Assessing future climate change with a weather generator: A case study in Bali, Indonesia

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Abstract. Bali is one of the largest rice granaries in Indonesia, with 668,612 tons produced in 2023. Hence, agriculture is one of the crucial sectors in Bali. Climate change can affect the agriculture sector in many ways. It can cause the conditions to be better or worse for growing plants in distinct areas. Forecasting future climate change is needed to understand extreme conditions in the long term. Thus, climate change scenarios are required to evaluate agriculture impacts. We use the MarkSim weather generator with 17 models under different scenarios and collected rainfall and temperature data from 2026-2091. The MarkSim weather generator can be utilized to predict future climate change in Bali, Indonesia. Rainfall in the coming years is expected to fluctuate annually, yet it will remain within a relatively stable range of 2066 to 2170 mm. Both maximum temperature (Tmax) and minimum temperature (Tmin) are projected to continue to rise, with increases of up to 2 °C. This study offers valuable insights into climate change impact models on agriculture, which is helpful for farmers, researchers, planners, and decision-makers.

1 Introduction

Climate change is a complex phenomenon involving interactions between the atmosphere and Earth's surface [1]. Weather factors, such as rainfall and temperature, influence climate change [2]. Climate change scenarios are needed to evaluate its future impacts, especially on the agricultural sector. Future weather conditions will play an essential role in farmers' decision-making process.

Bali, Indonesia, is famous for its tourism sectors. Nevertheless, the agricultural sector also plays a vital role for the Balinese [3]. In 2023, Bali produced 667,612 tons of rice, which makes it one of the most enormous rice granaries in Indonesia. However, the agricultural sector contributes to greenhouse gas (GHG) emissions in Indonesia [4], significantly affecting future climate change [5]. Besides, unpredictable extreme weather can have a negative impact on agricultural yields in Indonesia. Therefore, it is crucial to understand future climate change trends to mitigate its adverse effects.

MarkSim is an online weather generator that generates simulated weather data for various locations worldwide [6]. In several countries, the limited availability of climate data

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can restrict research and development in agriculture [7]. MarkSim provides free and open access to past, current, and future climate data, which is helpful for understanding climate variation and its impacts on agriculture. MarkSim has been shown to perform appropriately in simulating weather patterns [8]. Its output can be combined with agricultural models to evaluate crop cultivation risks and can be easily accessed through the website [9, 10]. Since there is uncertainty in climate modeling, it is essential to consider multiple scenarios [11]. MarkSim uses Representative Concentration Pathways (RCP) scenarios to project future climate change. RCPs are scenarios that describe the concentration levels of greenhouse gases in the atmosphere [12]. They are employed in climate modeling to evaluate possible future climate conditions based on emission levels.

This study recommends using a simple and easy climate model to assess future climate change using the MarkSim weather generator. This climate model is usually combined with other models, such as crop or hydrological models. Previous research conducted by Naylor et al. (2007) discussed the impacts of El Nino on rice farming in Indonesia using the GCM model from the Intergovernmental Panel on Climate Change AR4 report [13]. Hartkamp et al. (2003) employed the MarkSim weather generator to observe daily weather data [9]. Other studies have used weather generators in several countries to predict future climate change [6, 10, 14].

Different from prior research, this study employed a MarkSim weather generator to project future climate change based on rainfall and temperature trends in Bali, Indonesia. Understanding future climate change is essential to anticipate extreme weather conditions in the long term, which is the first step towards climate change adaptation and mitigation. Further, this study can provide helpful information for agricultural impact models and a reference for researchers, planners, and policymakers.

2 Methodology

The research site was located in Bali Province, Indonesia, at coordinates 8° 24' 34.2648" S and 115° 11' 20.1084" E, with latitude 8.409519 and longitude 115.188919 (Fig. 1). Bali has a monsoon climate where the rainy season occurs from September to February and the dry season is from March to August.

The study used the MarkSim weather generator (Fig. 1) (https://gisweb.ciat.cgiar.org/MarkSimGCM/ accessed on September 18, 2024) with a two-stage third-order Markov chain model calibrated from GCMs (General Circulation Models) to match the WorldClim dataset. Here, 17 climate models were applied, including BCC-CSM1-1, BCC-CSM1-1-M, CSIRO-Mk3-6-0, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MRI-CGCM3, and NorESM1-M. Parameter and model uncertainty occurs in a system and various climate scenarios. Therefore, all models and scenarios available in the generator cover various possible outcomes. To operate this site, we select a location by entering latitude and longitude coordinates, select the desired model, determine the number of replications, and then click the 'Climate Diagram' option to get the weather results in a diagram. Then, the precipitation and temperature data with the models were collected from 2026 to 2091. Further, this study used four RCP scenarios of RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5, with 10 replications for each scenario. The average temperature and total rainfall data generated by the MarkSim weather generator were visualized using charts. Data were analyzed using Microsoft Excel software. Interviews were also conducted with several farmers in Bali to obtain complete data. Interviews were conducted with Subak organization leaders and farmers using an in-depth interview method, selected through purposive sampling. The leaders were chosen based on their knowledge relevant to this study, their role as elders in the local indigenous community, and their willingness to participate in the interviews.

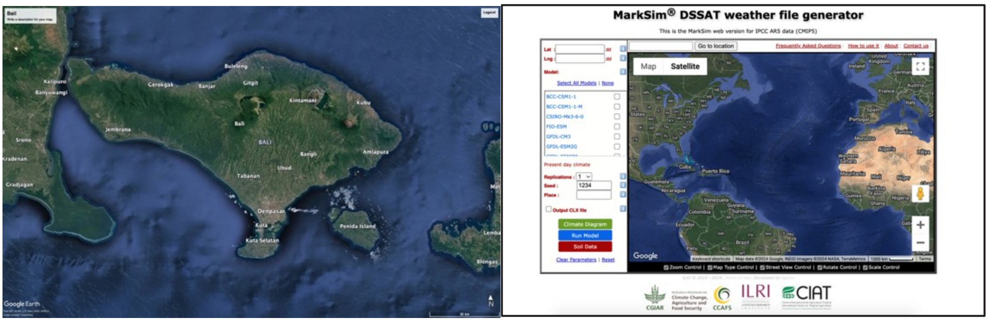

Fig. 1. The study site for future climate change area and MarkSim weather generator

3 Results and Discussion

The future climate in Bali was evaluated through four RCP scenarios from 2026 to 2091. Here, annual rainfall is expected to fluctuate in the future (Fig. 2). In the RCP 2.6 scenario, the highest rainfall is projected to reach 2,127 mm/year, while the lowest is 2,066 mm/year. In the RCP 4.5 scenario, the highest rainfall is estimated to reach 2,153 mm/year, and the lowest is 2,100 mm/year. In the RCP 6.0 scenario, the highest rainfall is estimated to reach 2,153 mm/year, and the lowest is 2,112 mm/year. Meanwhile, in the RCP 8.5 scenario, the highest rainfall is estimated to reach 2,170 mm/year, and the lowest is 2,134 mm/year. In 2071, 2076, 2081, and 2086, the RCP 8.5 scenario demonstrates the highest increase in rainfall compared to the other scenarios.

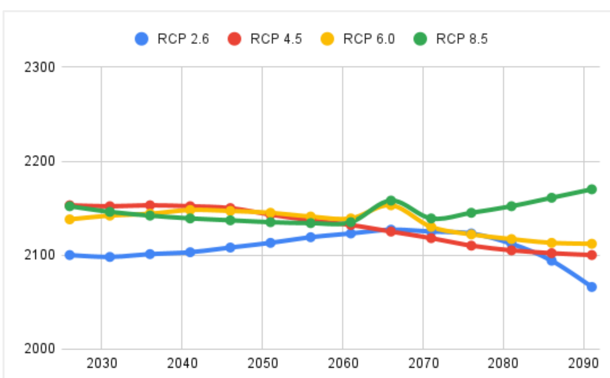

Fig. 2. Rainfall prediction on future climate change with various scenarios

Tmax and Tmin in this region are predicted to rise gradually during the years observed. Based on Fig. 3, Tmax is projected to grow by 0.2 °C in the RCP 2.6 scenario, 0.9 °C in the RCP 4.5 scenario, 1.3 °C in the RCP 6.0 scenario, and 2.5 °C in the RCP 8.5 scenario. The results are in line with the Tmin prediction (Fig. 4), where it is projected to increase by 0.1 °C in the RCP 2.6 scenario, 0.9 °C in the RCP 4.5 scenario, 1.3 °C in the RCP 6.0 scenario, and 2.5 °C in the RCP 8.5 scenario. The highest projected Tmax and Tmin are 28.1 °C and 20.69 °C, respectively, achieved at the RCP 8.5 scenario, subsequently followed by RCP 6.0, RCP 4.5, and RCP 2.6. Thus, the RCP 8.5 scenario causes a more significant increase in the temperature compared to the other scenarios.

Further, the results reveal that the RCP scenarios affect the prediction of future climate change according to their emission levels. They exhibit that RCP 2.6 is a low-emission scenario while RCP 4.5 and 6.0 are medium-emission scenarios, and RCP 8.5 is a high-emission scenario. The higher future emissions denote the greater climate change risk on rainfall and temperature.

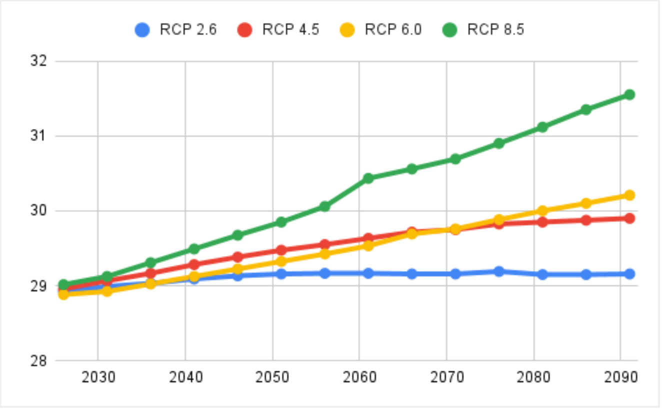

Fig. 3. Tmax prediction on future climate change with various scenarios

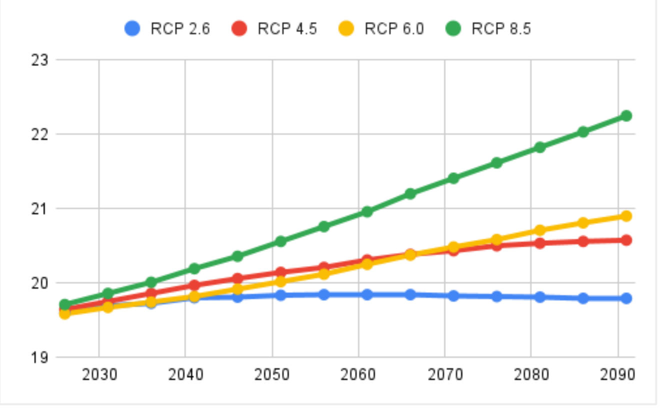

Fig. 4. Tmin prediction on future climate change with various scenarios

Fig. 5 displays the rainfall distribution in the four scenarios each month throughout the years, revealing that rainfall in Bali varies each month. It demonstrates that high rains occur from December to February, which is more than 300 mm per month. In contrast, relatively low rainfalls happen from August to September, which is below 90 mm per month. Based on the results, the varying rainfall for the next few years in the four scenarios is still relatively stable, where the changes only occur in rainfall intensity. This information is vital for farmers because water availability affects crop production and determines the planting date in each season.

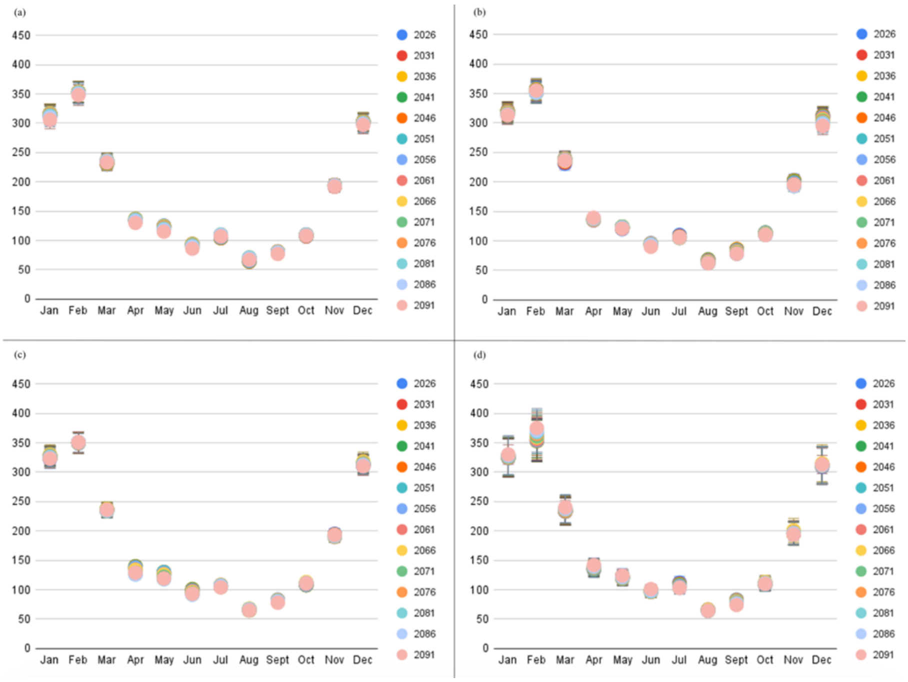

Fig. 5. Rainfall prediction on future climate change with various scenarious of (a) RCP 2.6, (b) RCP 4.5, (c) RCP 6.0, (d) RCP 8.5

In Bali, most farmers grow rice in rice fields using the *Subak* system. The system is dependent on water availability from natural springs because most *Subak* do not use water pumps or wells. Therefore, rainfall is an important indicator to ensure adequate water supply throughout the year. Sufficient rainfall is needed to maintain a stable spring flow and support even water distribution throughout the *Subak* network. In addition, understanding rainfall patterns can also help minimize the risk of hydrometeorological disasters in the future [15]. Agricultural land with the *Subak* system usually has a terraced topography with a particular slope that makes it vulnerable to natural disasters, such as landslides. Besides, increasing temperatures can cause extreme changes in rainfall patterns. Higher temperatures will increase the evaporation rate so the atmosphere can hold more water vapor. This condition can cause more extreme rainfall because when the atmosphere is saturated, the rainfall can be very intense and prolonged [16]. In addition, temperature change can also affect plant pests and diseases, such as pests' behavior and life cycle. Warmer temperatures tend to accelerate the growth and reproductive cycles of many pests. In the end, the results exhibit how agriculture in Bali is affected by climate change, especially in terms of rainfall and temperature.

Month	Day	Cultivation stage (three times a year)	
February	1 - 10	Nursery	
	11 - 20	Land preparation	
	21 - 30	Planting	Fertilizer (manure)
March	1 - 10	Irrigation	Fertilizer (composite)
	11 - 20	Drying	Weeding
	21 - 30	Irrigation	Fertilizer (advanced)
April	1 - 10	Drying	Weeding
	11 - 20	Irrigation	Fertilizer (composite)
	21 - 30	Drying	Fertilizer (advanced)
May	1 - 10	Irrigation	
	11 - 20	Drying	
	21 - 30	Harvesting	
June	1 - 10		
	11 - 20		
	21 - 30		
July	1 - 10		
	11 - 20		
	21 - 30	Secondary crop/fallow	
August	1 - 10		
	11 - 20		
	21 - 30		
September	1 - 10		
	11 - 20		
	21 - 30	Nursery	
October	1 - 10	Land preparation	
	11 - 20	Planting	Fertilizer (manure)
	21 - 30	Irrigation	Fertilizer (composite)
November	1 - 10	Drying	Weeding
	11 - 20	Irrigation	Fertilizer (advanced)
	21 - 30	Drying	Weeding
December	1 - 10	Irrigation	Fertilizer (composite)
	11 - 20	Drying	Fertilizer (advanced)
	21 - 30	Irrigation	
January	1 - 10	Drying	
	11 - 20	Harvesting	
	21 - 30		

Month	Day	Cultivation stage (two times a year)	
January	1 - 10	Land preparation	Nursery
	11 - 20	Planting	Fertilizer (manure)
	21 - 30	Irrigation	Fertilizer (composite)
February	1 - 10	Drying	
	11 - 20	Irrigation	
	21 - 30	Drying	Weeding
March	1 - 10	Irrigation	Fertilizer (advanced)
	11 - 20	Drying	Fertilizer (composite)
	21 - 30	Irrigation	Weeding
April	1 - 10	Drying	Fertilizer (advanced)
	11 - 20	Irrigation	
	21 - 30	Drying	
May	1 - 10	Irrigation	
	11 - 20	Drying	
	21 - 30	Drying	
June	1 - 10	Harvesting	
	11 - 20	Harvesting	
	21 - 30		
July	1 - 10	Fallow	
	11 - 20		
	21 - 30		
August	1 - 10	Nursery	
	11 - 20	Land preparation	
	21 - 30	Planting	Fertilizer (manure)
September	1 - 10	Irrigation	Fertilizer (composite)
	11 - 20	Drying	Weeding
	21 - 30	Irrigation	Fertilizer (advanced)
October	1 - 10	Drying	Weeding
	11 - 20	Irrigation	Fertilizer (composite)
	21 - 30	Drying	Fertilizer (advanced)
November	1 - 10	Irrigation	
	11 - 20	Drying	
	21 - 30	Drying	
December	1 - 10	Harvesting	
	11 - 20		
	21 - 30		

Fig. 6. Rice planting season during the year

The impact of rainfall patterns and temperature changes is significant for cultivating rice plants. Generally, rice cultivation has various stages, including pre-planting, planting, and post-planting. The pre-planting period consists of preparation, soil cultivation, and nursery stages. The planting period comprises transplanting, irrigation, fertilization, and pest management. Meanwhile, post-planting includes harvesting, straw removal, and storing rice in barns. However, due to technological developments and climate change that impact agriculture in Bali, rice cultivation in each *Subak* is different. Each *Subak* has different environmental conditions, leading to cultivation practices that align with specific needs. In addition, planting intensity and annual cropping patterns are different. Several *Subaks* undertake three cycles per year (e.g., paddy-paddy-secondary crops or paddy-paddy-fallow), while others have two cycles (e.g., paddy-secondary crops or paddy-fallow) (Fig. 6). Therefore, understanding monthly rainfall and temperature patterns is essential, as these factors directly influence planting intensity and timing. Besides, rainfall also impacts specific cultivation stages. For instance, in heavy rainfall during fertilization, the right strategy is needed to ensure that fertilization occurs efficiently and avoid the loss of nutrients due to leaching. Furthermore, fertilization during the dry season with low rainfall and water deficiency can affect the absorption of nutrients in plants.

In *Subak Dalem*, Tabanan Regency, a three-crop annual cropping pattern is practiced (paddy-paddy-secondary crops or paddy-paddy-fallow) [17]. Nursery, land preparation, and planting occur in February when rainfall is high. Irrigation, fertilization, and weeding begin in March, along with the vegetative phase and grain filling, where the water requirements for field preparation and rice growth are met due to the high rainfall. Paddy fields in *Subak* utilize an intermittent irrigation system where the fields are dried out for 7-10 days. Then, irrigation continues to April and early May. Although rainfall begins to decrease and limit, irrigation water is still available. Fields are then drained in preparation for the harvest in May. By mid-May, as irrigation is no longer required, the floodgates are closed. This is in line with the low rainfall entering the dry season.

After harvest, secondary crops are planted between June and early September, which require less water. Land preparation for the next planting season begins in October. However, during this period, water availability is minimal due to low rainfall in the dry season. Sufficient irrigation is needed from September to October for plant growth. Consequently, several farmers either rotate crops or skip a planting cycle to conserve water. Then, rainfall resumes in November and intensifies throughout December and February. Harvesting is carried out in December and January and the fields must be drained prior to the harvesting.

In another location, *Subak Jatiluwih*, Tabanan Regency, a twice-yearly cropping pattern is implemented [18]. This differs from *Subak Dalem* even though it is in the same district. The type of rice cultivated is also dissimilar, influencing the rice growth period. *Subak Jatiluwih* primarily cultivates local rice, namely Jatiluwih Red Rice, with a single planting cycle of up to six months. *Subak Jatiluwih* also divides the planting system into two periods. The first period is for local Balinese rice (January - May/June), and the second is for rice varieties (August - November). During the second period, farmers may also choose to plant secondary crops or leave the land fallow. Local rice must be planted early during the rainy season to ensure sufficient water availability. Planting intensity, cropping patterns, cultivation stages, and related practices are regulated by the head of the *Subak* organization according to water availability and climate patterns. Continuous rainfall can damage rice cultivation and inhibit plant growth. Meanwhile, the paddy receives much water when it requires dry conditions [18]. However, farmers need to understand and anticipate upcoming climate patterns, which a weather generator can facilitate to access climate prediction.

MarkSim weather generator can provide results in the form of variations in rainfall and temperatures. None of the weather generators are comparable to each other; they have different methods of collecting data. Nevertheless, MarkSim is effective for locations with unstable weather distribution and fluctuating data [9]. In addition, this tool can also be used in locations with limited data availability. MarkSim is easily accessible to farmers to help them predict future climate conditions. Therefore, farmers are required to understand and anticipate the changes to maintain agricultural productivity and reduce losses due to pests. Adaptation and mitigation to climate change are necessary for the sustainability of agriculture in the future. Moreover, this study has certain limitations. It focuses solely on Bali, which may restrict the applicability of its findings to other regions with different environmental or socio-cultural conditions.

4 Conclusion

The MarkSim weather generator has proven suitable for predicting future climate change in Bali, Indonesia, up to 2091. Future rainfall is expected to vary yearly but remains within a relatively stable range of 2066 to 2170 mm. Future temperatures are projected to continue increasing up to 2 °C. This study will have broader implications for agriculture, water resource management, and policymaking in Bali. It will benefit farmers, researchers, academics, government officials, and other stakeholders involved in related fields.

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