Exploring climate change threats to rice production in Indonesia using CMIP6 projections

Armi Susandi[1*] and *Angga Fauzan* Pratama[2]

[1]Department of Meteorology, Faculty of Earth Science and Technology, Institut Teknologi Bandung, Bandung, Indonesia
[2]Karbon Natura Indonesia, Bogor, Indonesia

Abstract. Rice is the staple food for most Indonesians, making stable rice production central to national food security. Java and Sumatera, the two most populous and agriculturally important islands, together contribute around 75% of national rice output, yet a large share of paddy cultivation remains rainfed and reliant on traditional practices. This dependence on natural rainfall and temperature regimes heightens the sensitivity of rice production to climate variability and intensifies its vulnerability under climate change. This study assesses future risks to rice production in Java and Sumatera by analysing projected changes in extremely hot days and consecutive dry days (CDD) under multiple greenhouse gas emission scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Using downscaled projections from the NEX-GDPP CMIP6 dataset, the heat- and drought-stress evolution across two major planting seasons and the associated implications for rice yields is explored. The results show substantial increases in both hot days and CDD. Heat- and drought-stress intensify even under a low-emission pathway, which threaten Indonesia's rice production. By linking projected changes in climate extremes with potential yield impacts, the study underscores the dual importance of determined mitigation and targeted adaptation to support climate-resilient rice production and safeguard Indonesia's food security.

1 Introduction

Rice is the central pillar of Indonesia's food systems, serving as the main source of calories for most Indonesians and shaping national food security priorities. Java and Sumatera, the two most densely populated and agriculturally productive islands in the country, contribute roughly three quarters of national rice output [1]. The planting cycle across these islands follows the monsoonal climate and typically consists of three planting seasons known as *masa tanam* or MT. The first planting season called MT1 begins with the arrival of the monsoon from November to February. The second planting season spans March to June and marks the transition from the wet season to the early dry season. The third planting season MT3 occurs from July to October and coincides with the driest period of the year [2]. These seasonal patterns guide planting decisions for both irrigated and rainfed farmers. Irrigated

* Corresponding author: armi.susandi@itb.ac.id

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

fields have more secure water supply, yet their planting schedules generally follow the same MT structure because planting is coordinated at the community level and depends on shared management practices and labour cycles. As a result, the timing of rainfall during MT1, MT2 and MT3 strongly influences overall crop establishment across the region.

Rainfed agriculture remains widespread in Java and Sumatera. Rainfed farmers depend on the availability of monsoonal rainfall, making their production particularly sensitive to delayed rainfall onset, early cessation or extended dry periods. Temperature conditions also influence rice performance. Rice is sensitive to high temperatures during reproductive stages such as panicle initiation, anthesis and grain filling. Exposure to extreme heat during these phases can reduce pollen viability, increase spikelet sterility and accelerate grain filling in ways that reduce final yield. These sensitivities highlight the importance of adequate soil moisture and moderate temperatures for both MT1 and MT2 when most rice cultivation takes place.

With the strong influence of rainfall and temperature on rice cultivation, climate change presents a growing challenge for Indonesia's rice production. Scientific assessments indicate that rainfall patterns are expected to shift and extreme temperatures are projected to become more frequent in the future [3]. The latest assessment from the Intergovernmental Panel on Climate Change shows that the magnitude of these changes depends on future greenhouse gas emissions. To explore these possible futures, global climate models are coordinated through the sixth phase of the Coupled Model Intercomparison Project (CMIP6), which provides a common framework for climate projections. Within this framework, ScenarioMIP experiments represent different future development and emission pathways through Shared Socioeconomic Pathways [4]. These scenarios range from strong mitigation and adaptation efforts (SSP126) to low mitigation and adaptation efforts (SSP585) which cause different levels of future warming and changes in rainfall regimes.

Understanding how these climate futures affect Java and Sumatera is essential for anticipating risks to rice production. However, a significant gap exists in current understanding regarding the spatial and temporal evolution of climate change impacts on specific planting seasons, particularly when considering different future climate scenarios. This study offers novelty in bridging that gap by evaluating projected changes in extreme temperature and consecutive dry days during MT1 and MT2. Selection focused on these wet-season periods because the rainfed system relies entirely on rainfall. By examining the evolving climate conditions that shape rice production during these key planting seasons, the study contributes insights that support efforts to strengthen climate resilient agricultural planning and safeguard future food security in Indonesia.

2 Data and Methods

2.1 Study Data

The analysis uses climate projections from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) based on CMIP6 [5]. This dataset provides statistically downscaled and bias corrected daily data at a spatial resolution of 0.25°, which refines the original CMIP6 resolution of about 1°. The analysis focuses on land areas in Java and Sumatera, which are the main rice producing islands considered in this study.

The NEX-GDDP CMIP6 data used here include a historical baseline and future projections under SSP scenarios that form the basis of the climate change impact assessment. Among the CMIP6 models available in NEX GDDP, the study uses the ACCESS-ESM1-5 model. Precipitation is a key variable in this analysis, and ACCESS-ESM1-5 reproduces the

spatial and temporal variability of rainfall over Indonesia the closest to satellite observations [6].

Two daily variables are used in the analysis, maximum temperature ($tasmax$) and precipitation (pr). Maximum temperature is critical for evaluating heat extremes and is widely used to assess heat stress in rice [7]. Precipitation determines water availability, particularly in rainfed systems, and is therefore also included to represent hydrological constraints on rice production. Together these variables provide the climatic basis for constructing the heat and dry spell indicators analysed in this study.

2.2 Methods

The analysis begins by extracting daily maximum temperature and daily precipitation from the dataset for all land grid cells within the study domain. Before any calculation, two physical unit conversions are applied. Temperature values are originally provided in Kelvin and are converted to degrees Celsius using Equation (1).

$$tasmax_C = tasmax_K - 273.15 \quad (1)$$

Precipitation is provided as a daily surface flux with $kg\,m^{-2}\,s^{-1}$ as the unit. Since 1 $kg\,m^{-2}$ is equal to 1 mm and one day contains 86,400 seconds, daily precipitation accumulation in millimetres is obtained using Equation (2).

$$Pr_{acc,mm} = Pr_{flux,kg\,m^{-2}\,s^{-1}} \times 86400 \quad (2)$$

Daily time series are then grouped into the two rice planting seasons used in this study, which are MT1 (November-February) and MT2 (March-June). These two planting-season is chosen as analysis because rainfed system which are prone to climate change mostly plant only in these two planting-season.

Daily time series are then grouped into the two rice planting seasons used in this study, MT1 from November to February and MT2 from March to June. These two planting seasons are selected because rainfed systems that are sensitive to climate variability mostly cultivate rice during these periods. Because MT1 crosses the calendar year boundary, seasons are defined by their harvest year to remain consistent with rice production impacts. For example, MT1 in 2091 refers to the period from November 2090 to February 2091. Each MT1 season is treated as a single continuous sequence even when it spans years N − 1 and N, which avoids artificial breaks at the calendar boundary and preserves realistic representations of dry spells and heat events throughout the planting season.

To quantify the heat stress indicator this study counts the number of days with extremely high maximum temperature, hereafter referred to as "hot days". A day is classified as a hot day when the daily maximum temperature exceeds $35°C$ ($T_{max} > 35°C$). This threshold corresponds to the heat stress threshold for rice reported in the literature [8]. For each grid cell, year, and season the number of hot days is calculated using Equation (4).

$$HotDays = Number\ of\ (tasmax_C > 35°C) \quad (4)$$

For the dry spell indicator, the analysis uses the Consecutive Dry Days (CDD) index, which was developed by the Expert Team on Climate Change Detection and Indices ETCCDI for monitoring changes in climatic extremes. A day is considered dry when the daily rainfall accumulation is less than 1 mm ($Pr_{acc} < 1$). In this way CDD represents periods when there is no effective rainfall input to the rainfed system. Within each planting season all uninterrupted sequences of dry days have lengths $L_1, L_2, \dots, L_n$. For each grid cell, year, and season the CDD value is the longest of these sequences as defined in Equation (5).

$$CDD = max\ (L_1, L_2, \dots, L_n) \quad (5)$$

Both indices are computed annually for every land grid cell on the native 0.25° grid. The annual values are then averaged within three multiyear windows, which are the historical

baseline (1951-2014), a mid-century window (2041-2050), and a late century window (2091-2100). For any given period, the mean number of extremely hot days is calculated using Equation (6) and the mean CDD is calculated using Equation (7).

$$AvgHotDays = \frac{\sum ExtremeHotDays_{year}}{N_{year}} \quad (6)$$

$$AvgCDD = \frac{\sum CDD_{year}}{N_{year}} \quad (7)$$

The resulting spatial fields of hot days and CDD provide the basis for evaluating how heat stress and prolonged dry spells may evolve and how these changes may affect rice production in Java and Sumatera.

3 Results and Discussion

3.1 Projected Changes in Maximum Temperature Extremes

3.2.1 First Planting Season (MT1)

During the historical period (1951-2014), MT1 shows extremely low frequencies of hot days across Java and Sumatera. Many grids recorded essentially zero days with maximum temperatures above 35°C. The highest frequency remained low, typically ranging from 1 to 14 days (0-2 weeks). Consequently, MT1 in the baseline climate is characterized by minimal exposure to extreme heat.

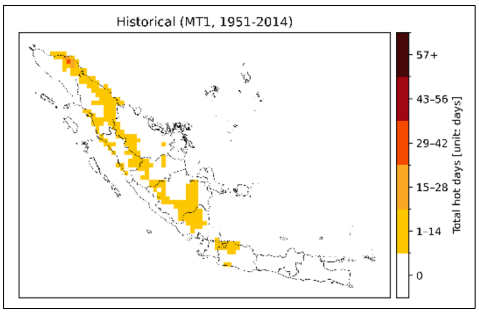

Fig. 1. Historical (1951-2014) average number of hot days in MT1

By mid-century (2041-2050), as shown in Figure 2, hot days begin to appear more in Sumatera, particularly on the east side of the Barisan Mountains (*Bukit Barisan*). These areas now mostly record a frequency of 1-14 days (0-2 weeks) of hot days. Meanwhile, most of Java remains at or near zero. The largest increases occur in northern Sumatera, where the number of hot days reaches around 29-42 days (4-6 weeks), significantly exceeding the historical baseline. However, the overall magnitude of change in MT1 remains moderate during this time-horizon.

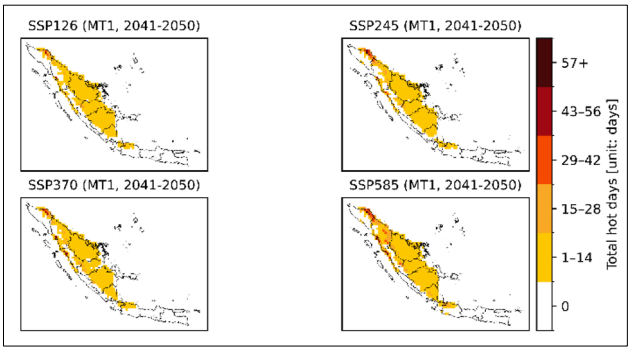

Fig. 2. Mid-centrury (2041-2050) average number of hot days in MT1

In contrast, as shown in Figure 3, the end-century period (2091-2100) exhibits a much clearer and more widespread signal depending on the climate change scenario. In the moderate-worst case (SSP370) and worst case (SSP585) scenarios, the frequency of hot days can reach over 57 days in a season (more than 8 weeks). Spatially, Sumatera exhibits greater vulnerability and Java experiences comparatively lower exposure. Central Java remains low in all cases, but the western and eastern sides of Java record a considerable number of hot days in SSP370 and SSP585 that were absent in the historical climate. This hot-days frequency increase is of particular concern given their role as key rice-producing regions.

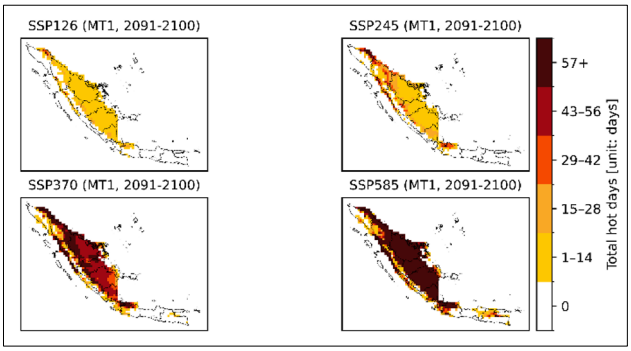

Fig. 3. Late century (2091-2100) average number of hot days in MT1

Across all time horizons and scenarios, the MT1 projections shows a consistent intensification of heat stress relative to the historical baseline (Figures 1-3). Inter-scenario differences remain minimal at mid-century, with all scenarios exhibiting comparable spatial patterns and hot day frequencies. By the end of the century, the difference in hot day frequency becomes highly visible. Under SSP126, seasonal totals generally remain in the range 15-28 days (2-4 weeks), though this still represents a significant increase compared to the historical climate. SSP245 projects a broader area of impact, with some regions reaching approximately 43-56 hot days (6-8 weeks). Crucially, under the higher-emission SSP370 and especially SSP585 scenarios, large portions of Sumatera exceed 43 days per season (more than 6 weeks), with widespread areas reaching and surpassing 57 hot days per season (over 8 weeks). These comparisons conclusively indicate that MT1 heat stress intensifies considerably over time and is strongly conditioned by the severity of the climate change emissions pathway, with the most severe late-century increases occurring under the worst-case scenarios.

3.2.2 Second Planting Season (MT2)

In the historical period (1950-2014), as shown in Figure 4, the frequency of hot days during MT2 is substantially higher than in MT1, while maintaining a similar spatial pattern with greater prevalence in Sumatera compared to Java. Most grid cells record 15-28 hot days (2-4 weeks), with a small area in northern Sumatera reaching 29-42 hot days (4-6 weeks). Consequently, MT2 under the baseline climate is characterized by some exposure to extreme maximum temperatures, in contrast to the minimal risk observed during MT1.

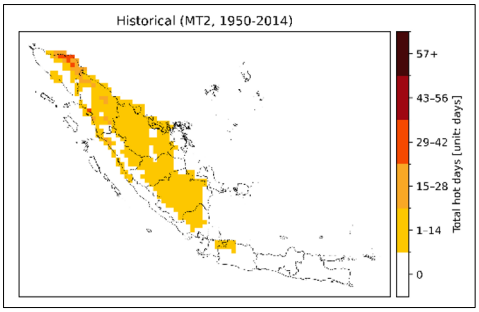

Fig. 4. Historical (1951-2014) average number of hot days in MT2

By mid-century (2041-2050), the frequency of hot days during MT2 increases more markedly than in MT1, particularly across Sumatera (Figure 5). A continuous zone from northern to central Sumatera consistently reaches 43-56 hot days per season (6-8 weeks), with peak frequencies in the worst-case scenario (SSP585) already reaching 57 or more days (over 8 weeks). This situation clearly exceeds the historical baseline. By contrast, Java remains largely unaffected, with most regions recording frequencies at or near zero hot days.

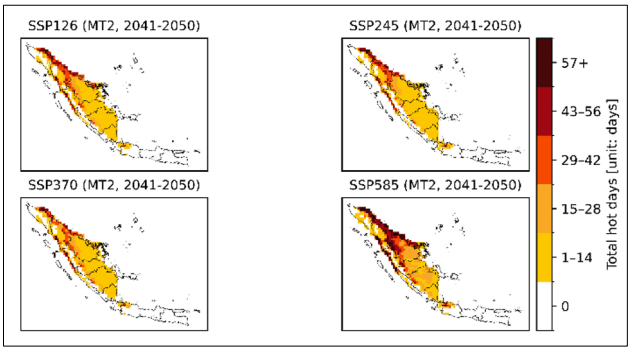

Fig. 5. Mid-centrury (2041-2050) average number of hot days in MT2

In the end-century period (2091-2100), the MT2 hot days strengthens substantially (Figure 6). The spatial pattern mirrors the MT1 end-century projections, but with substantially higher frequencies. Even in the moderate-mild scenario (SSP245), the frequency of hot days reaches 57 days or more (over 8 weeks) in some areas. In the moderate-worst scenario (SSP370) and worst scenario (SSP585), the majority of Sumatera experiences 57 hot days or more (8 weeks or more). In Java, while Central Java remains resilient with low frequencies across all scenarios, the western and eastern coastal regions record a considerable number of hot days under SSP370 and SSP585, which is a pattern entirely absent in the historical climate. This intensification is highly concerning as it indicates that rice cultivation during MT2 will become very challenging across large portions of Sumatera.

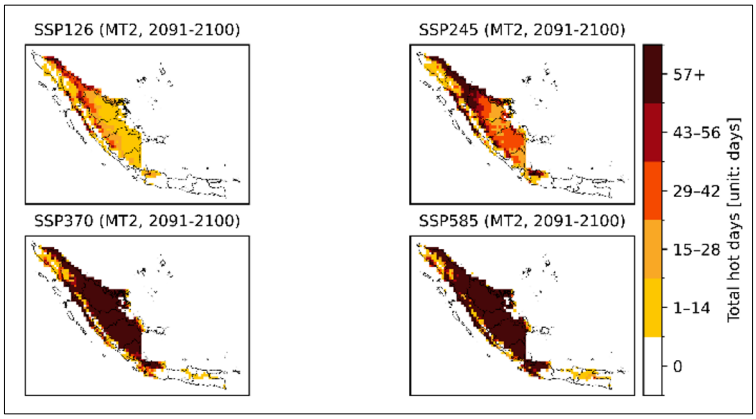

Fig. 6. Late century (2091-2100) average number of hot days in MT2

Across all time horizons and scenarios, MT2 projections display a clear and progressive intensification of heat stress compared with the historical baseline (Figures 4-6). Inter-scenario differences become apparent at mid-century. The SSP126, SSP245, and SSP370 scenarios generally keep Sumatera's exposure below 57 hot days per season (less than 8 weeks) and Java consistently near zero, whereas SSP585 already produces substantial localized exposure, reaching 57 or more hot days (over 8 weeks). By the end of the century, this difference in hot days becomes highly visible. Under SSP1-2.6, seasonal totals remain within the 15-28 days (2-4 weeks) range. SSP2-4.5 significantly increases exposure, projecting some areas exceeding 57 hot days per season (over 8 weeks). Crucially, under SSP370 and especially SSP585, most of Sumatera exceeds 57 hot days per season (over 8 weeks). In SSP585, concerning exposure emerges in the western and eastern coastal regions of Java. These comparisons indicate that MT2 heat stress not only intensifies more strongly than MT1 but is also profoundly sensitive to the climate change severity, with the most substantial late-century increases emerging even in the moderate-worst-case scenario (SSP370).

3.2 Projected Changes in Consecutive Dry Days Events

3.2.1 First Planting Season (MT1)

In the historical period (1951-2014), as shown in Figure 7, MT1 already features multi-day dry spells across much of Java and Sumatera. Typical spell durations range from about 1-7 consecutive dry days over Java and Sumatera, with northern Sumatera experiencing longer consecutive dry days, reaching 8-14 consecutive dry days (1-2 weeks). This indicates that even in the baseline climate, the MT1 already faces significant vulnerability to prolonged dryness in northern Sumatera.

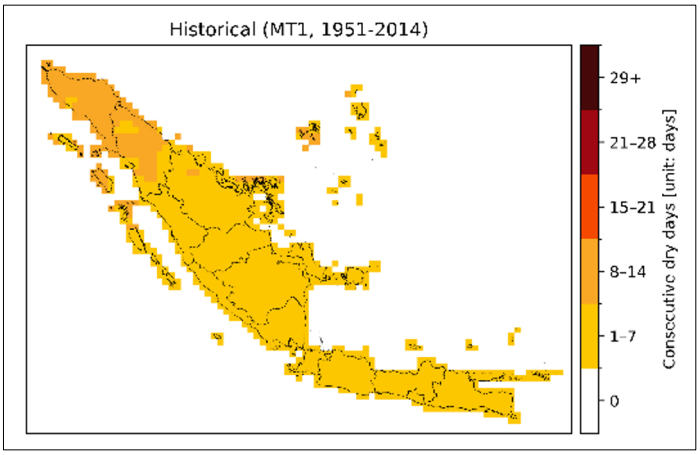

Fig. 7. Historical (1951-2014) average number of consecutive dry days in MT1

By mid-century (2041-2050), as shown in Figure 8, the overall spatial pattern of MT1 CDD changes little. The maximum CDD duration remains within the 8-14 days (1-2 weeks) range. However, inter-scenario differences manifest primarily in the spatial extent of the 8-14 day CDD regions in the northern Sumatera. Consequently, these results suggest that the MT1 rainfall pattern in the mid-century remains broadly similar with the historical baseline, with the greatest change being the expansion of vulnerability to moderate dry spells.

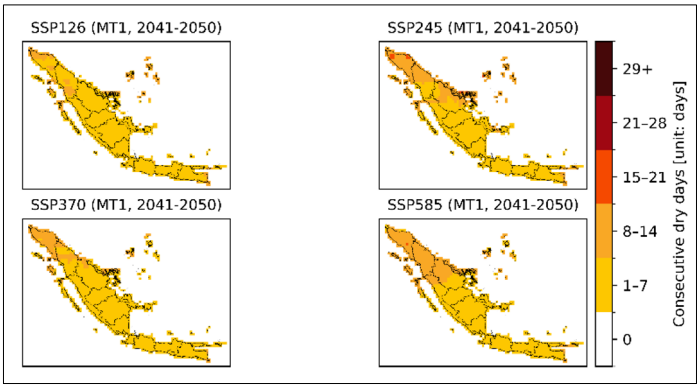

Fig. 8. Mid-century (2041-2050) average number of consecutive dry days in MT1

In the late-century period (2091-2100), MT1 exhibits a more noticeable intensification of consecutive dry days, although the basic spatial pattern persists, with northern Sumatera retaining the highest CDD frequencies (Figure 9). Several areas in northern Sumatera now reach 15-21 consecutive dry days (2-3 weeks). Java continues to exhibit shorter sequences overall, with most locations still below about 8-14 days (1-2 weeks). This implies that the intensification of MT1 dryness at end-century is strongest in regions already vulnerable to prolonged dry spells in the historical baseline (northern Sumatera).

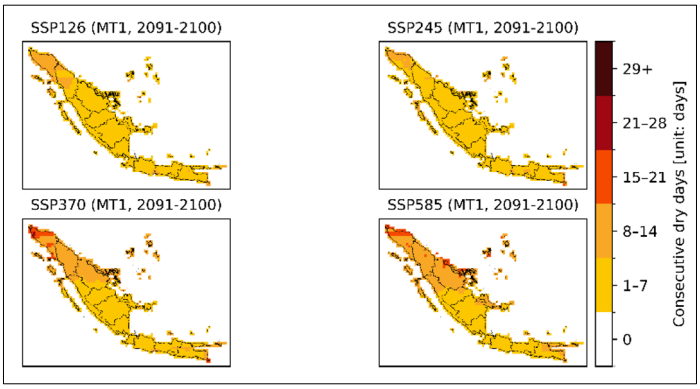

Fig. 9. Late century (2091-2100) average number of consecutive dry days in MT1

Across all scenarios and time horizons, differences in MT1 CDD are relatively modest when viewed against the historical baseline (Figures 7-9). At mid-century, all scenarios produce very similar outcomes, maintaining the maximum CDD duration within the historical 8-14 days (1-2 weeks) range. The differences between scenarios are in the spatial extent of these moderate dry spells. By the end of the century, this pattern remains consistent, although intensification is more noticeable. The SSP370 and SSP585 scenarios produce the most prolonged spells, causing several areas in northern Sumatera to reach 15-21 consecutive dry days (2-3 weeks). Overall, MT1 CDD respond to climate forcing mainly through the gradual lengthening of dry spells in established, already-vulnerable areas (northern Sumatera), rather than through the emergence of new regions of continuing dryness. This limited expansion and minimal intensification confirms that the rainfall pattern change is minimal in MT1.

3.2.2 Second Planting Season (MT2)

In the historical period (1950-2014), as shown in Figure 10, MT2 already features visible consecutive dry spells across much of Java and Sumatera. Over northern Sumatera, typical sequences range from about 8-14 consecutive dry days (1-2 weeks), while southern Sumatera exhibits slightly shorter spells of 1-7 consecutive dry days. Crucially, most of Java also frequently experiences longer dry spells, similar in duration to northern Sumatera. These observations indicate that the MT2 is historically more exposed to prolonged dryness than MT1.

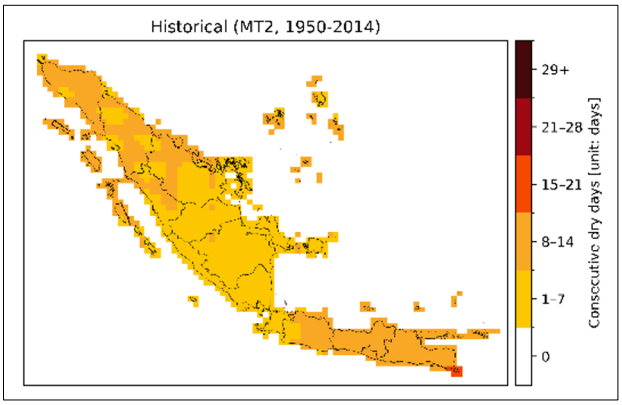

Fig. 10. Historical (1951-2014) average number of consecutive dry days in MT2

By mid-century (2041-2050), as shown in Figure 11, the overall spatial pattern of MT2 CDD remains broadly similar, but the intensity of dry spells increases in the existing areas that are already experiencing prolonged dry spells. Across all scenarios, the established vulnerable regions, including eastern Java and northern Sumatera, exhibit more frequent and intense consecutive dry days. Similar to MT1, mid-century MT2 projections show minimal divergence across the scenarios. This indicates that the MT2 rainfall pattern change at mid-century is minimal.

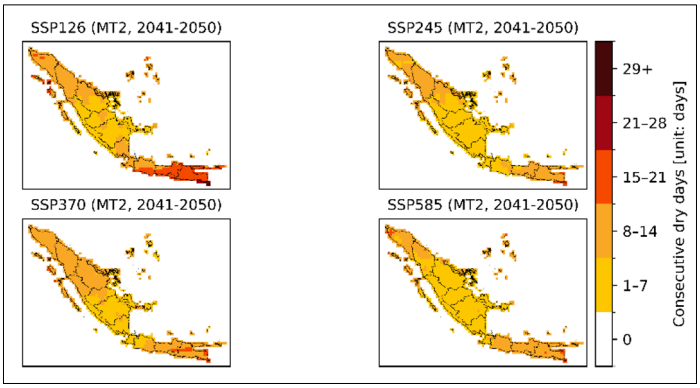

Fig. 11. Mid-century (2041-2050) average number of consecutive dry days in MT2

In the late-century period (2091-2100), MT2 dry spells intensify further, particularly under the higher-emission scenarios (Figure 12). Crucially, southern and eastern Java, along with neighboring eastern islands, show extensive areas with dry spells exceeding 29 consecutive dry days (over 4 weeks), indicating that month-long dry periods become a recurrent feature of the second planting season. Sumatera also experiences a modest lengthening of dry spells, with most locations remaining within the 8-14 consecutive dry days (1-2 weeks) range. However, the northern tip and southern regions show an intensification, reaching 15-21 consecutive dry days (2-3 weeks).

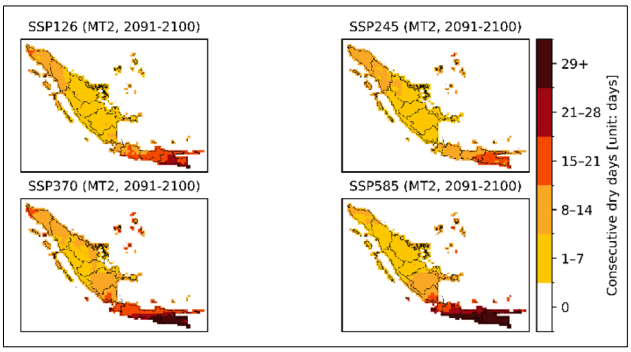

Fig. 12. Late century (2091-2100) average number of consecutive dry days in MT1

Across all scenarios and time horizons, MT2 CDD exhibits a clear progression and intensification relative to the historical baseline (Figures 10-12). At mid-century, all scenarios yield very similar outcomes in terms of spatial pattern and dry spell length. At the end of the century, the change becomes significantly more distinct. One consistent finding is that all scenarios project a lengthening of dry spells in eastern Java. However, worse scenarios show significantly longer durations. Beginning with the moderate-worst case (SSP370) scenario, the consecutive dry days consistently exceed 28 days (over 4 weeks).

Overall, MT2 consecutive dry days respond more strongly and extensively than MT1 to future warming, primarily through the further lengthening of dry spells in pre-existing dryness hotspots, particularly in eastern Java.

3.3 Discussion

Differences in projected heat and dryness between Java and Sumatera, and between MT1 and MT2, are consistent with the underlying climatology of the Indonesian monsoon system. The distinct geographical setting and topography of each island shape the local weather systems [9] and therefore modulate their future climate responses. The contrast between MT1 and MT2 mainly reflects the timing of the monsoon. MT1 coincides with the rainy season, when cloud cover and frequent rainfall dampen both maximum temperature and the length of dry spells, whereas MT2 occurs closer to the transition toward the dry season, when clearer skies and reduced rainfall favour higher maximum temperatures and longer consecutive dry days.

The projected changes in hot days and consecutive dry days imply substantial risks for rice production in Indonesia. Hot spells reduce rice yield significantly when they occur during critical growth stages such as flowering and grain filling [10]. Studies show that for each 1°C increase in daytime or nighttime temperature, rice yields decline up to 8% because high maximum temperatures become more frequent [11]. Meanwhile, dry spells constrain soil moisture during key vegetative and reproductive phases and thereby cause drought stress. This stress inhibits plant growth and leads to changes in leaf characteristics and number, as well as reduced root growth [12,13]. Drought stress can result in yield reductions of up to 55% [14]. Given that the results show more frequent hot days and longer CDD, these changes represent a significant threat to rice production, with the potential for substantial yield losses.

The strong contrast between low- and high-emission scenarios in the projections highlights the importance of mitigation, including within the agricultural sector. Moving from SSP585-like to SSP126-like pathways in this study reduces the area experiencing adverse climate impacts and directly limits the likelihood of heat and drought stress on rice.. This situation reveals a clear necessity to reduce emissions from agriculture to lessen the emerging threat to Indonesian rice production. Practices such as alternate wetting and drying and improved fertiliser management are particularly relevant for lowering emissions in rice production systems.

Finally, the results show that adaptation will remain essential even under the mildest climate-change scenario. In SSP126, hot days and CDD still increase implying that historical planting calendars and varieties will face more frequent stress events. Effective adaptation therefore needs to work at multiple, mutually reinforcing levels, combining climate informed practices and appropriate technologies at the farm level, such as effective irrigation system that are a critical factor in agricultural yield [15], collective action and shared facilities at the group level, and evidence-based policy, early warning systems and targeted infrastructure at the institutional level, in line with the principles of climate smart agriculture. With coherent governance and accountable financing that support these layered efforts, Indonesia can strengthen the adaptive capacity of its food system and maintain more stable and resilient production under a changing climate.

4 Conclusion

The analysis projects that climate change will intensify hot days and consecutive dry days (CDD) across Java and Sumatera, with MT2 being the most vulnerable planting season. Hot days are more frequent in Sumatera, while consecutive dry days are more frequent in Java. Hot days and CDD are set to increase even under the mildest climate change scenario

(SSP126), which impacting rice production. More severe climate change scenario (SSP370 and SSP585) indicates a much more dangerous climate for rice production, with very frequent hot days reaching over 56 days (8 weeks) and dry spells over 28 days (4 weeks). These threats will likely cause significant reductions in rice yield due to increased heat and drought stress during critical growth stages. There is a strong contrast between low and high-emission futures, which underscores the critical importance of both mitigation and adaptation to sustain rice production and strengthen the resilience of Indonesia's food system.

References

1. B. P. Statistik, Statistik Indonesia 2025 (Statistical Yearbook of Indonesia 2025) (BPS-Statistics Indonesia, Jakarta, 2025)
2. C. A. W. Cahyo and A. Maulidiyah, Analisis efektivitas dan efisiensi jaringan irigasi terhadap pola tanam di Daerah Irigasi Pejangkungan. Jurnal Teknik Sipil. **8**, (2023). https://doi.org/10.56071/deteksi.v8i2.632
3. IPCC, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, Geneva, 2023)
4. B. C. O'Neill, C. Tebaldi, D. P. van Vuuren, V. Eyring, P. Friedlingstein, G. Hurtt, R. Knutti, E. Kriegler, J.-F. Lamarque, J. Lowe, and G. A. Meehl, The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. Geoscientific Model Development. **9**, (2016). https://doi.org/10.5194/gmd-9-3461-2016
5. B. Thrasher, W. Wang, A. Michaelis, F. Melton, T. Lee, and R. Nemani, NASA Global Daily Downscaled Projections, CMIP6. Scientific Data. **9**, (2022). https://doi.org/10.1038/s41597-022-01393-4
6. M. Mahmud, I. Narulita, S. B. Sipayung, L. Toersilowati, M. R. Djuwansah, W. E. Cahyono, W. Ningrum, Suciantini, E. R. Dewi, S. A. Rahayu, and Muzirwan, Performance Analysis of CMIP6 Climate Models for the Precipitation of Indonesia Region in *Springer Proceedings in Physics* (Springer, Singapore, 2024), pp. 577–589
7. Y. Wang, L. Wang, J. Zhou, S. Hu, H. Chen, J. Xiang, Y. Zhang, Y. Zeng, Q. Shi, D. Zhu, and Y. Zhang, Research progress on heat stress of rice at flowering stage. Rice Science. **26**, (2019). https://doi.org/10.1016/j.rsci.2018.06.009
8. S. V. K. Jagadish, M. V. R. Murty, and W. P. Quick, Rice responses to rising temperatures -- challenges, perspectives and future directions. Plant, Cell \& Environment. **38**, (2015). https://doi.org/10.1111/pce.12430
9. Y. Yulizar and C. Asdak, The joint variation of temperature and precipitation across Indonesia: A seasonal and regional analysis. Theoretical and Applied Climatology. **156**, (2025). https://doi.org/10.1007/s00704-025-05872-7
10. Q. Su, J. S. Rohila, S. Ranganathan, and R. Karthikeyan, Rice yield and quality in response to daytime and nighttime temperature increase -- a meta-analysis perspective. Science of The Total Environment. **898**, (2023). https://doi.org/10.1016/j.scitotenv.2023.165256
11. Y. Song, C. Wang, H. W. Linderholm, Y. Fu, W. Cai, J. Xu, L. Zhuang, M. Wu, Y. Shi, G. Wang, and D. Chen, The negative impact of increasing temperatures on rice yields in southern China. Science of The Total Environment. **820**, (2022). https://doi.org/10.1016/j.scitotenv.2022.153262
12. S. S. Yuwono, I. Lubis, M. Ghulamahdi, and E. R. Palupi, Morphological,

physiological and rice yield in lowland and upland under drought stress. Australian Journal of Crop Science. **19**, (2025). https://doi.org/10.21475/ajcs.25.19.04.p264

13. S. Margaret, N. Nafisah, S. Sujinah, I. A. Rumanti, and N. Yunani, Effect of drought periods on rice lines growth and yield. Jurnal Teknik Pertanian Lampung (Journal of Agricultural Engineering). **13**, (2024). https://doi.org/10.23960/jtep-l.v13i1.49-59
14. T. Hussain, N. Hussain, M. Tahir, A. Raina, S. Ikram, S. Maqbool, M. F. Ali, and S. Duangpan, Impacts of drought stress on water use efficiency and grain productivity of rice and utilization of genotypic variability to combat climate change. Agronomy. **12**, (2022). https://doi.org/10.3390/agronomy12102518
15. S. Sumani, K. Komariah, S. Suntoro, M. Mujiyo, and H. Ullah, Rainfall, drought, and irrigation in relation to crop patterns in the volcanic topo sequence of Central Java, Indonesia. SAINS TANAH - Journal of Soil Science and Agroclimatology. **22**, 1 (2025). https://doi.org/10.20961/stjssa.v22i1.87786