFF CHANGE (%) FOR CMIP6 MODELS FOR SSP2-4.5 WITH RESPECT TO THE IMD OBSERVATIONS BASED SIMULATIONS (1985-2014). THE LEFT-HAND SIDE REPRESENTS NON-ADJUSTED MODELS, AND THE RIGHT-HAND SIDE REPRESENTS BIAS-ADJUSTED MODELS. THE INSET REPRESENTS THE PDF PLOT FOR MMM WITH THE BLACK LINE REPRESENTING THE MEAN VALUE AND THE DASHED LINE SHOWING ITS CONFIDENCE INTERVAL. THE AREA BETWEEN THE SHADED BLUE REGION REPRESENTS THE 95% CONFIDENCE INTERVAL..... 58

FIGURE 3-6: PDF OF JJAS-TOTAL SURFACE RUNOFF CHANGE (%) FOR CMIP6 MODELS FOR SSP5-8.5 WITH RESPECT TO THE IMD OBSERVATIONS BASED SIMULATIONS (1985-2014). THE LEFT-HAND SIDE REPRESENTS NON-ADJUSTED MODELS, AND THE RIGHT-HAND SIDE REPRESENTS BIAS-ADJUSTED MODELS. THE INSET REPRESENTS THE PDF PLOT FOR MMM WITH THE BLACK LINE REPRESENTING THE MEAN VALUE AND THE DASHED LINE SHOWING ITS CONFIDENCE INTERVAL. THE AREA BETWEEN THE SHADED BLUE REGION REPRESENTS THE 95% CONFIDENCE INTERVAL..... 59

FIGURE 3-7: PARETO PLOT FOR VARIANCE FRACTION TO REPRESENT THE CONTRIBUTION OF CLIMATE MODEL (CM), PRE-PROCESSING (PP), CLIMATE SCENARIO (CS) AND THEIR INTERACTIONS ON VARIABILITY IN RUNOFF PROJECTIONS IN THE 2030S (2015-2040), 2060S (2041-2070), AND 2090S (2071-2100). THE PROJECTED RUNOFF UNCERTAINTY ACROSS DIFFERENT CMIP6 MODELS (COMBINED UNCERTAINTY RANGE FOR NON-ADJUSTED AND BIAS-ADJUSTED MODELS) FOR SSP5-8.5 AND SSP2-4.5 ARE REPRESENTED BY THE INSET BOX PLOTS. THE GREEN LINE REPRESENTS THE PERCENTAGE OF UNCERTAINTY CONTRIBUTION..... 61

FIGURE 4-1: MODELING FRAMEWORK FOR ASSESSING THE HYDROLOGICAL IMPACTS UNDER 1.5°C GLOBAL WARMING LEVEL FOR SURFACE RUNOFF, BLUE WATER, AND GREEN WATER. 72

FIGURE 4-2: NUMBER OF YEARS (VERTICAL BARS) AND NUMBER OF DECADES (COLORED PATCHES) REPRESENTING THE 1.5°C INCREASE IN GLOBAL MEAN TEMPERATURE RELATIVE TO THE PRE-INDUSTRIAL PERIOD (1850-1900) FOR EACH CMIP6 MODEL USING A 1-YEAR INTERVAL BASED MOVING 10-YEAR PERIOD FROM 2015 ONWARDS. 73

FIGURE 4-3: HISTOGRAM PLOT FOR CHANGES (°C) IN THE SEASONAL (JJAS) MEAN OF THE DAILY MEAN TEMPERATURE OF CMIP6 MODELS WITH RESPECT TO THE IMD (OBSERVED) HISTORICAL PERIOD (1985-2014) UNDER A 1.5°C GLOBAL WARMING LEVEL FOR SSP2-4.5 AND SSP5-8.5 SCENARIOS OVER THE MAHANADI SUB-BASIN OF CENTRAL INDIA. BARS REPRESENT THE FREQUENCY OF CORRESPONDING TEMPERATURE CHANGE, THE BLACK LINE REPRESENTS THE MEAN VALUE, AND THE DASHED LINE SHOWS ITS CONFIDENCE INTERVAL. 74

FIGURE 4-4: HISTOGRAM PLOT SHOWING CHANGE (%) IN THE SEASONAL (JJAS) TOTAL PRECIPITATION OF THE 21 CMIP6 MODELS WITH RESPECT TO THE IMD (OBSERVED) HISTORICAL PERIOD (1985-2014) AT 1.5°C GLOBAL WARMING LEVEL UNDER SSP2-4.5 AND SSP5-8.5 SCENARIOS OVER THE MAHANADI SUB-BASIN IN CENTRAL INDIA. BARS REPRESENT THE FREQUENCY OF CORRESPONDING PRECIPITATION CHANGE, THE BLACK LINE REPRESENTS THE MEAN VALUE, AND THE DASHED LINE SHOWS ITS CONFIDENCE INTERVAL. 75

FIGURE 4-5: PERCENTAGE CHANGE IN THE SEASONAL (JJAS) TOTAL RUNOFF WITH RESPECT TO THE IMD (OBSERVED) BASED HISTORICAL PERIOD (1985-2014) UNDER 1.5°C WARMING LEVEL FOR SSP2-4.5 (TOP) AND SSP5-8.5 (BOTTOM) OVER THE MAHANADI SUB-BASIN OF CENTRAL INDIA. 76

FIGURE 4-6: PERCENTAGE CHANGE IN SEASONAL (JJAS) GREEN (GREEN BARS) AND BLUE (BLUE BARS) WATER WITH RESPECT TO IMD (OBSERVED) BASED HISTORICAL PERIOD (1985-2014) UNDER 1.5°C WARMING LEVEL FOR THE SSP2-4.5 SCENARIO OVER THE MAHANADI SUB-BASIN OF CENTRAL INDIA..... 77

FIGURE 4-7: PERCENTAGE CHANGE IN SEASONAL (JJAS) GREEN (GREEN BARS) AND BLUE (BLUE BARS) WATER WITH RESPECT TO THE IMD(OBSERVED) BASED HISTORICAL PERIOD (1985-2014) UNDER 1.5°C WARMING LEVEL FOR THE SSP5-8.5 SCENARIO OVER THE MAHANADI SUB-BASIN OF CENTRAL INDIA.... 78

FIGURE 5-1 STEPS INVOLVED IN THE ASSESSMENT OF RICE YIELD IMPACTS AND ECONOMIC IMPACTS. 88

FIGURE 5-2: STEPS INVOLVED IN THE FORECASTING USING ARIMA MODELS..... 89

FIGURE 5-3: RESIDUAL RANDOMNESS TEST RESULTS FOR ARIMA (1, 2, 1) MODEL. 90

FIGURE 5-4: FORECASTED LOG VALUES OF CONSUMER (RETAIL) PRICE OF RICE FOR CHHATTISGARH..... 91

FIGURE 5-5: PDF PLOT OF RICE YIELD CHANGES UNDER 1.5°C GLOBAL WARMING LEVEL BASED ON SIX CMIP6 MODEL OUTPUTS (2018-2033) AS COMPARED TO THE IMD-BASED HISTORICAL SIMULATIONS (1985-2014). RAINFED CONDITIONS ARE REFERRED AS SSP245NOIRR AND SSP585NOIRR AND IRRIGATED CONDITIONS ARE REFERRED AS SSP245IRR AND SSP585IRR. THE INSET REPRESENTS THE BOX PLOT OF RICE YIELD CHANGES FOR THE FOUR DESIGNED EXPERIMENTS. 96

FIGURE 5-6: PDF PLOT OF ECONOMIC IMPACTS ASSOCIATED WITH RICE YIELD CHANGES UNDER 1.5°C GLOBAL WARMING LEVEL BASED ON SIX CMIP6 MODEL OUTPUTS (2018-2033). RAINFED CONDITIONS ARE REFERRED AS SSP245NOIRR AND SSP585NOIRR AND IRRIGATED CONDITIONS ARE REFERRED AS SSP245IRR AND SSP585IRR. THE INSET REPRESENTS THE MEAN OF ALL SIX CMIP6 MODELS FOR THE FOUR DESIGNED EXPERIMENTS. 98

FIGURE 5-7: HISTOGRAM PLOT OF CHANGES IN JJAS PERIOD TOTAL PRECIPITATION, MEAN MINIMUM TEMPERATURE, MEAN MAXIMUM TEMPERATURE FOR SSP2-4.5 (TOP PANEL) AND SSP5-8.5 (BOTTOM PANEL) FOR 1.5°C GLOBAL WARMING LEVEL USING SIX CMIP6 MODEL OUTPUTS (2018-2033) AS COMPARED TO THE IMD OBSERVATIONS (1985-2014). THE BLACK SOLID LINE REPRESENTS THE MEAN OF ALL SIX CMIP6 MODELS AND THE DASHED LINES REPRESENT THE 95TH PERCENTILE OF THE MEAN. 99

FIGURE 5-8: HISTOGRAM PLOT OF CHANGES IN BLUE WATER (TOP PANEL) AND GREEN WATER (BOTTOM PANEL) OF JJAS PERIOD FOR SSP2-4.5 (RIGHT PANEL) AND SSP5-8.5 (LEFT PANEL) SCENARIOS UNDER 1.5°C GLOBAL WARMING LEVEL BASED ON SIX CMIP6 MODEL OUTPUTS (2018-2033) AS COMPARED TO THE IMD OBSERVATIONS (1985-2014). THE BLACK SOLID LINE REPRESENTS THE MEAN OF ALL SIX CMIP6 MODELS AND THE DASHED LINES REPRESENT THE 95TH PERCENTILE OF THE MEAN. 101

FIGURE 5-9: PROJECTED OCCURRENCE OF FD EVENTS IN THE MAHANADI BASIN OF CHHATTISGARH DURING THE RICE GROWING KHARIF SEASON (JUNE-OCT) AT 1.5°C GLOBAL WARMING LEVEL (USING SIX MODELS REACHING THE WARMING LEVEL BY 2018-2033). THE BLUE LINE REPRESENTS THE PROGRESSION OF FD EVENTS IN SSP2-4.5 SCENARIO AND THE ORANGE LINE REPRESENTS THE PROGRESSION OF FD EVENTS IN SSP5-8.5 SCENARIO. THE DASHED RED REPRESENTS THE INITIATION (RCI =1) OF FD AND THE DASHED YELLOW AND BLACK LINE REPRESENT THE ONSET (RCI =1 AND ESI < -1) AND RAPID INTENSIFICATION (FDI=1; RCI =1 FOR AT LEAST 14-DAYS AND ESI < -1 BY THE END OF THIS PERIOD) OF FD RESPECTIVELY. THE GREEN DASHED LINE REPRESENTS THE TERMINATION OF FD (ESI > -1). 102

FIGURE A-1: THREE NON-IRRIGATED DISTRICTS (> 80% OF THE AREA IS RAINFED) OF CHHATTISGARH THAT ARE COMPLETELY ENCLOSED IN THE SUBBASIN BOUNDARIES AND WERE USED FOR THE CALIBRATION AND VALIDATION OF CROP YIELD. 133

FIGURE A-2: SPATIAL PATTERN OF BIASES (%) IN TOTAL PRECIPITATION OF DOWNSCALED AND BIAS-ADJUSTED EC-EARTH3-VEG CMIP6 MODEL USED IN THIS STUDY (LEFT) AND DOWNSCALED AND BIAS-ADJUSTED EC-EARTH3-VEG DATA OBTAINED FROM NEX-GDDP FOR JJAS (JUNE-JULY-AUG-SEP) AS COMPARED TO IMD OBSERVATIONS FROM 1985-2014. 133

FIGURE A-3: SPATIAL PATTERN OF BIASES (%) IN TOTAL PRECIPITATION OF DOWNSCALED AND BIAS-ADJUSTED EC-EARTH3-VEG CMIP6 MODEL USED IN THIS STUDY (LEFT) AND DOWNSCALED AND BIAS-ADJUSTED EC-EARTH3-VEG DATA OBTAINED FROM NEX-GDDP FOR JJAS (JUNE-JULY-AUG-SEP) AS COMPARED TO IMD OBSERVATIONS FROM 1985-2014. 134

FIGURE A-4: SPATIAL PATTERN OF BIASES IN THE SEASONAL MEAN OF THE DAILY MAXIMUM TEMPERATURE OF DOWNSCALED AND BIAS-ADJUSTED EC-EARTH3-VEG CMIP6 MODEL USED IN THIS STUDY (LEFT) AND DOWNSCALED AND BIAS-ADJUSTED EC-EARTH3-VEG DATA OBTAINED FROM NEX-GDDP FOR JJAS (JUNE-JULY-AUG-SEP) AS COMPARED TO IMD OBSERVATIONS FROM 1985-2014. 134

FIGURE A-5: BIAS (%) IN PRECIPITATION INDICES (TOP PANEL) AND BIAS (°C; BOTTOM PANEL) IN MAXIMUM TEMPERATURE (TMAX) AND MINIMUM TEMPERATURE (TMIN) FOR BIAS-ADJUSTED AND STATISTICALLY DOWNSCALED 21 CMIP6 MODELS RELATIVE TO IMD OBSERVATIONS FOR JJAS SEASON FROM 1985-2014. 136

FIGURE A-6: SHOWS PRECIPITATION (A-B) AND RUNOFF (C-D) ANOMALIES (%) WITH RESPECT TO THE HISTORICAL PERIOD (1985-2014) UNDER SSP2-4.5 AND SSP5-8.5. THE SHADED REGION REPRESENTS ±

STANDARD DEVIATION. THE LEFT-HAND SIDE REPRESENTS NON-ADJUSTED MODELS, AND THE RIGHT-HAND SIDE REPRESENTS BIAS-ADJUSTED MODELS..... 136

FIGURE A-7: PDF OF JJAS-TOTAL SURFACE RUNOFF CHANGE (%) FOR CMIP6 MODELS UNDER THE SSP2-4.5 AND SSP5-8.5. THE SOLID LINE REPRESENTS MMM OF ALL 21 RETAINED CMIP6 MODEL FOR THE TWO SSPS. THE DASHED LINE REPRESENTS CONSTRAINED MMM OF CMIP6 MODELS, AFTER DISCARDING THE MODELS WITH HIGH ECS VALUES ($>4^{\circ}\text{C}$)..... 137

List of Tables

TABLE 1-1: PREVIOUS STUDIES ON THE IMPACT OF CLIMATE CHANGE ON AGRICULTURAL IN CHHATTISGARH....	8
TABLE 2-1 GCMS INFORMATION FROM CMIP6 MODELS USED IN THIS STUDY.....	21
TABLE 2-2: DESCRIPTION OF PRECIPITATION INDICES USED IN THE STUDY.	25
TABLE 2-3 CROP MANAGEMENT DATA FOR THE KHARIF SEASON (JUNE-OCTOBER) OVER A RICE-GROWING REGION (RAIPUR) IN THE BASIN.....	26
TABLE 2-4 CALIBRATED FITTED RANGE OF THE SENSITIVE PARAMETERS ACROSS THE HRUS OF THE SWAT MODEL.	28
TABLE 2-5 STATISTICAL METRICS USED FOR THE CALIBRATION AND VALIDATION OF THE SWAT MODEL.	29
TABLE 2-6 PERFORMANCE METRICS OF THE SWAT MODEL FOR CALIBRATING AND VALIDATING MONTHLY MEAN DISCHARGE AT THE CATCHMENT OUTLET (BASANTPUR STATION).	38
TABLE 2-7 PERFORMANCE METRICS OF SWAT MODEL FOR THE CALIBRATION AND VALIDATION OF RICE YIELD OVER THREE DISTRICTS.	39
TABLE 3-1 CLASSIFICATION OF CMIP6 MODELS BASED ON THE BIASES IN TOTAL PRECIPITATION, AND MEAN TEMPERATURE FOR JJAS FROM 1985-2014	53
TABLE A-1: CLIMATOLOGICAL MEAN (1985-2014) PRECIPITATION (MM) OF CMIP6 MODELS AT NATIVE RESOLUTION, RE-GRIDDED AT 1.5° RESOLUTION AND RE-GRIDDED AT 1° RESOLUTIONS OVER INDIA....	132
TABLE A- 2 BIASES IN PRECIPITATION INDICES (%) IN MAXIMUM TEMPERATURE (TMAX; °C) AND MINIMUM TEMPERATURE (TMIN; °C) FOR BIAS-ADJUSTED AND STATISTICALLY DOWNSCALED 21 CMIP6 MODELS RELATIVE TO IMD OBSERVATIONS FOR JJAS SEASON FROM 1985-2014.	135
TABLE A- 3 LINEAR REGRESSION RESULTS FOR STATIONARY TIME SERIES OF CHANGES JJAS PERIOD TOTAL PRECIPITATION, MINIMUM TEMPERATURE, AND MAXIMUM TEMPERATURE (DEPENDENT VARIABLES) AND CHANGES IN RICE YIELD (INDEPENDENT VARIABLE) FOR 2018-2033 (1.5°C GLOBAL WARMING PERIOD) UNDER SSP2-4.5 SCENARIO GENERATED IN R SOFTWARE.....	138
TABLE A- 4 LINEAR REGRESSION RESULTS FOR STATIONARY TIME SERIES OF CHANGES JJAS PERIOD TOTAL PRECIPITATION, MINIMUM TEMPERATURE, AND MAXIMUM TEMPERATURE (DEPENDENT VARIABLES) AND CHANGES IN RICE YIELD (INDEPENDENT VARIABLE) FOR 2018-2033 (1.5°C GLOBAL WARMING PERIOD) UNDER SSP5-8.5 SCENARIO GENERATED IN R SOFTWARE.....	139

List of Acronyms

ADF	Augmented Dickey Fuller
ARIMA	Autoregressive Integrated Moving Average
CCS	Climate Change Signal
CDD	Consecutive Dry Days
CM	Climate Model
CMIP	Coupled Model Inter-comparison Project Phase
CS	Climate Scenario
CWD	Consecutive Wet Days
DEM	Digital Elevation Model
ECS	Equilibrium Climate Sensitivity
ESI	Evaporative Stress Index
FAO	Food and Agriculture Organization
FD	Flash Drought
FDI	Flash Drought Index
GCM	Global Climate Model
HRU	Hydrologic Response Units
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change

JJAS	June-July-August-September
LUC	Land Use Change
LULC	Land Use Land Cover
MMM	Multi-Model Mean
NDVI	Normalized Difference Vegetation Index (NDVI),
PDF	Probability Density Function
PP	Pre-Processing
PRCPTOT	Total Precipitation
QM	Quantile Mapping
RCI	Rapid Change Index
RCP	Representative Concentration Pathways
SDII	Simple Precipitation Intensity Index
SPI	Standard Precipitation Index SPI
SRTM	Shuttle Radar Topography Mission
SSP	Shared Socioeconomic Pathways
SUFI-2	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
UNFCCC	United Nations Framework Convention on Climate Change
VHI	Vegetation Health Index