Projected Shifts in Rainfall-Based Climate Impact Drivers in Thailand

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ABSTRACT

Thailand has experienced increasing impacts from rainfall-related extremes, including recurrent floods and prolonged dry spells, posing serious challenges to water resources, agriculture, and disaster risk management. In 2025, multiple heavy rainfall and flood events were reported across northern, northeastern, and central Thailand, particularly in major river basins, while several regions also faced extended dry conditions during the late dry season, reflecting growing rainfall variability associated with climate change. Climate Impact Drivers (CIDs) provide a useful framework for assessing the mechanisms and impacts of climate-related extremes, and this study focuses on rainfall-based CIDs, including maximum 5-day precipitation (Rx5day), the number of heavy rainfall days exceeding 35 mm (R35mm), and consecutive dry days (CDD), to investigate changes in extreme rainfall and drought characteristics across Thailand. Monthly CID indices were derived from daily grid-based CMIP6 climate data (~0.05° × ~0.05°) using three global climate models (CMCC, EC-Earth3, and MIROC6) under four emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5), and near-term projections for 2015-2040 were evaluated relative to a historical baseline period of 1981-2014. The results indicate pronounced spatial and seasonal changes in rainfall extremes, with Rx5day and R35mm showing increasing probability and intensity in many regions, suggesting heightened flood risk, particularly in central, eastern, and southern Thailand, whereas CDD exhibits longer and more frequent dry spells in northern and northeastern regions, indicating elevated drought risk. Probability density function analysis reveals a clear shift toward more extreme conditions, accompanied by changes in the seasonal timing of both heavy rainfall and dry periods, highlighting the importance of CID-based assessments for near-term climate risk management and the development of effective adaptation and early warning strategies in Thailand.

Keywords: CID/ Climate Impact Driver/ CMIP6/ Rainfall/ Thailand

1. INTRODUCTION

Climate change is altering the global hydrological cycle and influencing the frequency, intensity, duration, and spatial distribution of weather and climate extremes. In particular, heavy precipitation events are projected to become more intense in many regions as global temperatures rise, while changes in precipitation variability can also modify the occurrence and persistence of dry conditions [1]. These changes have important implications for flood and drought hazards, water resource availability, agricultural production, infrastructure, and ecosystem functioning. Because changes in precipitation extremes are not spatially or seasonally uniform, regional and national-scale climate information is essential for identifying areas and periods that may experience increasing climate-related pressures. Thailand is highly influenced by seasonal rainfall variability and is repeatedly affected by both heavy rainfall and prolonged dry periods. Previous studies have demonstrated that changes in precipitation extremes across Thailand are spatially heterogeneous. Amnuaylojaroen [2], for example, projected changes in precipitation intensity and wet-dry characteristics across Thailand and reported increasing precipitation intensity together with shifts in consecutive wet and dry days. More recently, de Oliveira-Júnior et al. [3] used climate model simulations to examine drought and extreme precipitation across Thailand and similarly identified substantial regional differences in projected dry conditions and precipitation extremes. These findings indicate that climate change may not simply produce uniformly wetter or drier conditions; instead, it can modify the intensity, frequency, persistence, and seasonal

timing of rainfall events. Consequently, examining multiple dimensions of rainfall extremes is necessary to provide climate information that is relevant to near-term adaptation and risk management. The Climatic Impact-Driver (CID) framework provides a systematic approach for translating physical climate information into information relevant to impacts, vulnerability, adaptation, and risk assessment. CIDs are broadly defined as physical conditions of the climate system, including means, events, and extremes, that may affect elements of society or ecosystems [4]. Rather than considering changes in average precipitation alone, rainfall-related CIDs can be used to characterize specific aspects of extreme wet and dry conditions. Climate extreme indices based on daily precipitation have been widely applied to monitor changes in the magnitude, frequency, and duration of extreme events [5]. In this study, three rainfall-based CIDs were considered: maximum 5-day precipitation (Rx5day), representing the intensity of accumulated heavy rainfall; the number of days with daily precipitation of at least 35 mm (R35mm), representing the frequency of heavy rainfall events; and consecutive dry days (CDD), representing the persistence of dry spells defined by daily precipitation below 1 mm. Together, these indices provide complementary information on rainfall intensity, heavy-rainfall frequency, and dry-spell duration. The Coupled Model Intercomparison Project Phase 6 (CMIP6) provides a coordinated multi-model framework for examining future climate conditions under different socioeconomic and greenhouse gas forcing pathways [6]. Its multi-model simulations are particularly valuable for assessing regional climate changes while accounting for differences among climate models and future scenarios. Therefore, this study aims to assess the spatial and seasonal changes in rainfall-based CIDs across Thailand using bias-corrected daily CMIP6 climate data from three global climate models, namely CMCC-ESM2, EC-Earth3, and MIROC6. Monthly changes in Rx5day, R35mm, and CDD during the near-term period of 2015-2040 were evaluated relative to the historical baseline of 1981-2014 using grid-based climate information at approximately 0.05° spatial resolution. By integrating indicators of heavy rainfall intensity, frequency, and dry-spell persistence, this study seeks to identify areas and seasons in which rainfall-related climate conditions may shift and to provide scientific information to support water resource management, disaster preparedness, early warning, and climate change adaptation planning in Thailand.

2. METHODOLOGY

2.1 Climate Data and Study Design

Daily precipitation data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) [6] were used to assess rainfall-related Climatic Impact Drivers (CIDs) across Thailand. Three global climate models (GCMs), namely CMCC-ESM2, EC-Earth3, and MIROC6, were selected. Historical simulations for 1981–2014 were used as the reference period, while near-term climate projections for 2015–2040 were analyzed under three Shared Socioeconomic Pathway scenarios: SSP2-4.5, SSP3-7.0, and SSP5-8.5. Daily precipitation data were extracted and prepared on a regular grid with an approximate spatial resolution of 0.05° × 0.05°, covering 18,513 grid points over Thailand. The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset was used as the observational reference for precipitation bias correction [7]. The historical CMIP6 simulations and CHIRPS observations were aligned over the common baseline period of 1981-2014 before application of the bias-correction procedure. The corrected daily precipitation datasets were subsequently used to calculate monthly rainfall-based CIDs for both the historical and future periods.

2.2 Bias Correction of Daily Precipitation

Systematic biases in daily precipitation simulated by the GCMs were corrected against CHIRPS observations prior to CID calculation. Bias correction was performed separately for each calendar month to preserve the seasonal characteristics of precipitation. Daily precipitation amounts below 0.1 mm were treated as dry days during the correction procedure. For wet-day precipitation, Gamma distributions were fitted separately to the observed, historical GCM, and future GCM datasets.

The corresponding cumulative distribution functions were then used to adjust precipitation magnitude and wet-day occurrence. The procedure accounted for differences in wet-day frequency between observations and historical model simulations and applied this adjustment to the projected period. A scaling factor derived from the relationship between future and historical GCM precipitation at corresponding cumulative probabilities was used to retain the projected climate-change signal. Return intervals of the observed, historical, and future distributions were subsequently adjusted, and corrected precipitation values were obtained using the inverse Gamma distribution based on the observational parameters. The procedure was repeated independently for all months and grid points to generate bias-corrected daily precipitation series for CID analysis.

2.3 Calculation of Rainfall-Based Climate Impact Drivers

Three rainfall-related CIDs were calculated from the bias-corrected daily precipitation data: maximum 5-day precipitation (Rx5day), number of heavy precipitation days (R35mm), and consecutive dry days (CDD). These indices were selected to represent complementary dimensions of rainfall extremes, including precipitation intensity, frequency of heavy rainfall, and persistence of dry conditions [5]. Rx5day was calculated as the maximum accumulated precipitation over any five consecutive days within each calendar month:

$$Rx5day_j = \max\left(\sum_{k=i}^{i+4} P_{k,j}\right)$$

where $P_{k,j}$ represents daily precipitation on day k of month j. Five-day windows crossing calendar-month boundaries were excluded. Rx5day was expressed in millimeters. R35mm was defined as the number of days within each month for which daily precipitation was equal to or greater than 35 mm:

$$R35mm_j = \sum_{i=1}^{n_j} I\left(P_{i,j} \geq 35\right)$$

where I is an indicator function and n_j is the number of days in month j. The resulting index was expressed as days per month. CDD was calculated as the maximum number of consecutive days within each month with daily precipitation below 1 mm:

$$CDD_j = \max\{L: P_{i,j} < 1 \text{ mm for } L \text{ consecutive days}\}$$

The consecutive-day count was reset when precipitation reached or exceeded 1 mm or when a new calendar month began. CDD was expressed in days.

Table 1. Rainfall-based Climate Impact Drivers used in this study

Index	Definition	Unit	Characteristic represented
Rx5day	Maximum precipitation accumulated over five consecutive days within a month	mm	Heavy rainfall intensity
R35mm	Number of days with daily precipitation ≥ 35 mm	days	Heavy rainfall frequency
CDD	Maximum number of consecutive days with precipitation < 1 mm	days	Dry-spell persistence

2.4 Spatial, Temporal, and Statistical Analyses

Monthly values of Rx5day, R35mm, and CDD were analyzed for Thailand as a whole and across six climatic regions: northern, northeastern, central, eastern, southern-eastern, and southern-western Thailand. Spatial distributions of the indices were generated on the 0.05° grid using a WGS84 geographic coordinate system. To examine temporal changes within the near-term projection period, the future simulations were summarized into five sub-periods: 2015-2020, 2021-2025, 2026-2030, 2031-2035, and 2036-2040, and compared with the historical baseline of 1981-2014. Differences in monthly mean CID values between the historical baseline and each future sub-period were assessed using independent-samples *t*-tests. Statistical significance was evaluated at the 95% confidence level ($p < 0.05$); Welch's *t*-test was considered when the assumption of equal variances was not satisfied [8]. Changes were evaluated separately for each GCM and SSP to characterize model- and scenario-dependent responses rather than relying on a single deterministic projection. This approach allowed the analysis to identify both the magnitude and seasonal timing of projected changes in heavy-rainfall and dry-spell characteristics across Thailand.

3. RESULTS AND DISCUSSION

3.1 Projected Changes in Heavy Rainfall Characteristics (Rx5day and R35mm)

The projected changes in heavy rainfall characteristics were assessed using Rx5day and R35mm, which represent the intensity and frequency of extreme precipitation events, respectively. The results indicate that future rainfall extremes over Thailand are expected to exhibit spatially and seasonally heterogeneous changes during the near-term period (2015-2040) compared with the historical baseline period (1981-2014). Although the magnitude of change varied among climate models and emission scenarios, several regions exhibited increasing tendencies in both accumulated extreme rainfall and the occurrence of heavy precipitation days. To further examine the seasonal characteristics and variability of rainfall extremes, Figure 1 presents the monthly distribution of Rx5 day for the ensemble of three CMIP6 GCMs under SSP2-4.5. The boxplots show the distribution of projected values across the historical baseline and five future sub-periods, while the green triangles indicate the ensemble mean. The results show a clear seasonal cycle, with relatively low Rx5 day values during the dry-season months and substantially higher values during the wet season, particularly from May to October. The highest values generally occur during May-August, reflecting the seasonal concentration of heavy rainfall over Thailand. For Rx5day, the projected changes demonstrate that extreme rainfall intensity is not uniformly distributed across Thailand. The largest increases were generally observed in regions and seasons associated with strong monsoon rainfall, particularly during the wet season. Under higher emission scenarios, especially SSP5-8.5, several areas showed stronger increases compared with lower emission scenarios, suggesting that enhanced radiative forcing may amplify short-duration extreme rainfall conditions. However, differences among GCMs were evident, reflecting uncertainties associated with model representation of regional precipitation processes. The monthly distributions under SSP2-4.5 also indicate that changes in Rx5 day are not necessarily monotonic across the future periods. For example, the ensemble distributions fluctuate among the five future sub-periods, with the magnitude and spread of the projected values varying by month. This variability indicates that the timing and magnitude of extreme rainfall conditions may change over the near-term period rather than increasing continuously from one period to the next. The trend statistics shown in Figure 1 provide additional evidence of monthly differences in rainfall behavior. A statistically significant increasing trend was identified for January ($p = 0.034$; Sen's slope = 0.615), whereas the remaining months did not show statistically significant trends at the 95% confidence level. This result suggests that changes in extreme rainfall intensity may occur during specific seasons or months rather than uniformly throughout the year. The increase in Rx5day indicates a potential intensification of rainfall accumulation within short periods. Such changes are particularly relevant for flood risk management because accumulated precipitation over consecutive days is strongly associated with riverine flooding,

flash floods, and water management challenges. Therefore, areas exhibiting consistent increases across multiple models may require enhanced consideration in climate adaptation planning and early warning development.

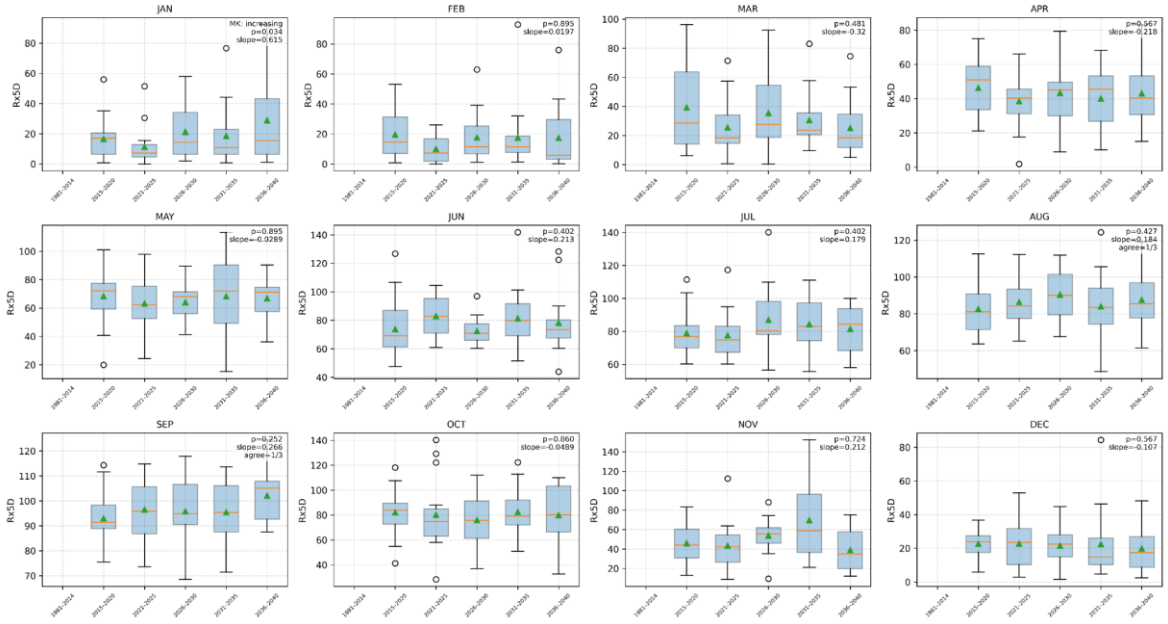

Figure 1. Monthly distribution of maximum Rx5day for Thailand under SSP2-4.5

Figure 2 presents the corresponding monthly distribution of R35mm, representing the number of days with daily precipitation ≥35 mm. In contrast to Rx5day, R35mm shows relatively low values during the early part of the year and substantially higher values during the monsoon season. The highest distributions are generally observed during June-October, with particularly high values in July-September. This seasonal pattern indicates that heavy rainfall days are concentrated during the monsoon period, consistent with the seasonal characteristics of precipitation over Thailand. Similar patterns were observed for R35mm, which represents the frequency of heavy rainfall days. The projected changes indicate that some regions may experience an increased number of days with intense rainfall events, particularly during the monsoon season. The combination of increased Rx5day and R35mm suggests that future rainfall changes may involve not only more intense individual events but also a higher occurrence of heavy rainfall conditions. The R35mm trend analysis further indicates that the magnitude and direction of change differ among months. Among the 12 months, September exhibited the strongest statistically significant increasing trend ($p = 0.017$; Sen's slope = 0.00764 days per year), whereas the other months did not show statistically significant trends. This finding suggests that the frequency of heavy rainfall events may become particularly important during the late monsoon season. Importantly, the future distributions shown in Figures 1 and 2 indicate that the projected changes are accompanied by variations in the spread of the distributions. Wider interquartile ranges and the presence of upper outliers in several months demonstrate that extreme rainfall conditions remain highly variable, even under the same emission scenario. Such variability is important for climate risk assessment because changes in the mean alone may not adequately represent the potential occurrence of unusually intense or frequent rainfall events. These findings highlight that rainfall-related climate risks in Thailand should not be evaluated solely based on changes in annual precipitation totals. Instead, changes in both rainfall intensity and event frequency should be considered because they represent different dimensions of climate-related hazards.

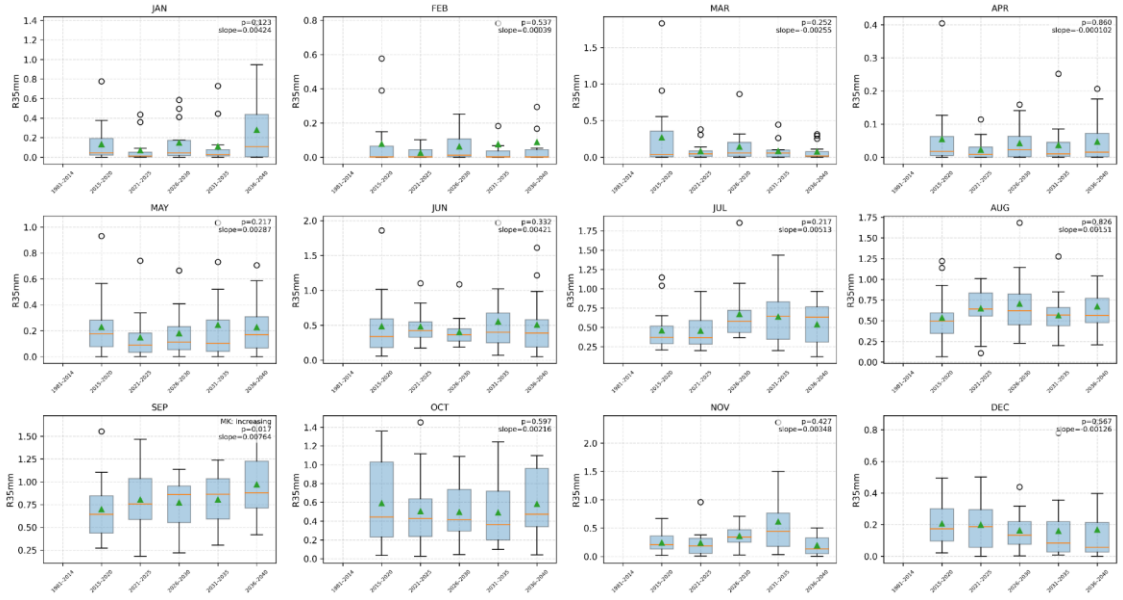

Figure 2. Monthly distribution of heavy rainfall days (R35mm) for Thailand under SSP2-4.5

3.2 Projected Changes in Dry Spell Characteristics (CDD)

The changes in dry spell characteristics were evaluated using consecutive dry days (CDD), which represents the persistence of precipitation deficits. Unlike heavy rainfall indicators, CDD reflects the temporal continuity of dry conditions and provides important information for drought-related risks. The results demonstrate that projected changes in CDD vary considerably among regions and seasons, indicating that climate change may modify not only the amount of rainfall but also the temporal distribution of rainfall events. Figure 3 presents the monthly distribution of CDD for the ensemble of three CMIP6 GCMs under SSP2-4.5. The results show a pronounced seasonal cycle, with substantially longer dry spells during the cool and dry season, particularly from November to March, whereas CDD values are considerably lower during the wet season from approximately June to September. January-March and November-December generally exhibit the longest dry-spell durations, while July-August show the shortest CDD values.

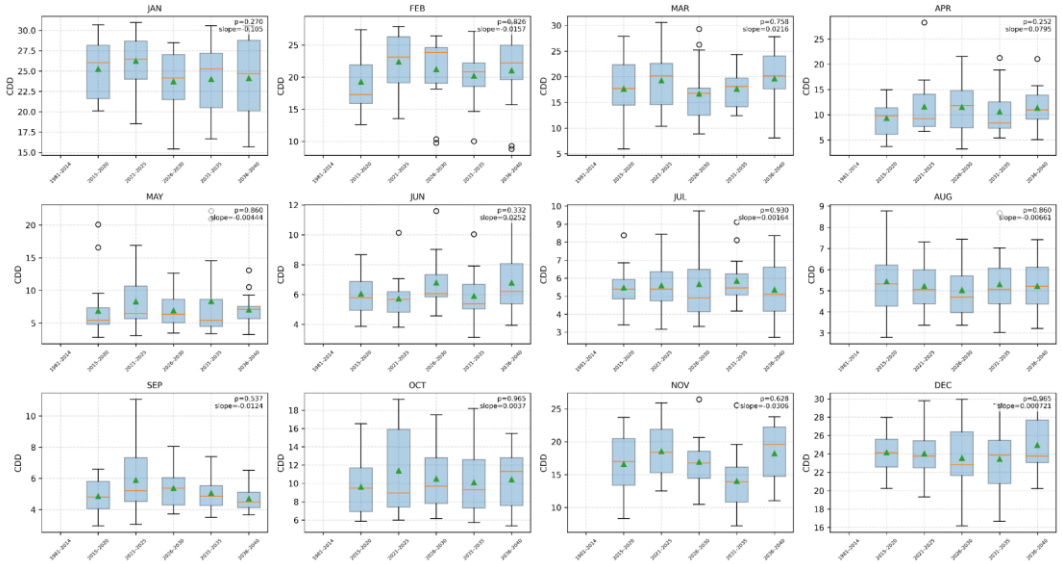

Figure 3. Monthly distribution of consecutive dry days (CDD) for Thailand under SSP2-4.5

Higher CDD values were generally observed in regions characterized by stronger seasonal rainfall variability, particularly during transition periods between dry and wet seasons. The northern and northeastern regions exhibited relatively higher dry-spell persistence compared with other areas, reflecting their sensitivity to changes in seasonal rainfall patterns. The monthly distributions also show that the future CDD values do not exhibit a consistent increase across all months. For example, January shows a gradual reduction in the central tendency of CDD across the future periods, whereas some months, such as March, April, June, and December, show periods of increasing or fluctuating values. This indicates that changes in dry-spell characteristics are strongly dependent on the seasonal timing of precipitation. Future projections indicate that changes in CDD differ among scenarios and climate models. Some periods showed increases in consecutive dry days, suggesting prolonged dry conditions, while other periods exhibited reduced CDD associated with shifts in rainfall timing. This indicates that climate change may alter the onset, duration, and interruption of dry periods rather than producing a simple nationwide increase in drought conditions. The trend statistics shown in Figure 3 support this interpretation, as none of the monthly CDD trends reached statistical significance at the 95% confidence level. Although some months show positive or negative Sen's slopes, the absence of statistically significant trends suggests that the changes in dry-spell duration are more variable and seasonally dependent than the changes observed for selected heavy-rainfall indicators. The changes in CDD have important implications for water resource management and agricultural adaptation. Longer dry spells may increase pressure on water availability, crop production, and ecosystem resilience, particularly in areas dependent on seasonal rainfall. Therefore, CDD should be considered together with heavy rainfall indicators to provide a more comprehensive understanding of future rainfall-related climate risks.

3.3 Spatial and Seasonal Variability of Rainfall-Based Climate Impact Drivers

The combined assessment of Rx5day, R35mm, and CDD demonstrates that rainfall-related climate changes in Thailand are characterized by strong spatial and seasonal variability. The three indicators capture different aspects of rainfall extremes, and their projected responses do not necessarily occur in the same direction or magnitude across regions. The monthly ensemble distributions shown in Figures 1-3 further demonstrate that the three CIDs have distinct seasonal signatures. Rx5day and R35mm increase to their highest levels during the wet and monsoon seasons, whereas CDD reaches its highest values during the dry and cool seasons. This seasonal contrast indicates that Thailand may experience different types of rainfall-related hazards at different times of the year, with heavy-rainfall conditions concentrated during the monsoon season and prolonged dry conditions occurring mainly during the dry season. Heavy rainfall-related indicators (Rx5day and R35mm) showed more pronounced changes in areas influenced by seasonal monsoon systems, where increases in precipitation intensity and frequency may contribute to greater flood-related risks. In contrast, CDD exhibited stronger regional variability, reflecting differences in rainfall seasonality and atmospheric circulation influences across Thailand. The comparison also demonstrates that changes in rainfall intensity, frequency, and dry-spell duration should not be interpreted independently. For example, an increase in Rx5day or R35mm does not necessarily imply a reduction in CDD, because these indicators describe different temporal characteristics of precipitation. The coexistence of heavy rainfall events and dry spells therefore suggests an increasing irregularity in the temporal distribution of rainfall rather than a simple shift toward wetter or drier conditions. The divergence among CID responses suggests that climate change may create compound challenges for water management, where some areas may simultaneously experience increasing risks from heavy rainfall events and longer dry intervals. This highlights the importance of using multiple climate indicators rather than relying on a single precipitation variable for climate risk assessment. The spatial variability identified in this study is consistent with the concept of Climatic Impact Drivers, which emphasizes that climate information should be interpreted according to specific impact mechanisms and regional contexts. Therefore,

rainfall-based CIDs can provide useful information for identifying climate-sensitive areas and supporting targeted adaptation strategies.

3.4 Implications for Climate Adaptation and Risk Management

The projected changes in rainfall-based CIDs provide important implications for climate adaptation and disaster risk management in Thailand. The results demonstrate that future rainfall risks cannot be adequately represented by changes in average precipitation alone because climate change influences multiple characteristics of rainfall extremes, including intensity, frequency, and persistence. The seasonal distributions presented in Figures 1-3 provide an additional basis for identifying periods of heightened climate-related hazard. The concentration of high Rx5day and R35mm values during the monsoon season highlights periods when flood preparedness and early warning systems may require greater attention, whereas the longer CDD values during the dry season emphasize the importance of seasonal water management and drought preparedness. The increasing tendency of heavy rainfall indicators highlights the need for improved flood preparedness, water infrastructure planning, and early warning systems, particularly in areas where multiple models indicate consistent increases. Meanwhile, changes in CDD emphasize the importance of drought preparedness, seasonal water allocation, and climate-resilient agricultural planning. The variability observed among future sub-periods also suggests that adaptation planning should account for uncertainty and temporal variability rather than relying on a single future-period estimate. In this context, the use of multiple CIDs and multi-model ensembles can provide a more robust representation of the range of possible rainfall conditions and help identify climate-sensitive periods and locations. The integration of CID-based information into adaptation planning can support more spatially targeted strategies by linking climate hazards with sectoral vulnerabilities. Such information can contribute to national and local adaptation planning by providing climate indicators that are directly relevant to water management, agriculture, and disaster risk reduction.

4. CONCLUSIONS

This study assessed near-term changes in three rainfall-based Climatic Impact Drivers (CIDs), namely maximum 5-day precipitation (Rx5day), heavy rainfall days exceeding 35 mm (R35mm), and consecutive dry days (CDD), using an ensemble of three CMIP6 global climate models over Thailand. The results demonstrate that rainfall-related climate conditions exhibit pronounced seasonal and temporal variability during 2015-2040 compared with the historical baseline of 1981-2014. Rx5day and R35mm showed distinct seasonal patterns, with higher values generally occurring during the wet and monsoon seasons, while CDD was highest during the dry and cool seasons. The trend analysis further indicated that statistically significant changes were detected only for selected months, with an increasing trend in Rx5day during January ($p = 0.034$) and in R35mm during September ($p = 0.017$), whereas no statistically significant monthly trend was identified for CDD. The results indicate that climate change may alter the timing, intensity, and frequency of rainfall extremes rather than producing a uniform shift toward wetter or drier conditions across Thailand. Differences among future periods, climate models, and emission scenarios further demonstrate the uncertainty and spatial heterogeneity of projected rainfall changes. Therefore, the combined use of multiple rainfall-based CIDs provides a more comprehensive representation of climate-related hazards than precipitation totals alone, by capturing complementary characteristics of heavy rainfall intensity, heavy rainfall frequency, and dry-spell persistence. The climate information generated in this study can support near-term climate risk assessment and adaptation planning by identifying climate-sensitive seasons and areas for enhanced flood and drought preparedness. The integration of CID-based indicators into water resource management, early warning systems, agricultural planning, and disaster risk reduction can contribute to more targeted and climate-resilient decision-making in Thailand.

Acknowledgement

The authors acknowledge the Department of Climate Change and Environment, Thailand, for financial support by Thailand Science Research and Innovation (TSRI) under the project entitled "Developing predicted climate-impact drivers (CIDs) for short-term hazard management" (Project code: 4823611).

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