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Research Article

Are the Rainfall Variability Signatures of the Four RCP Scenarios in the Southwestern Regions of Punjab, India, Consistent with the Projections outlined in the IPCC assessment reports?

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ABSTRACT

This study conducted an analysis of decadal (2000-2090) rainfall and rainy-day data simulated by the GISS-E2-R model, evaluating the impacts of four Representative Concentration Pathways (RCP 2.6, 4.5, 6.0, and 8.5) on the southwestern region of Punjab. According to study results, during the baseline period (2000-2015), the region received rainfall of 300-800 mm, distributed over 20-45 rainy days. The least pessimistic scenario (RCP 2.6) wherein peak radiative forcing (3.1 W/m^2) would reach around 2050, the sub-humid regions receiving 600-800 mm RF in 30-45 days are projected to receive lesser RF (400-600 mm) in the same number of days while the arid regions receiving 300-500 mm RF in 20-30 days projected to the same amount of RF in more (30-40) days. Most pessimistic scenario (RCP 8.5) indicative of no decline in radiative forcing, the sub-humid regions 600-800 mm RF in 30-45 days are projected to receive lesser RF (500-600 mm) in a lesser number of days (30-40), while the arid regions receiving 300-400 mm RF in 20-25 days projected to expand up to 2041-50 and then reappear during the last decades of the study with increase in number of days, i.e., 35-40. This study reveals variability in regional precipitation patterns, shifting from 300-800 mm to 500-700 mm over 30-45 days, consistent with IPCC's four emissions scenarios.

Key words: GISS-E2-R model, RCPs, Rainfall, Rainy days, South-West Punjab, India

Introduction

The earth-atmosphere system is dynamic and the Intergovernmental Panel on Climate Change (IPCC) is the United Nations (UN) body entrusted with assessing these changes. The IPCC's Fifth Assessment Report (2014) utilized four Representative Concentration Pathways (RCPs) – scenarios representing varying greenhouse gas (GHG) concentrations - to model the Earth-atmosphere system for climate change research and projections. According to the IPCC (2014), four Representative Concentration Pathways (RCPs) - RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 - assume radiative forcing levels of 2.6, 4.5, 6.0, and 8.5 W/m², respectively, by the year 2100. Based on these four scenarios, simulations from General Circulation Models (GCMs) and Regional Climate Models (RCMs) generate historical and projected weather data – temperature, rainfall, solar radiation, and wind – essential for conducting impact assessment research. The Intergovernmental Panel on Climate Change (IPCC, 2019) reports that global warming is altering regional water resources, thereby exacerbating issues such as droughts, floods, and water scarcity. Global studies highlight the critical need for water management strategies that can withstand the impacts of climate change.

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The uncertainty of rainfall, coupled with uneven spatial and temporal distribution, creates floods on the one hand and longer dry spells inducing drought conditions on the other hand. Notably, several studies have examined shifts in India's rainfall patterns, focusing on extremes, frequency, and distributional changes (Menon *et al*., 2013; Sharmila *et al*., 2015; Yaduvanshi and Ranade, 2017). North-West India has experienced a decline in monsoon rainfall, accompanied by increased drought frequency (Jena *et al*., 2016). Duncan *et al.* (2013) found that India's North East and South West Coasts exhibited the highest increases in summer monsoon rainfall, advanced monsoon onset, and enhanced interannual variability. Monsoon season in India brings rainfall to most parts of the country. South-East India primarily receives rainfall from the North-East monsoon (October-December), whereas the North-West region receives significant rainfall during winter (Rajeevan *et al*., 2012).

In India and particularly Punjab, a large variability in rainfall has been observed in different studies. In a regional survey conducted by Kaur *et al*. (2021), simulated results revealed that during the mid-century, annual, *kharif*, and *rabi* seasons rainfall in Punjab state is projected to decline from the baseline period by 33-554 mm, 20-443 mm, and 20-110 mm, respectively. Additionally, declines of 3-610 mm, 14-506 mm, and 17-107 mm are projected for these seasons, respectively, by the end of the century. Abohar is projected to receive an increase in rainfall (11-41 mm while it may decline at Amritsar (49-128 mm), Ballowal Saunkhri (501-554 mm), Ludhiana (131-152 mm), Patiala (148-187), Bathinda (49-82 mm) and Faridkot (33-67 mm).

However, a critical question remains: do the results of regional studies using climate model outputs align with the projected outcomes outlined in the IPCC's Representative Concentration Pathway (RCP) scenarios? With this hypothesis in mind, this study aims to assess the spatiotemporal variability in rainfall and rainy days projected by the GISS-E2-R model in the agriculturally fertile yet water-scarce southwestern region of Indian Punjab, in line with IPCC-guided scenarios.

Material and Methods

Site description and model data used

The study area was the southwestern (SW) region of Indian Punjab with a latitudinal extent of 29°33"N to 30°56"N and a longitudinal extent of 73°53"E to 76°56"E (Fig. 1). The investigators

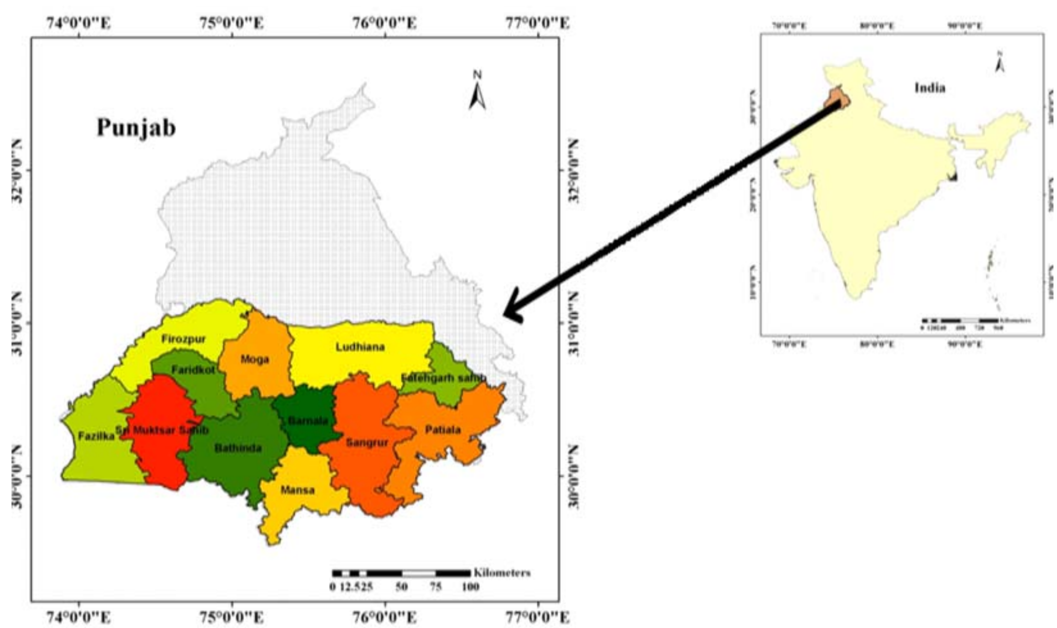

Fig. 1. Rainfall stations selected for the study

analyzed and compared the available historical weather database records with the simulated weather data of GISS-E2-Rmodel developed by NASA Goddard Institute for Space Studies. Daily data on rainfall (RF) for the baseline period (2000-2015) and downloaded projected data for seven decades (2021-2030, 2031-2040, 2041-2050, 2051-2060, 2061-2070, 2071-2080 and 2081-2090) under four scenarios (RCPs 2.6, 4.5, 6.0 and 8.5) from the site *http://gismap.ciat.cgiar.org/MarkSimGCM/* for five locations, i.e., Ludhiana, Patiala, Bathinda, Faridkot and Abohar. The downscaled data was subsequently corrected using the difference method outlined in Kaur *et al*. (2021). The corrected rainfall data analyzed for calculating the India Meteorological Department (IMD) defined rainy day (RD), i.e., a day having a rainfall ≥ 2.5 mm (https://www.hindawi. com/journals/2012/894313/).

Representative Concentration Pathway (RCP)

The IPCC's Fifth Assessment Report (2014) presents four RCP scenarios, which describe distinct climate futures depending on GHG emission levels, summarized in Table 1. Four pathways include a stringent mitigation scenario (RCP 2.6), two intermediate stabilization scenarios (RCP 4.5 and RCP 6.0), and one pessimistic scenario with very high GHG emissions (RCP 8.5).

Results and Discussion

The decadal spatiotemporal changes in rainfall and rainy days simulated by the GISS-E2-R model as compared to baseline RF of 300-800 mm received in 20-45 RD (Table 2) in the SW region of Indian Punjab are described below :

Spatio-temporal variability under RCP 2.6 scenario

The RCP 2.6 scenario, characterized by peak radiative forcing (3.1 W/m²) in 2050 and subsequent decline, reveals that researchers project decadal-scale spatiotemporal variability in RF and RD across the region. Researchers project that subhumid regions, which currently receive moderate RF of 600-800 mm in 30-45 days, will receive lesser RF of 400-600 mm (Fig. 2) in the same number of days (30-45) (Fig. 3). Nevertheless, the arid regions receiving scarce RF between 300-500 mm in 20-30 days are projected to the same amount of RF (Fig. 2) in more number of days, i.e., 30-40 (Fig. 3). Decadal basis regions getting 300-400 mm RF are projected not to change upto 2081-90. However, projections indicate that regions receiving 400-500 mm of rainfall (RF) will replace those currently receiving 500-600 mm, while regions with 600-700 mm and 700-800 mm RF will be replaced by regions with 500-600 mm RF.

Table 1. Description of Representative Concentration Pathways (RCPs)

RCP	Description	Developed by
RCP 2.6	The radiative forcing level reaches approximately 3.1 W/m² by mid-century and then decreases to 2.6 W/m² by 2100	IMAGE modelling team of the Netherlands Environmental Assessment Agency
RCP 4.5	Under this stabilization scenario, greenhouse gas (GHG) emissions reach their peak around 2040 and subsequently decline, resulting in the stabilization of total radiative forcing by 2100	The MiniCAM model is developed and maintained by the Joint Global Change Research Institute, a collaborative partnership between the Pacific Northwest National Laboratory (PNNL) and the University of Maryland.
RCP 6.0	This scenario stabilizes total radiative forcing after 2100 by reducing GHG emissions, which peak around 2080	AIM modeling team at the National Institute for Environmental Studies), Japan
RCP 8.5	This scenario features continuously increasing GHG emissions throughout the 21st century, representing the most pessimistic outlook	MESSAGE modeling team and the IIASA Integrated Assessment Framework at the International Institute for Applied Systems Analysis (IIASA), Austria

Table 2. Comparison of the spatiotemporal changes in decadal rainfall and rainy days simulated by the GISS-E2-R model in South-Western Punjab with the IPCC emission-based scenarios of climate change

RCP	Description	Variability	Rainfall classes (mm)		Rainy day (#)	
			Baseline (2000-15)	The projected rainfall class is not available in the future	Baseline (2000-15)	The Projected rainy- day class is not available in the future
RCP 2.6	The radiative forcing level reaches approximately 3.1 W/m² by the mid-century.	Least	300-400, 400-500, 500-600, 600-700, 700-800	600-700 and 700-800 mm (All decades)	20-25, 25-30, 30-35, 35-40, 40-45	20-25 and 25-30 days (All decades)
RCP 4.5	Radiative forcing stabilized before 2100, following peak emissions around 2040 that subsequently decline.	More		600-700 (All decades except 2051-2060 and 2081-2090) 700-800 mm (All decades)		20-25 and 25-30 days (All decades) 40-45 days (All decades except 2031-2040, 2061-2070 and 2081-2090
RCP 6.0	Radiative forcing stabilizes after 2100, following peak emissions around 2080 that subsequently decline.	More		600-700 mm (2021-2030 and 2031-2040) 700-800 mm (All decades except 2081-2090)		20-25 and 25-30 days (All decades) 30-35 days (2062-2070 and 2071-2080) 40-45 days (All decades except 2041-2050 and 2051-2060
RCP 8.5	Greenhouse gas emissions (GHGs) steadily increase throughout the 21st century.	Peak		300-400 mm (2051-2060 and 2071-2080) 600-700 mm (2071-2080 and 2081-2090) 700-800 mm (All decades)		20-25 and 25-30 days (All decades) 30-35 days (2051-2060) 40-45 days (2041-2050, 2051-2060 and 2061-2070)

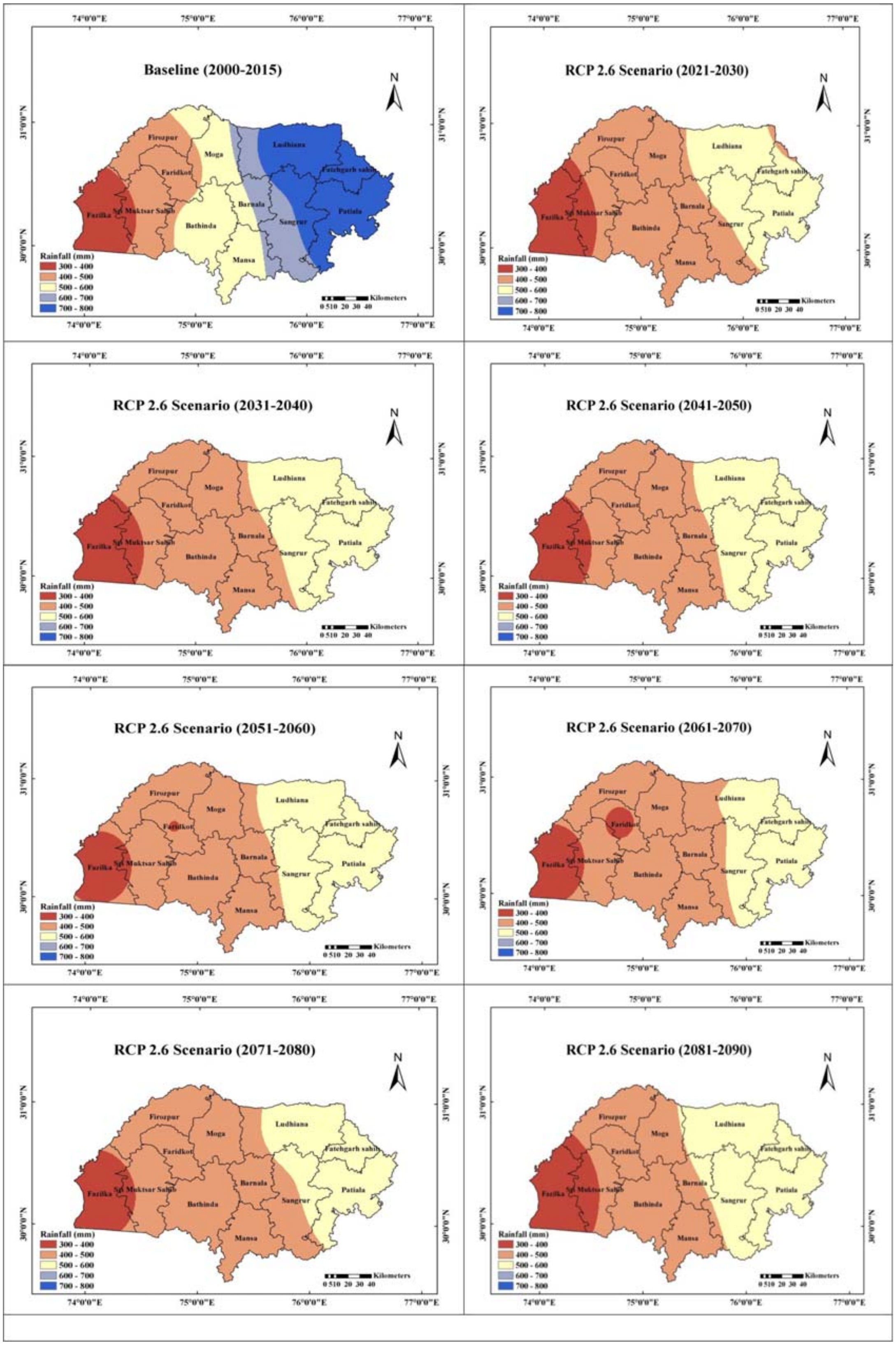

Fig. 2. Decadal variation in rainfall (mm) as predicted by GISS-E2-R model in South-Western Punjab under RCP 2.6 scenario

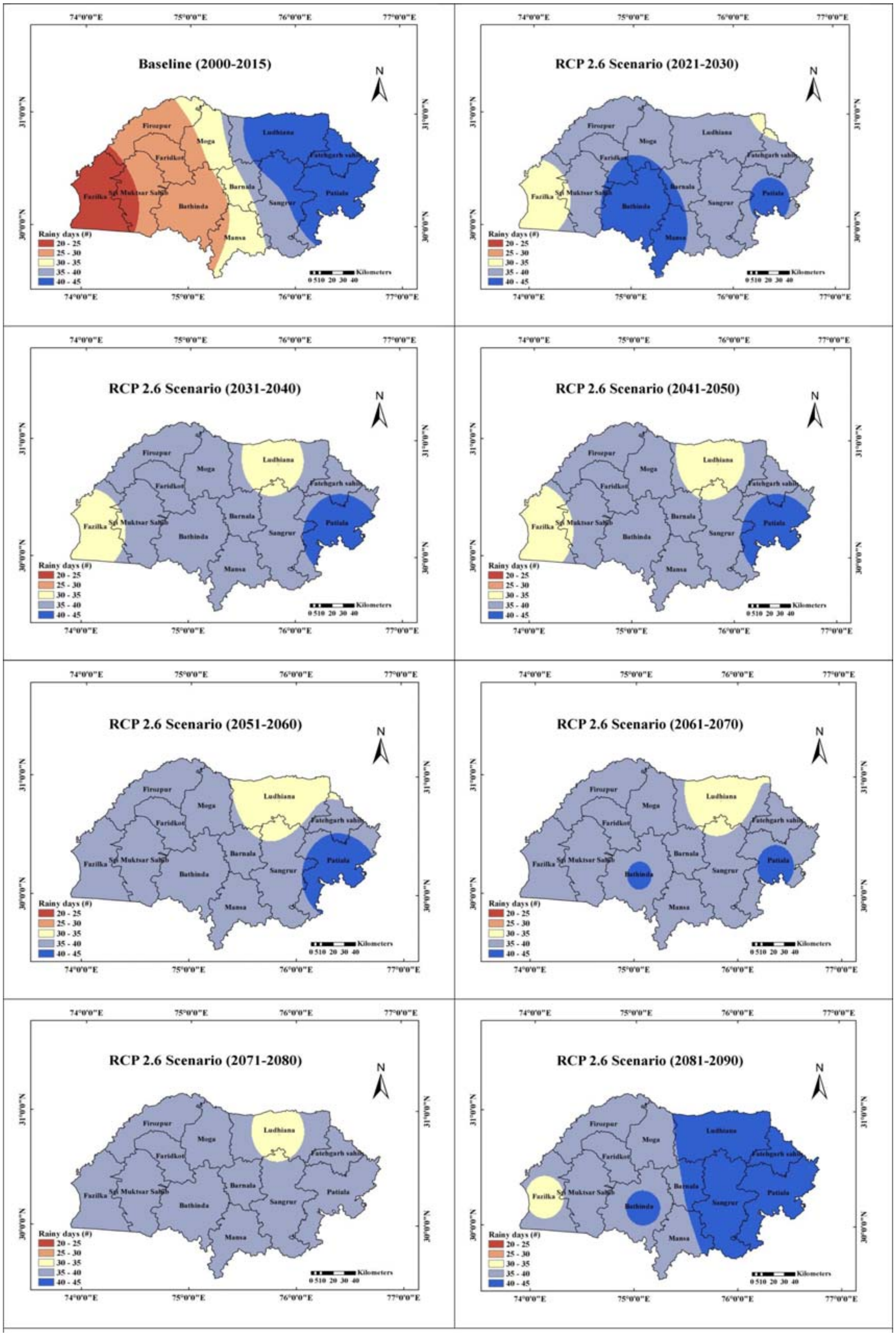

Fig. 3. Decadal variation in rainy days (#) as predicted by GISS-E2-R model in South-Western Punjab under RCP 2.6 scenario

Projections for Radiative Dynamics (RD) indicate that classes of 20-25 and 25-30 days will be entirely replaced by classes of 30-35 and 35-40 days. Although RF amounts are expected to decline, the increased frequency of RD will help mitigate this decrease, making it possible to sustain crop productivity in these regions during the 21st century with well-managed RF.

Spatio-temporal variability under RCP 4.5 scenario

Under the RCP 4.5 stabilization scenario, total radiative forcing stabilizes before 2100 because emissions peak around 2040 and then decline. Researchers project that radiative forcing (RF) and radiative dynamics (RD) in the region will exhibit spatiotemporal variability on a decadal scale. Specifically, sub-humid regions currently receiving moderate RF of 600-800 mm in 30-45 days will experience reduced RF of 400-600 mm (Fig. 4) over fewer days, 35-40 (Fig. 5). In contrast, the arid regions receiving scarce RF between 300-500 mm in 20-30 days are projected to the same amount of RF (Fig.4) in more number of days, i.e., 30-40 (Fig. 5). On decadal basis regions getting 300-400 mm rainfall is projected not to change upto 2051-60, but then during 2061-70 a part of this area will start getting more RF (400-500 mm) which during the last two decades (2071-80 and 2081-90) will be replaced entirely by RF class of 400-500mm. Projections indicate that regions receiving 400-500 mm of rainfall will expand, replacing those with 500-600 mm. Meanwhile, regions with 600-700 mm and 700-800 mm rainfall will contract, giving way to regions with 500-600 mm rainfall. For Radiative Dynamics (RD), projections indicate that classes of 20-25 and 25-30 rainy days will be entirely replaced by classes of 30-35 and 35-40 rainy days. According to projections, this region will receive rainfall on 30-40 days per decade during the periods 2021-2030, 2041-2050, and 2051-2060. Rainfall frequency (RF) will increase to 30-45 days in the decades 2031-2040 and 2061-2070. Then, it will further increase to 35-40 days in 2071-2080 and remain steady at 35-45 days in 2081-2090. Compared to RCP 2.6, RCP 4.5 exhibits increased spatio-temporal variability in RF and RD. These results are consistent with the findings of the Intergovernmental Panel on Climate Change (IPCC) in 2014. Although RF amounts are expected to decline under RCP 4.5, effective RF management can still support sustained crop productivity in this region during the 21st century, despite the rising number of RD events with some decadal fluctuations.

Spatio-temporal variability under RCP 6.0 scenario

Under the RCP 6.0 stabilization scenario, where total radiative forcing is stabilized before 2100 due to emissions peaking around 2080 and subsequently declining, radiative forcing (RF) and radiative dynamics (RD) in the region exhibit spatiotemporal variability on a decadal scale. Sub-humid regions receiving moderate RF between 600-800 mm in 30-45 days will shift to lower RF (400-600 mm) and fewer rainy days (30-40) (Figs. 6-7). According to projections, arid regions receiving scarce RF (300-500 mm) in 20-30 days will expand during 2021-30 and 2031-40. However, these regions will then experience a decrease in area coverage during 2041-50 and 2051-60. Eventually, they will revert to the original pattern of the baseline period during the last two decades of the 21st century, with rainfall occurring over more days (35-45) (Figs. 6 and 7). On decadal basis regions getting 700-800 mm and 600-700 mm RF are projected to disappear but will reappear during 2081-90 and 2041-50, respectively. Regions with RF classes of 400-500 mm are expected to expand by replacing regions with higher RF up to 2061-2070, and then return to the original pattern of the baseline period. Under the RCP 6.0 scenario, climate models predict that the region's radiative dynamics (RD) will change, shifting from 20-45 days (baseline) to 30-45 days (2021-2040), then to 30-40 days (2041-2060), 35-40 days (2061-2080), and finally returning to 30-45 days by the last decade of the 21st century. So, both RF and RD indicate some signs of near stabilization by the previous decade (2081-90) of the study period. Compared to RCP 2.6, our study reveals more significant spatiotemporal variability in radiative forcing (RF) and radiative dynamics (RD) under RCP 4.5 and 6.0 scenarios. However, RCP 6.0 indicates signs of stabilization. These findings align with critical highlights from the IPCC (2014) report.

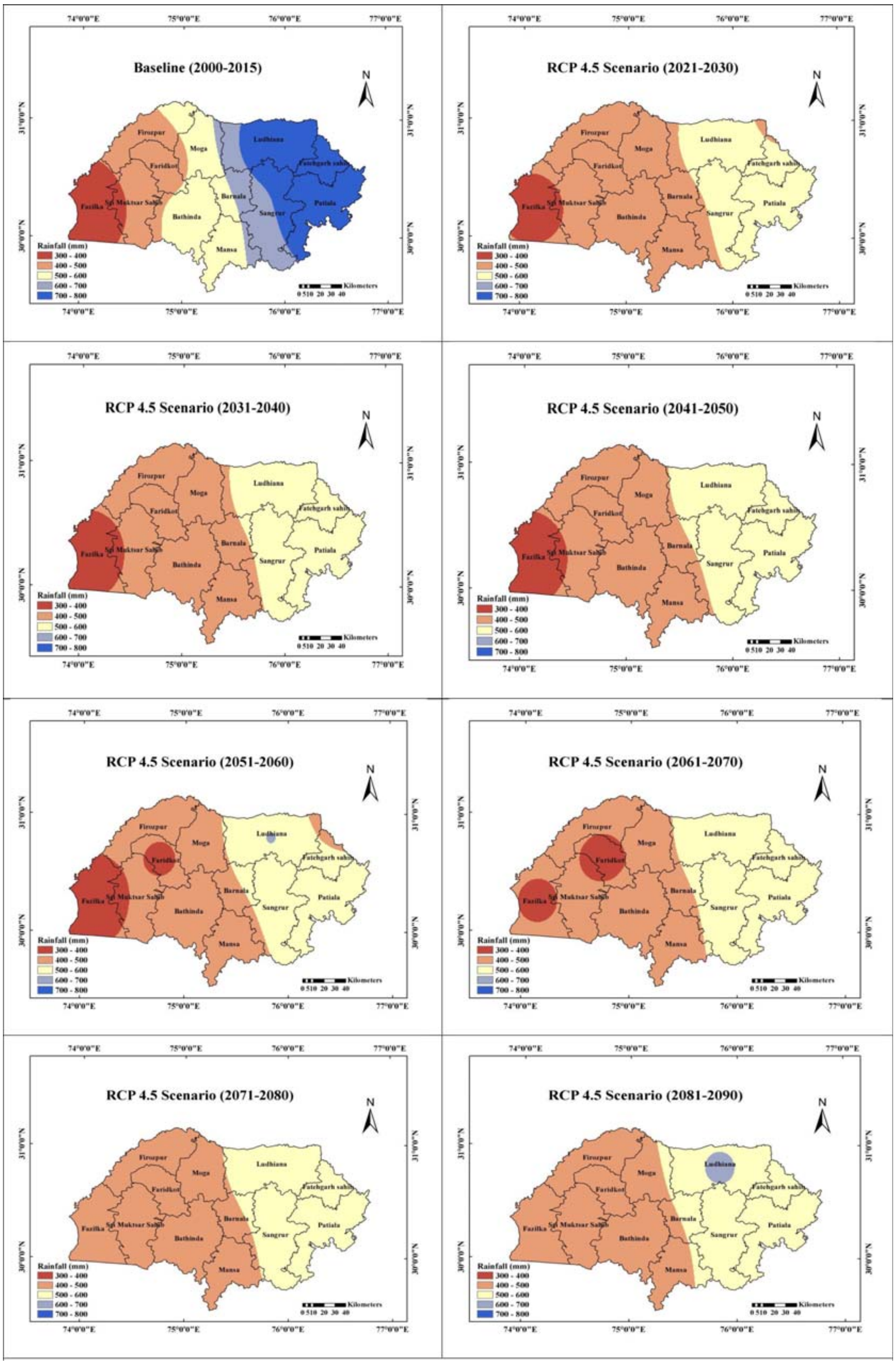

Fig. 4. Decadal variation in rainfall (mm) as predicted by GISS-E2-R model in South-Western Punjab under RCP 4.5 scenario

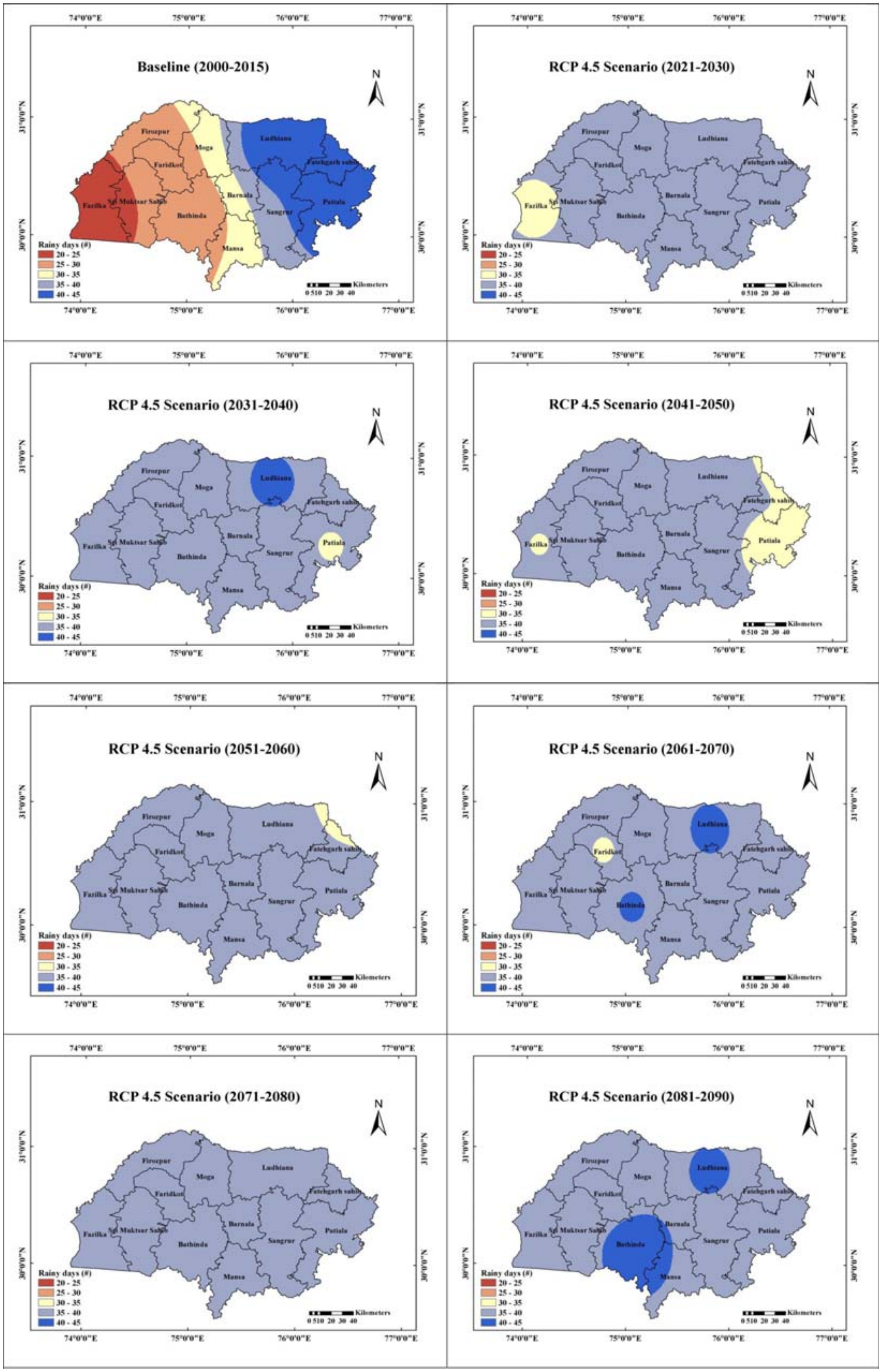

Fig. 5. Decadal variation in rainy days (#) as predicted by GISS-E2-R model in South-Western Punjab under RCP 4.5 scenario

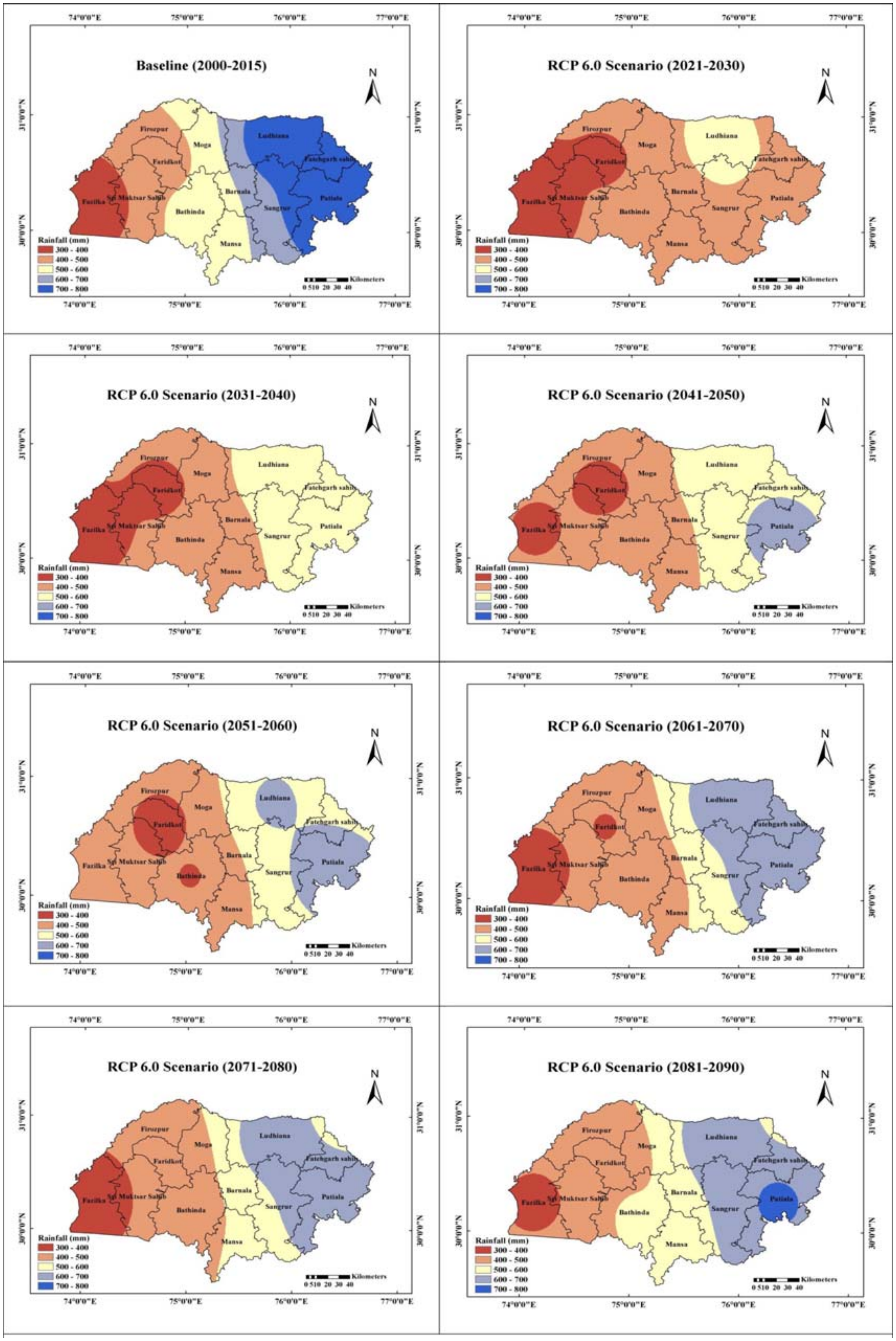

Fig. 6. Decadal variation in rainfall (mm) as predicted by GISS-E2-R model in South-Western Punjab under RCP 6.0 scenario

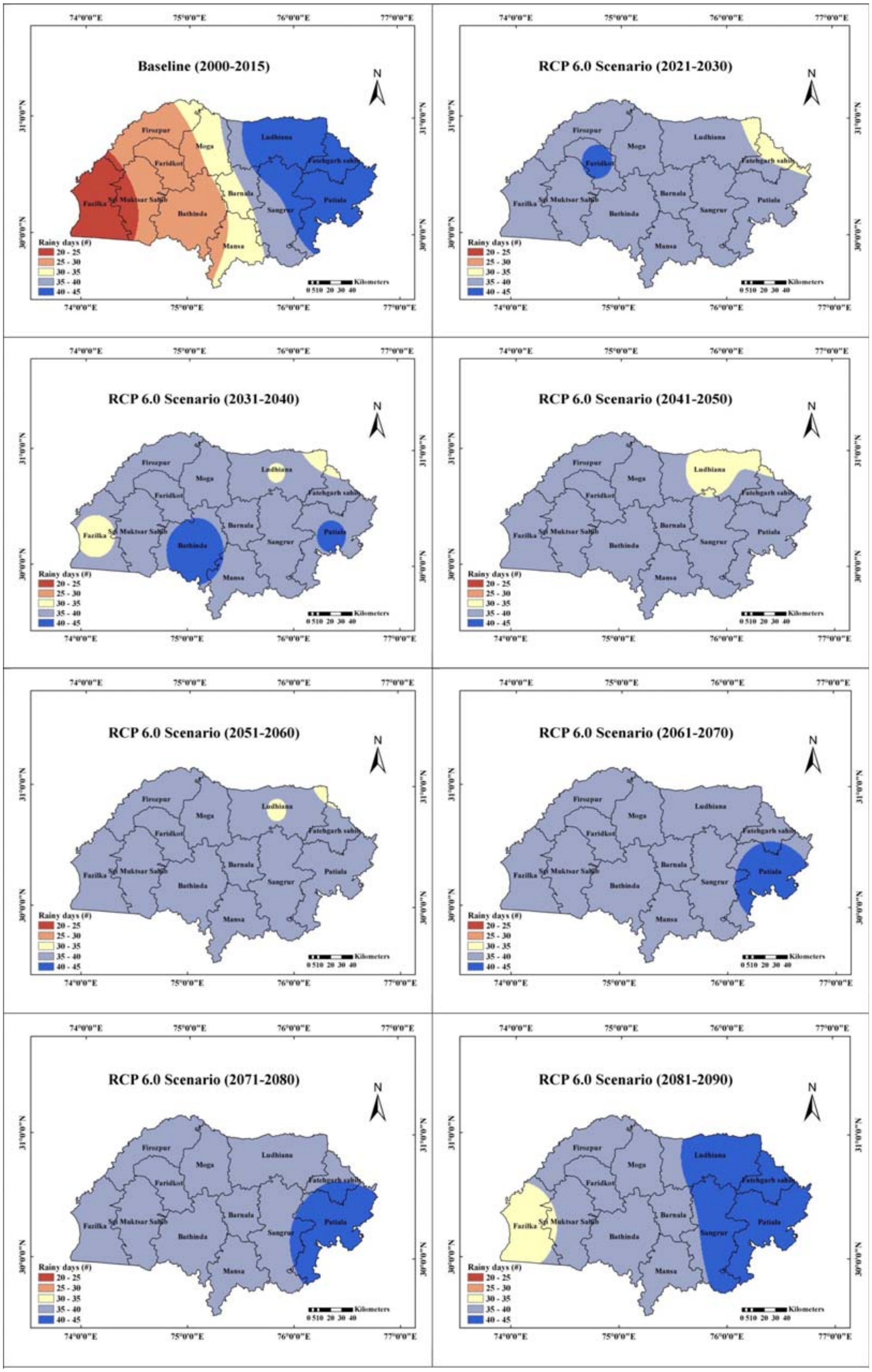

Fig. 7. Decadal variation in rainy days (#) as predicted by GISS-E2-R model in South-Western Punjab under RCP 6.0 scenario

Notably, under RCP 6.0, researchers project that although RF amounts will decrease, the number of RD events will increase, albeit with decadal variations. Effective management of RF amounts can sustain crop productivity levels throughout the 21st century in this region.

Spatio-temporal variability under RCP 8.5 scenario

Under the most pessimistic scenario (RCP 8.5), where greenhouse gas emissions continuously increase, regional RF and RD exhibit spatial and temporal variability on a decadal basis. Sub-humid regions are projected to experience changes in rainfall patterns. Currently, these regions receive moderate rainfall of 600-800 mm over 30-45 days, but projections indicate a decrease to 500-600 mm (Fig. 8) over fewer days, specifically 30-40 days (Fig. 9). However, arid regions receiving scarce RF (300-400 mm) over 20-25 days (baseline) are projected to decrease by 2041-50, but then increase again during the study's final decades (Fig. 8), with RF occurring over 35-40 days (Fig. 9). On a decadal basis, regions receiving 700-800 mm and 600-700 mm of RF are projected to disappear, with some sporadic recurrence of 600-700 mm. Areas with a rainfall (RF) class of 400-500 mm are expected to expand by replacing lower (300-400 mm) RF areas from 2051-60 to 2071-80, after which they will revert to the original pattern of the baseline period. According to the RCP 8.5 scenario, projections indicate that the number of RD in the region will change from 20-45 days (baseline) to 30-40 days (2041-50 and 2061-70), 30-45 days (2021-30 and 2031-40), 35-40 days (2051-60), eventually reaching 35-45 days in the last two decades of the study. Both RF and RD exhibit significant inter-decadal variability. Compared to RCP 2.6, RCP 4.5, and 6.0, the present study observes the maximum variability during the RCP 8.5 scenario. These results are consistent with some highlights from the IPCC (2014) report. Under the RCP 8.5 scenario, although RF amounts are projected to decrease, the increase of RD suggests that if RF amounts managed judiciously, they could sustain crop productivity levels in this region of the state during the 21st century.

Discussion

The reports prepared by the IPCC emphasize changes in the Earth's atmospheric hydrological cycle (IPCC, 2019). Punjab, earlier studies on projected changes in rainfall have revealed a declining trend. Kaur *et al*. (2021) estimated an average precipitation of 405 mm for the Present Time Slice (PTS) in the Sirhind Canal Tract (Punjab). They predicted that this average would decline by 22.4% under RCP 4.5 and 17.2% under RCP 6.0 during the mid-century period (2020-2050), and later by 4.7% and 18.0%, respectively, by the end of the century (2065-2095). However, Dar *et al*. (2019) reported that the HAD GEM2-ES model projected contrasting rainfall trends for Ludhiana (Punjab) under different RCP scenarios. Specifically, under RCP 4.5, the model predicted declines in rainfall of 12.8% and 11.8% during the mid-century and end-century periods, respectively. Conversely, under RCP 8.5, the model projected increases in rainfall of 20% and 33% during the same periods. Kaur *et al.* (2015) utilized climate outputs under the A1B climate scenario from the PRECIS model and reported comparable increases in rainfall of 19.7% and 18.0% during the mid-century and end-century, respectively, in Ludhiana (Punjab). Nayak *et al.* (2015) utilized the PRECIS model's A1B scenario to predict increases in rainfall over the Satluj River Basin in India of 13.6% by mid-century and 24.4% by end-century. The reduced rainfall variability, from 300-800 mm to 300-600 mm, supports earlier research and the projections outlined in the IPCC's four RCP scenarios.

Conclusions

This study tested the hypothesis that the GISS-E2-R model's simulated spatiotemporal variability in RF and RD in southwestern Indian Punjab aligns with the four Representative Concentration Pathways (RCP) scenarios guided by the IPCC. Results of the study have shown that as per IPCC scenarios, i.e., least pessimistic (RCP 2.6) to stabilization scenarios (RCP 4.5 and RCP 6.0) to most pessimistic (RCP 8.5), the RF indicates a declining trend, i.e., RF classes of 600-700 mm and 700-800 mm, and RD classes of 20-25 days and 25-30 days, present during the baseline period, are projected to disappear in the

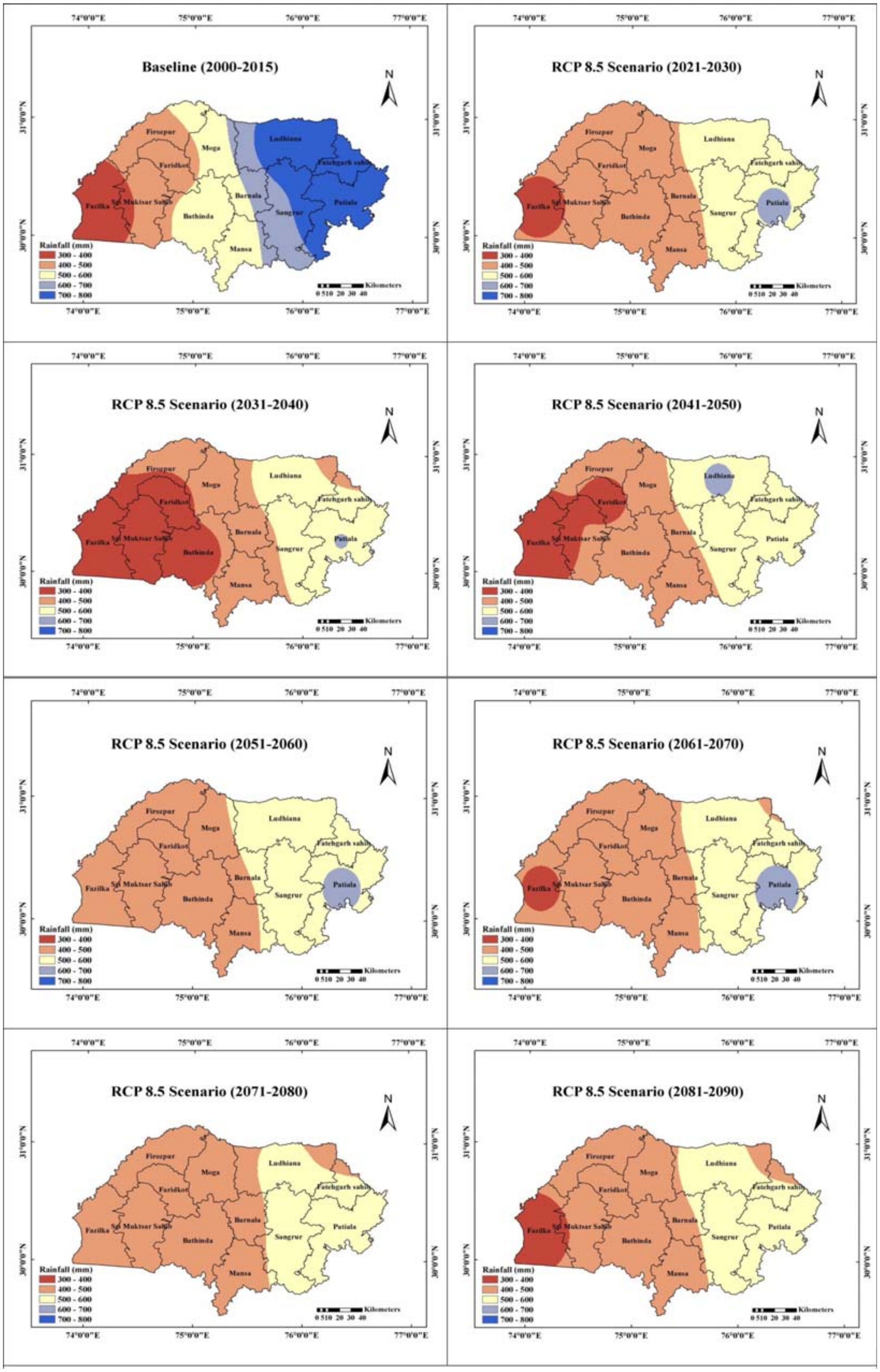

Fig. 8. Decadal variation in rainfall (mm) as predicted by GISS-E2-R model in South-Western Punjab under RCP 8.5 scenario

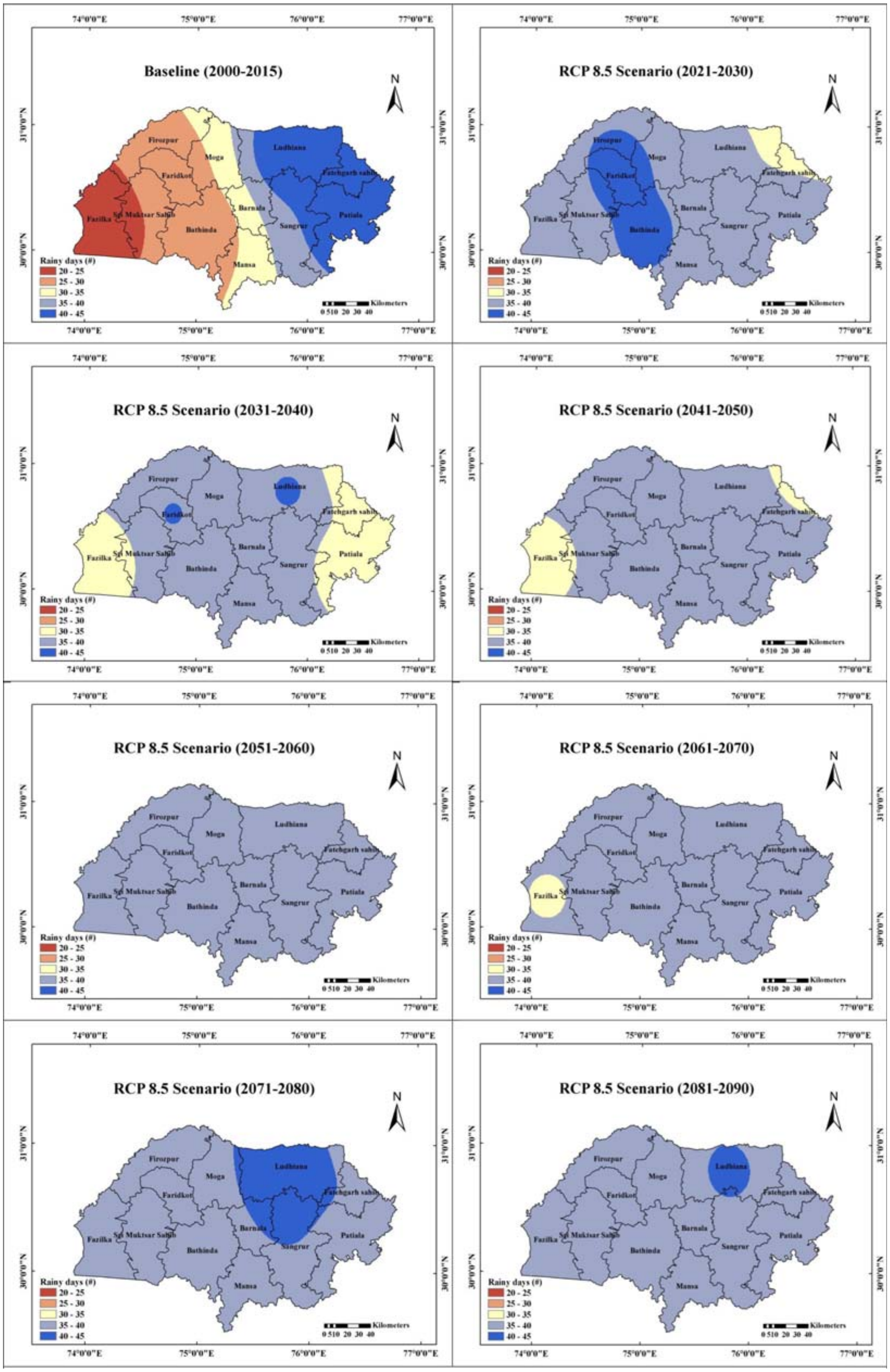

Fig. 9. Decadal variation in rainy days (#) as predicted by GISS-E2-R model in South-Western Punjab under RCP 8.5 scenario

region (Table 2). This means the region will get less intense rainfall, with smaller amounts spread out over more day. The decadal analysis of RF and RD from 2021 to 2090 shows increasing variability from RCP 2.6 (least variable) to RCP 8.5 (most variable), with intermediate increases under RCP 4.5 and RCP 6.0. Hence, the results confirm the hypotheses of the IPCC scenarios. Regional analysis of the RF and RD data points out the need for the plant breeders to focus on the development of cultivars having higher water use efficiency, agronomists need to re-define the irrigation schedules for the crops cultivated in the region, and weather forecasters to play a pro-active role in providing the timely forecast of rainfall to ensure sustainable usage, strategies can be implemented to manage the decreasing rainfall amounts effectively. The policy planners should focus on redefining the cultivation of crops suitable for harnessing the benefits of available rainwater without hampering the food availability scenarios for the increasing food demands in the region.

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Declarations

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were conducted by Jatinder Kaur, Prabhjyot-Kaur, Sandeep Singh Sandhu, and Shivani Kothiyal. The first draft was written by [Jatinder Kaur], and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability

The datasets generated and/or analyzed during this study are currently unavailable for public access, as they are being utilized for ongoing research. However, data access may be granted upon reasonable request to the corresponding author.

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