Received: 9 October 2022 | Revised: 16 April 2023 | Accepted: 20 April 2023 | Published on: 17 May 2023

DOI: 10.1002/joc.8098

RESEARCH ARTICLE

International Journal of Climatology RMetS

Climate change over Indonesia and its impact on nutmeg production: An analysis under high-resolution CORDEX-CORE regional simulation framework

Nuralfin Anripa[1,2] | A. Kumar[3] | Pyarimohan Maharana[2,4] | A. P. Dimri[5,6]

[1]Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, Thailand

[2]School of Ecology and Environment Studies, Nalanda University, Rajgir, Bihar, India

[3]School of Management Studies, Nalanda University, Rajgir, Bihar, India

[4]Department of Environmental Studies, DCAC, University of Delhi, New Delhi, India

[5]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi, India

[6]Indian Institute of Geomagnetism, New Panvel, Navi Mumbai, India

Correspondence
Pyarimohan Maharana, Department of Environmental Studies, DCAC, University of Delhi, New Delhi, India.
Email: maharanapyarimohan@gmail.com

Abstract

Nutmeg is an important spice and contributes significantly to the gross domestic product of Indonesia. The study examines the impact of climate change on Indonesia and the production of nutmeg over Banda Neira Island. For this, the outputs from high-resolution regional climate models under different representative concentration pathways (RCP2.6, RCP4.5 and RCP8.5), within the framework of Coupled Model Intercomparison Project 5/Coordinated Regional Climate Down-scaling Experiment-Coordinated Output for Regional Evaluations (CMIP5/CORDEX-CORE) over southeast Asia domain are employed. The representation of the spatial structure of rainfall and temperature climatology is found to be much better in ensembles as compared to individual model experiments. The behaviour of simulated rainfall and temperature from the model experiments is examined to check whether the projected climate favours an increase in nutmeg production. The study found that projected changes in the number of wet days (ideal 100–160 wet days), heavy rainfall events, rising mean temperature above the optimum temperature range (25–26°C), increasing heatwave spells, and prolongation of the warm period led to an unfavourable climate for nutmeg production. Based on the analysis of dynamically produced (model simulated) climate variables, the study rejects the forecasted increase in nutmeg production using a statistical regression model due to the unfavourable climatic conditions that are likely to affect the growth, production and quality of nutmeg. The changing climate not only reduces regional agricultural production but also impacts the socio-economic condition of the people of Indonesia. Therefore, the study emphasizes implementing stringent climate laws and policies at global, regional and local levels to curb greenhouse gas emissions and reduce the negative impact of climate change.

KEYWORDS

climate change, nutmeg, production, rainfall, temperature

1 | INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as an identifiable form of change in climatic conditions with a change in the average and/or variability of its components over a long period of time, generally a decade or more (IPCC, 2007). It was formally defined in 1992 by the United Nations Framework

Convention on Climate Change (UNFCCC, 1992). It has been reported that the changing climate has led to extremes of both precipitation and temperature in the form of heat-waves and intense rainfall episodes (Maharana et al., 2021; Mohammed et al., 2017; Schleussner et al., 2016). It has been observed that these extremes are on the constant rise under the recent accelerated human-induced climate change and will be more frequent in the future (Maharana et al., 2021; Rai et al., 2020; Rao et al., 2014; Shahi et al., 2021). According to the Fifth Assessment Report of IPCC (AR5), various scientific indicators reveal that the planet Earth is naturally undergoing significant changes in the global climate. The global temperature has been increasing for the last three decades in a row. It has already been estimated that the earth's temperature has increased by about 0.8°C in the last century. Further, the temperature is expected to increase by 1.8–4°C and 2.5–4.7°C by the end of the century with respect to the 1980–1999 average and pre-industrial times (1750), respectively (IPCC, 2013). The recent accelerated global temperature rise has stronger regional impacts in different parts of the world (Maharana, Agnihotri, & Dimri, 2021). The increase in temperature in land areas is higher than in the seas due to the higher specific heat capacity of the water. Studies reveal a significant increase in sea-level rise from the 19th century, which can be attributed to the decline in the glaciers and snow cover in both hemispheres (Schewe et al., 2011; UNFCCC, 1992).

This changing climate is manifested as the change in the mean structure of regional precipitation and climate extremes, posing a threat to various ecosystems and agricultural productivity (Wing et al., 2021). The impact of climate change on weather parameters has been studied by various scientists across the world (D'Agostino & Schlenker, 2016; Iizumi & Ramankutty, 2016; Konduri et al., 2020; Lesk et al., 2016; Lobell & Field, 2007; Zhao et al., 2017). Global rainfall pattern has changed in various regions, with a decrease in the south and an increase in the north (Trenberth et al., 2003). Climate change has impacted all parts of the world and Southeast Asia; the Indonesian regions are no exception. Indonesia experiences a hot and humid climate for most parts of the year with high rainfall. In a regional study, the climatology and variability of the rainfall over Indonesia have been studied using a high-resolution regional climate model (RCM; Ratna et al., 2017). Putra et al. (2020) used multiple global climate models (GCMs) to examine the behaviour of the climate indices over Indonesia under different representative concentration pathways (RCPs). In Indonesia, the average annual temperature has increased by 0.3°C/decade, while the annual rainfall has decreased by 2%–3%. Climatic factors such as rainfall and temperature serve as important direct inputs to the crop sector; any change and variability in these parameters are inevitable to have a significant effect on cropping patterns, planting time, growth, quality and crop yields (Barnwal & Kotani, 2013; Gornall et al., 2010; Guntukula & Goyari, 2020; Shikha et al., 2018). Climate change reduces agricultural production potential and regional water availability due to rising temperatures and droughts; it can negatively impact agricultural yields and affect food security (Arora, 2019; Stevanović et al., 2016). Climate change can have a negative impact on plant growth and productivity by influencing plant physiology. The respiration and transpiration of plants are affected by an increase in air temperature (Luttge & Pitman, 2011). This also accelerates fruit and seed ripening, reducing crop quality along with the growth of pests and diseases (Juroszek & von Tiedemann, 2011; Oerke, 2006). Variations in rainfall patterns within the season also impact crop production.

Nutmeg (*Myristica fragrans Houtt*) is a native Indonesian plant with several benefits, including a distinctive aroma and high oil yield. It is an important spice with high economic value as it is an important raw material for different industries such as pharmaceuticals, perfumes, cosmetics, food and beverages. Mace and seeds from the old nutmeg are used as spices. The nutmeg oil, which is used as medicine is derived from the young fruit (Nurdjannah, 2007). Indonesia is one of the largest nutmeg-producing and exporting countries in the world. The Banda Islands, Maluku Province, are the area of origin for the nutmeg plant (Indonesian ministry of Agriculture, 2016). To date, the traditional agricultural practices have been followed by the farmers and hence the yield is still low but they still maintain the high quality of nutmeg (Nurdjannah, 2007). The nutmeg export earned Indonesia a foreign exchange of USD135.9 million or IDR1.3 trillion in 2017 (Indonesian ministry of Agriculture, 2016). Further, the Indonesian Government is trying to restore the past glory of Maluku Island as 'Spice Island' with priority production of spices.

Nutmeg production depends upon various factors such as crop factors, external input in the form of fertilizer and pesticides, climate and harvested area. The land expansion is impossible because of the available land limitations within the islands. Therefore, climatic variables such as rainfall, temperature and relative humidity play an important role in nutmeg productivity (Hadad et al., 2006). The ideal growth of the nutmeg plant requires the annual rainfall in the range between 2000 and 4500 mm, 100–160 wet days, 25–26°C average temperature and 60%–80% relative humidity. The study of air temperature and rainfall indicates that the climate over the region is under constant change for the last 50–100 years (Hidup, 2004). Therefore, to address the threat to state revenues and farmers' livelihoods caused by climate change, effective strategies need to be formulated and implemented (Rehatta et al., 2021).

This study focuses on the present climate and its projections over Indonesia by examining the nature of the precipitation and temperature from high-resolution RCM outputs. This study further examines the impact of the changing climate on nutmeg production with special reference to the Maluku Island of Maluku Province, Indonesia, during the rainy season (October–March). The simulated climate variables are examined for the climate suitability for nutmeg production under different climate change scenarios. Further, the present work uses the 36 high-resolution model output from CORDEX-CORE framework for the first time, which has not been used for the southeast Asian domain earlier.

2 | DATA AND METHODOLOGY

The following section explains the different datasets used and the methodology adopted in the present study.

2.1 | Dataset used

The present study employed various datasets to explore future climate projections and their impact on nutmeg production. The details of the datasets procured from different agencies for analysis are provided as follows.

2.1.1 | Regional climate models

Among the climate models, the RCMs are getting popularity because of their ability to produce high-resolution regional information (Giorgi, 2019). The Coordinated Regional Climate Down-scaling Experiment (CORDEX) is an international project supervised by the WCRP (World Climate Research Program) and produces detailed high-resolution climate change scenarios standardized for each region (Bukovsky & Mearns, 2020; Giorgi et al., 2009, 2012; Maharana, Agnihotri, & Dimri, 2021; Maharana et al., 2021; Shahi et al., 2021). The vision of CORDEX is to advance and coordinate the science and application of regional climate downscaling through global partnerships. In the initial phase, the project aims to get high-resolution climate information at 50 km horizontal resolution, which further improves to 25 km in the second phase, that is, CORDEX-Coordinated Output for Regional Evaluations (CORE) project across various domains around the world (Giorgi & Gutowski, 2015). Because of the higher horizontal resolution, the CORDEX-CORE model experiments are chosen for the present analysis above the coarse resolution CORDEX (50 km) experiments and Coupled Model Intercomparison Project Phase 6 (CMIP6) model experiments.

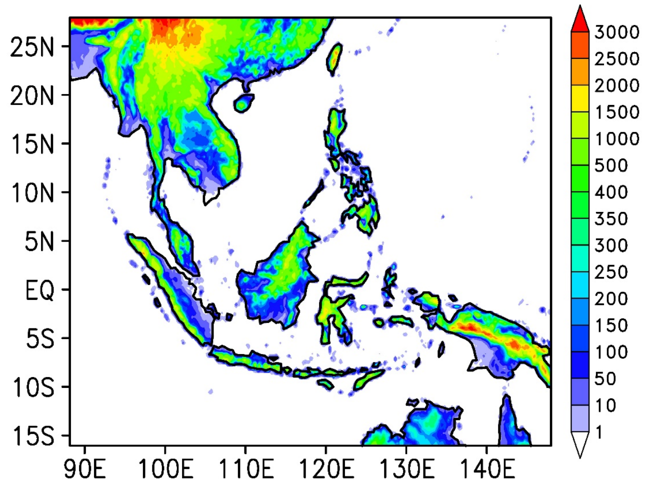

FIGURE 1 The domain of Coordinated Regional Climate Down-scaling Experiment-South East Asia showing topography (m). [Colour figure can be viewed at wileyonlinelibrary.com]

The climatic parameters (rainfall and temperature) are procured over the South East Asian domain (CORDEX-SEA) from Earth System Grid Federation (ESGF)-CORDEX-CORE. The SEA domain is confined within the coordinates of 0–50°N and 60°–180°E and the study area or area of interest that is, the Indonesian region lies in this domain (Figure 1). The datasets are procured for the historical period, RCP2.6 (Van Vuuren et al., 2011), RCP4.5 (Thomson et al., 2011) and RCP8.5 (Riahi et al., 2011). The RCP2.6 is considered as the most optimistic scenario where the global greenhouse gas (GHG) concentration peaks in the early part of the century, then stabilizes and gradually declines by the end. While the RCP8.5 is the 'business as usual scenario', where the GHG concentration keeps on increasing at the same rate till the end of the century. The emission is highest for this scenario hence representing the worst-case scenario of climate change. The RCP4.5 is in between these two scenarios in terms the GHG emission. Like the RCP2.6, the peak stabilizes at the end of the century. The climatic variables such as precipitation, mean temperature, minimum temperature and maximum temperature are downloaded for the present analysis. The present study considered 12, 6, 6 and 12 model experiments for the historical period, RCP2.6, RCP4.5 and RCP8.5, respectively. Here, model outputs are the result of the dynamically downscaled product of GCMs using RCMs at a very high horizontal resolution and have been utilized by many researchers (Maharana, Agnihotri, & Dimri, 2021; Maharana et al., 2021; Shahi et al., 2021). The model (GCM-RCM)

TABLE 1 The model experiments used for different representative concentration pathways.

Experiments	Model combinations (GCM–RCM) used for downscaling
Historical	NorESM1_REMO, NorESM1_RegCM4.7, MPI_REMO, MPI_RegCM4.3, MPI_RegCM4.7, CNRM_RegCM4.3, CNRM_RCA4, HadGEM2_REMO, HadGEM2_RegCM4.7, HadGEM2_RCA4, ICHEC_RegCM4.3, IPSL_RegCM4.3
RCP2.6	HadGEM2_REMO, HadGEM2_RegCM4.7, MPI_REMO, MPI_RegCM4.7, NorESM1_REMO, NorESM1_RegCM4.7
RCP4.5	HadGEM2_RCA4, HadGEM2_RegCM4.3, MPI_RegCM4.3, CNRM_RCA4, ICHEC_RegCM4.3, IPSL_RegCM4.3
RCP8.5	CNRM_RCA4, HadGEM_RCA4, HadGEM_REMO, HadGEM_RegCM4.3, HadGEM_RegCM4.7, MPI_REMO, MPI_RegCM4.3, MPI_RegCM4.7, NorESM_REMO, NorESM_RegCM4.7, ICHEC_RegCM4, IPSL_RegCM4.3

experiments selected for the study are based on the availability on the website for the user community and details are provided in Table 1. The climate datasets were processed using Climate Data Operator Software and the spatial plots of the climatic variables were prepared using the Matplotlib package in python3 (Hunter, 2007).

2.1.2 | Observational datasets

1. Climate Research Unit gridded Time Series version 4 (CRU-TS4) data have been used to validate the model experiments and their ensembles (Harris et al., 2020). The monthly mean rainfall, mean temperature, maximum temperature and minimum temperature are used in this study. The CRU TS has been widely used in a variety of research fields and applications, such as calibrating paleoclimate reconstructions (Nagavciuc et al., 2019; Yao et al., 2017), studying climate variability (Wang et al., 2013), bias correction for global models (Miao et al., 2016), validation of RCMs (Maharana & Dimri, 2014a, 2014b, 2016; Nabat et al., 2015) and reanalysis (Weedon et al., 2014).
2. The annual nutmeg production data from Indonesia has been procured from 1980 to 2016 (Secretariat General of the Ministry of Agriculture of the Republic of Indonesia, 2016).
3. The daily climate data from a meteorological station in Banda Neira Island have been downloaded for 20 years (1992–2011) to study the impact of nutmeg production and climatic variability (Meteorological and Geophysical Agency, Indonesia).

2.2 | Methodology

The nutmeg is grown during the rainy season, which lasts from October to March (ONDJFM) in Indonesia. Therefore, only the seasonal climate data for the rainy season has been selected for examining its relation with nutmeg production. The validation of model experiments against observations is important to ensure that the models are capturing the essential features of the climate system accurately. The model experiments and their ensemble are validated against the CRU gridded observation for the historical period (1976–2005). The climate projections are examined for two different time periods termed as the mid-century (2036–2065, MC hereafter) and end of the century (2071–2100, EC hereafter) under three different RCPs (RCP2.6, RCP4.5 and RCP8.5) to understand the short-term and long-term climate change under different levels of greenhouse gas emissions on the future climate.

A linear regression analysis has been carried out to find the relationship between rainfall and temperature with the observed annual nutmeg production over Banda Island. Further, multiple linear regression analysis was also carried out to see the combined relationship of the climatic parameters (rainfall and temperature) with nutmeg production. Afterwards, this relationship is utilized to forecast nutmeg production. The model data over the Banda Island are extracted for different climate projections using the nearest neighbour interpolation technique for the analysis. The dynamically produced climatic parameters are examined for climate suitability for future annual nutmeg production and the accuracy of the statistical forecast.

3 | RESULTS AND DISCUSSION

In this section, the ability of the model experiments and their ensembles are examined to check whether they are able to replicate the climatological rainfall and temperature over the study domain during the historical period. The climate projections of rainfall and temperature along with their changing behaviour are examined and their relation with nutmeg production is deliberated subsequently.

3.1 | Rainfall climatology

The climatological seasonal-averaged precipitation during the rainy period (ONDJFM) over Indonesia from

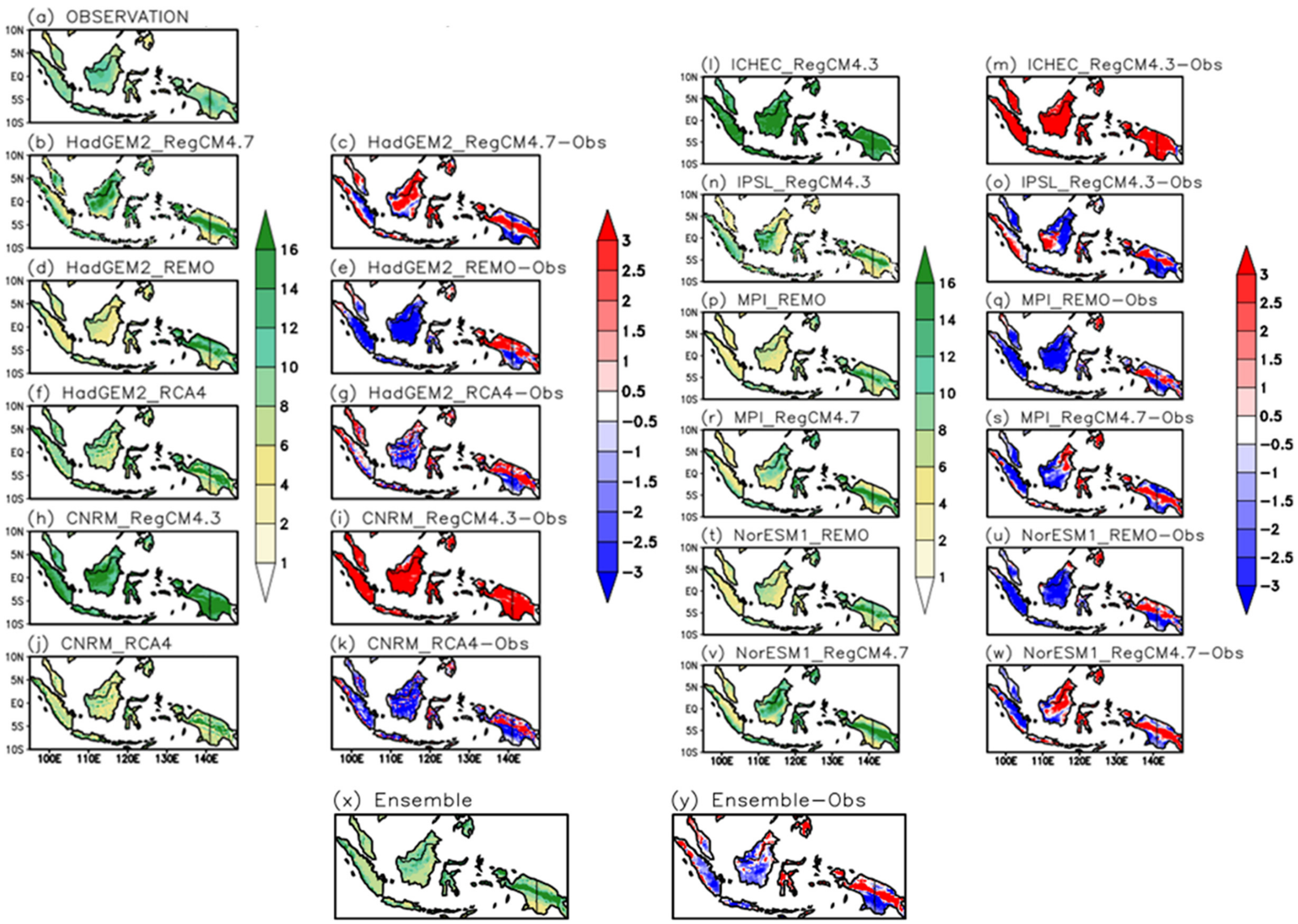

FIGURE 2 The seasonal precipitation climatology (ONDJFM: mm day^{-1}) from Climate Research Unit observation, different model experiments, their ensembles and their corresponding bias for the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

different model experiments are compared with the same from the CRU observations for the historical period (Figure 2). The observed climatological rainfall varies in the range of 8–14 mm/day across Indonesia with an almost uniform spread of rainfall across the country (Figure 2a). Among individual models, the magnitude is comparable in most of the models across the domain. However, a few models show higher and lower precipitation with respect to the observation. Among the models, HadGEM_RegCM4.7, HadGEM_RCA4, IPSL_RegCM4.3, MPI_RegCM4.7 and NorESM1_RegCM4.7 are showing better performance in reproducing the climatological rainfall across the country. The CNRM_RegCM4.3 and ICHEC_RegCM4.3 show a wet bias (14–16 mm/day) with a bias range of more than 3 mm/day, while HadGEM_REMO, MPI_REMO and NorESM_REMO exhibit a specific behaviour of dry bias over the western part of the domain (more than 3 mm/day) and wet/dry bias over eastern islands (more than 3 mm/day). The analysis reflects that the simulated precipitation varies among the model; this may be attributed to differences in their physics and dynamics, which drive the models. However, the multi-model ensemble provides the closest representation of the rainfall to the observation with the least bias (−2 to 2 mm/day) across the study domain.

3.2 | Temperature climatology

The simulated temperature from the individual models is also validated with respect to the observed CRU dataset over the Indonesian landmass for the historical period (Figure 3). The observed temperature during the historical period varies from 22 to 28°C across Indonesia. The model experiments nicely simulated the spatial distribution of temperature across Indonesia. The highlands are much cooler than the plains by 2–4°C. The spatial distribution of the temperature is nicely represented by most

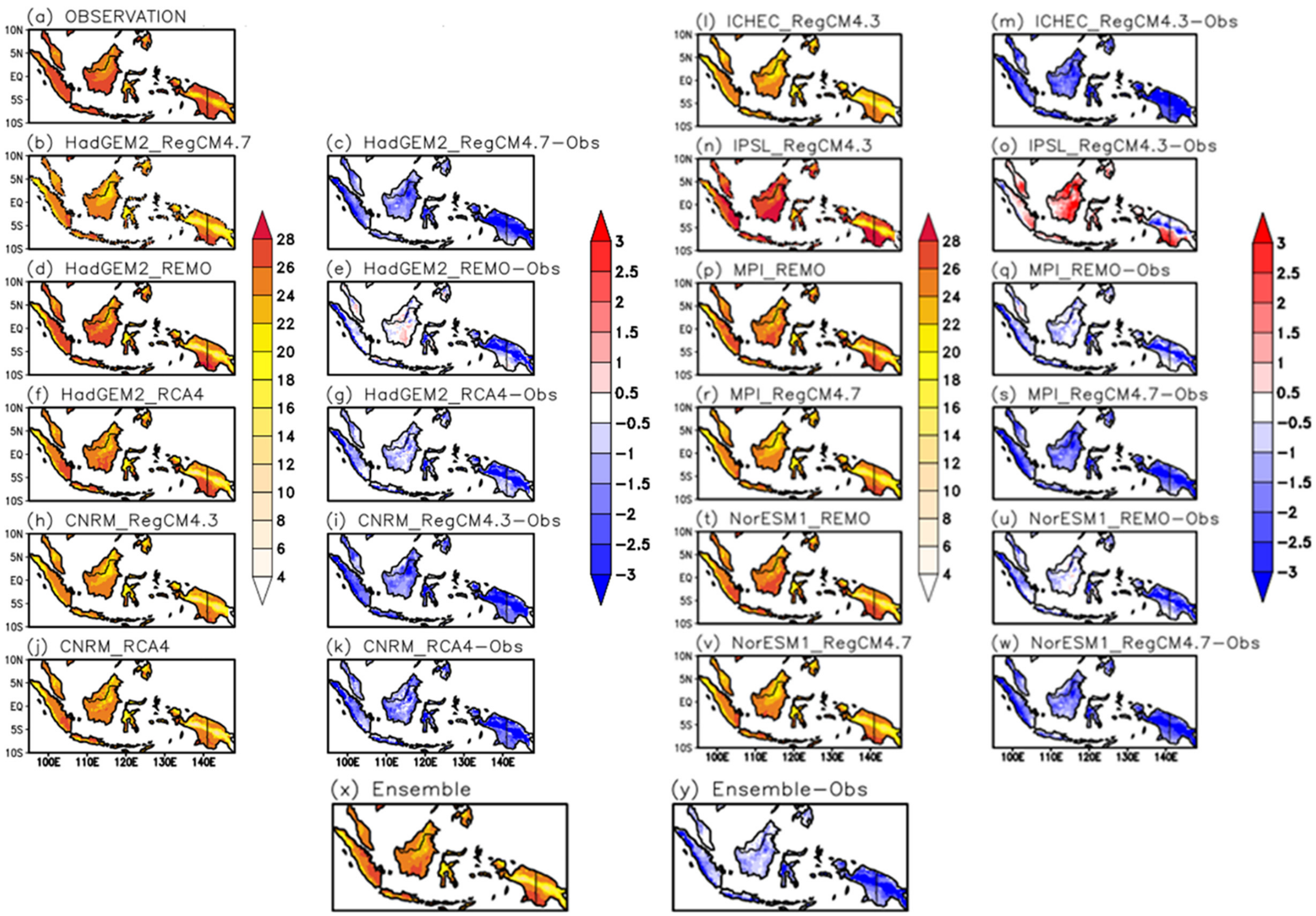

FIGURE 3 The seasonal temperature climatology (ONDJFM: °C) from Climate Research Unit observation, different model experiments, their ensembles and their corresponding bias for the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

of the model experiments with spatial accuracy, except for HadGEM_RegCM4, ICHEC_RegCM4 and MPI_RegCM4. These models underestimate the temperature across the study area and in contrast to these IPSL_-RegCM4.3 simulated a warm temperature ranging from 22 to 28°C with warm bias ranging from 2 to 3°C. The lower magnitude of the cold bias reflects that the representation of the temperature is robust in these model experiments. Similar cold bias in RCM over the south Asian region has also been reported by earlier researchers (Maharana & Dimri, 2014a). Overall, most model experiments have fairly captured the spatial representation of the temperature along with the model ensemble.

3.3 | Probability density function of rainfall and temperature

The seasonally averaged rainfall and temperature distribution over Indonesian landmass during the historical period are examined through the probability density function (PDF) curve. It provides the knowledge of the range, mean and nature of the distribution of the climatic parameter over the domain. In the rainfall PDF, the CNRM_RegCM4 model experiments show much higher range (35–70 cm) and mean (52 cm) as compared to the observation (mean value 37 cm) and other model experiments (Figure 4). It shows that the distribution of rainfall in the model ensemble is much closer to the observation than the individual model experiments with a mean value of ~40 cm, reflecting a better representation of simulated rainfall. Unlike precipitation, the representation of the temperature is much better for all model experiments, which lies in the range of 26–30°C. The CNRM_RegCM4 and CNRM_RCA4 model experiments have presented the mean temperature value quite well but the range is not well reproduced (Figure 4), while other model experiments show slight deviation. Interestingly, the PDF curve reflects that the ensemble is much closer to CRU observation in terms of the magnitude of the mean (27.5°C) and range. Therefore, the model ensemble has

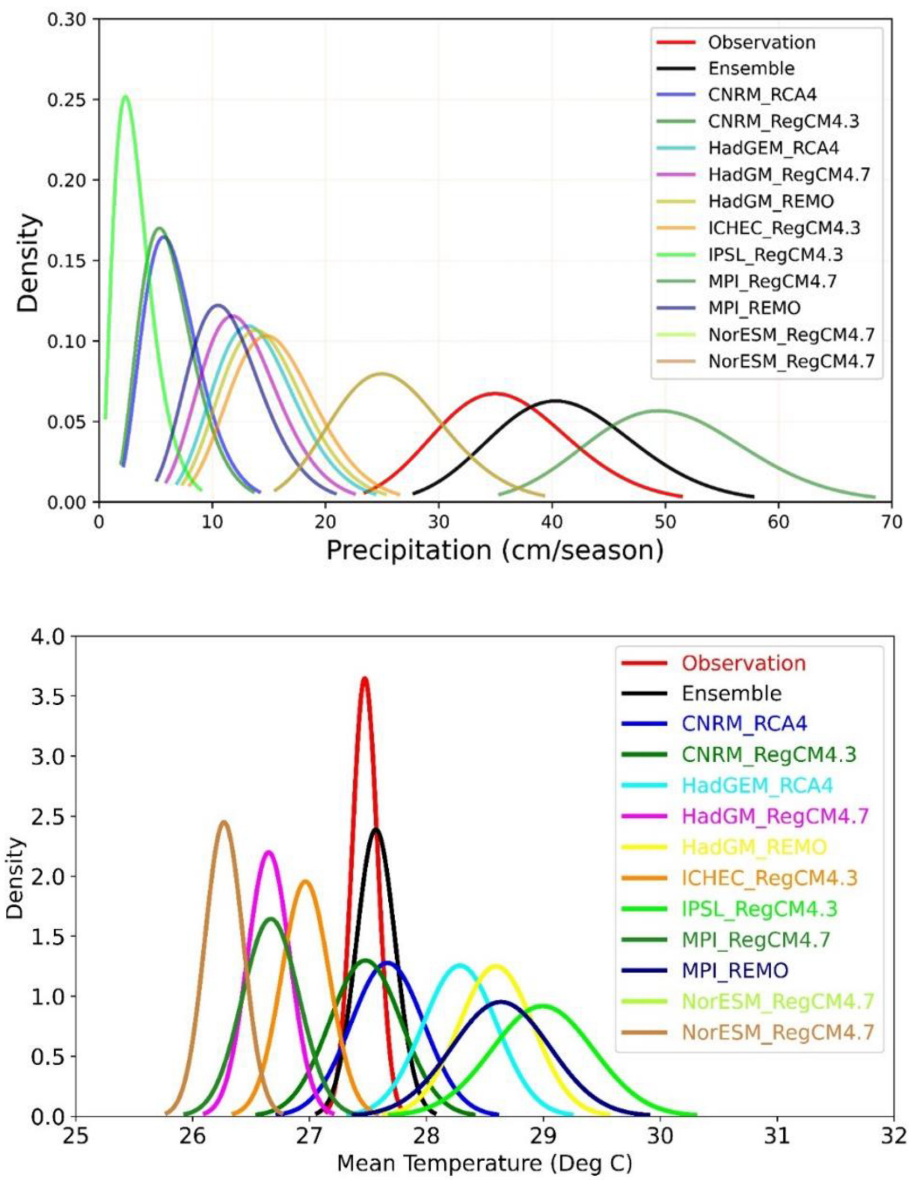

FIGURE 4 The probability density function of the daily mean seasonal rainfall (ONDJFM; upper) and temperature (lower) averaged over the Indonesia domain for Climate Research Unit observation, model experiments and their ensemble for the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

a better representation of the temperature over the study domain (Figure 4).

It is well-known that each model experiments have its own strengths and weaknesses in presenting precipitation and temperature climatology over a region. The validation process reflects that the bias range among the model experiments is not large and least in the ensemble for the historical period and hence can be considered for the study of future climate as well. The study will consider an ensemble approach from now onwards, which is the average of outputs from all the model experiments considered in the study. This will help to further reduce the individual model bias and provide the best possible representation of the projected climate. This ensemble approach has widely been used in the modelling community (Maharana, Agnihotri, & Dimri, 2021; Maharana et al., 2021; Shahi et al., 2021).

4 | CLIMATE PROJECTION OVER INDONESIA

This section describes the impact of climate change through the projected behaviour of the rainfall and temperature in two time periods/slices under different RCPs using the ensemble approach. The change in the climate parameters is estimated with respect to the historical period.

4.1 | Change in the precipitation climatology

The present analysis aims to detect climate change in the MC and EC under different RCPs (RCP2.6, RCP4.5 and RCP8.5) considered in the study. Figure S1 depicts the

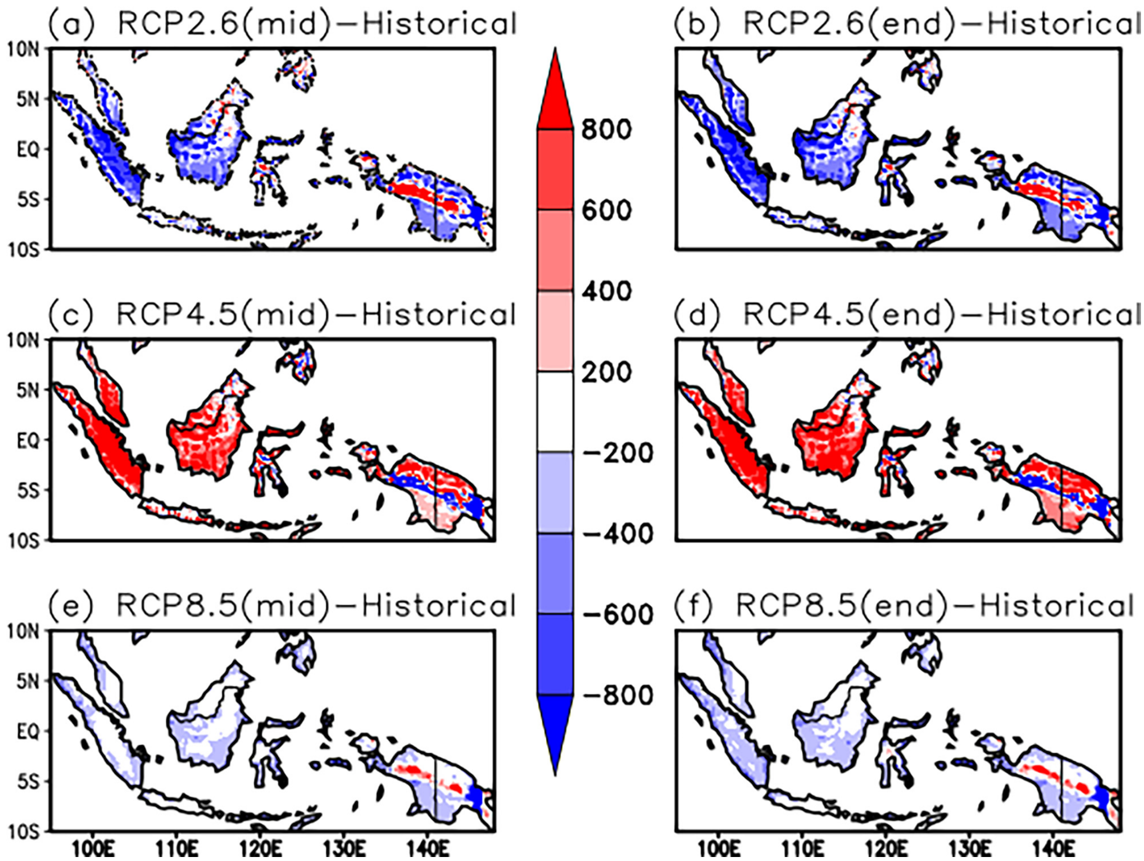

FIGURE 5 The difference of seasonal climatological cumulative rainfall (ONDJFM; mm/day) over Indonesia for the mid and end of the century under RCP2.6, RCP4.5 and RCP8.5 with respect to the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

climatological rainfall pattern during the historical period over Indonesia and its projections. The simulated historical rainfall shows high variability across Indonesia. The west coast of Sumatra Island and the mountainous areas in Papua receive precipitation of magnitude above 3500 mm/year while it ranges between 1500 and 2500 mm/year over the rest parts of Indonesia (Figure S1a). The mountainous regions experience higher rainfall than the other parts due to the orographic effect. The spatial structure of the rainfall matches quite well during MC and EC with higher rainfall over mountains in RCP2.6 (Figure S1b,c). The rainfall declines over Indonesia by 200–600 mm/season with the exception of the mountains of Papua during MC; these further decline by 400–800 mm/season at the EC (Figure 5a,b). Interestingly, the projected rainfall increases during MC and EC under RCP4.5 (Figure S1d,e). In ensemble, it rises by 600–800 mm/season with a sharp decline over the mountains (Figure 5c,d). This reflects that the increase in the GHG concentration favours rainfall across Indonesia under the RCP2.6 and RCP4.5 scenarios. Similar rainfall distribution under RCP8.5 reflects a slight decline in the rainfall during MC and EC (Figure S1f,g). The projected decline in rainfall during these periods ranges between 200 and 400 mm/season (Figure 5e,f). The rainfall is almost comparable to the historical period with minor changes in the distribution across the country. The change (declines) in the rainfall is least under RCP8.5, while it is highest (increases) under RCP4.5.

4.2 | Change in the temperature climatology

The climatological mean temperature for the historical period and the projected temperature for MC and EC under RCP2.6, RCP4.5 and RCP8.5 are analysed (Figure S2). The temperature in Indonesia is quite evenly distributed, ranging between 20 and 28°C during the historical period. Relatively higher temperatures, above 26°C are simulated on the eastern side of Sumatra island, the coast of the islands of Kalimantan and Java, and the southern part of the island of Papua (Figure S2a). The temperature is projected to rise with the increase in GHG concentration in the atmosphere. The most optimistic scenario, RCP2.6, shows a rise in temperature all across Indonesia, where it exceeds 28°C except over the highlands in the MC, with further intensification at EC (Figure S2b,c). The projected temperature rise lies

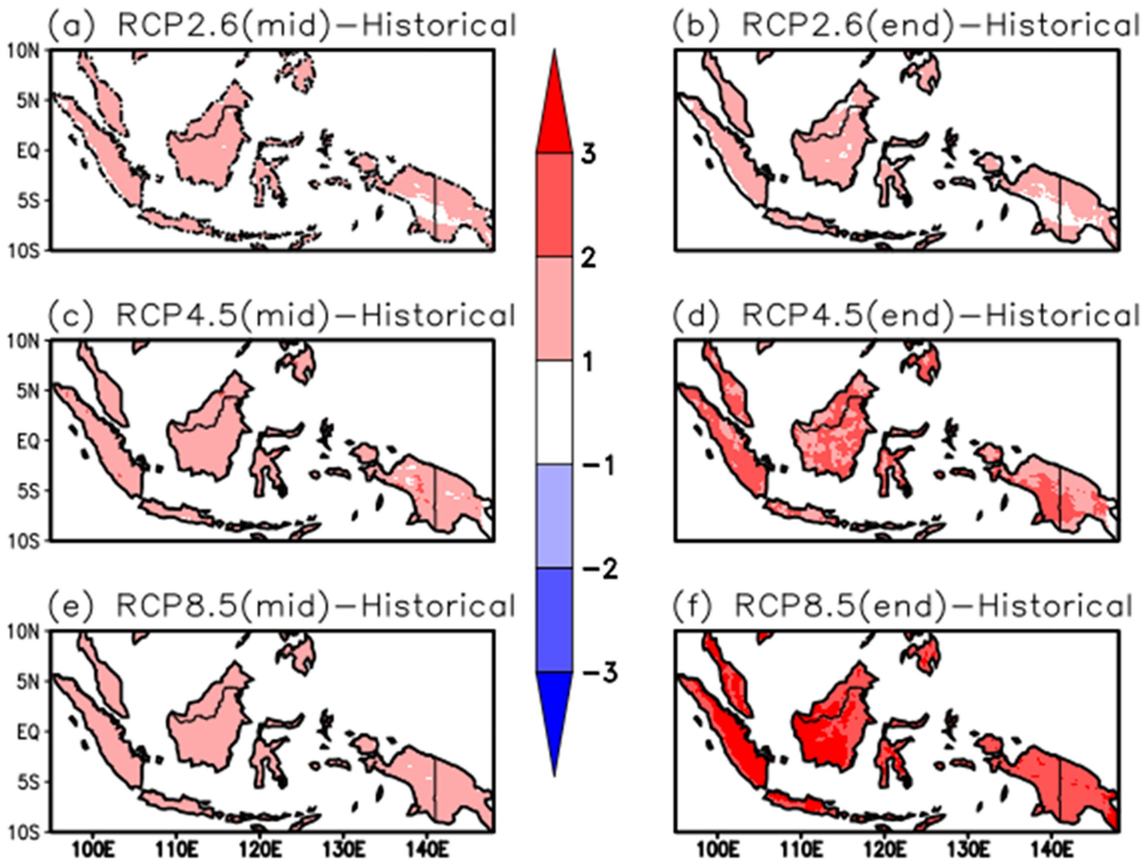

FIGURE 6 The difference of seasonal climatological temperature (ONDJFM; °C) over Indonesia for the mid and end of the century under RCP2.6, RCP4.5 and RCP8.5 with respect to the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

between 1 and 2°C for MC and EC over entire Indonesia under RCP2.6 (Figure 6a,b). The stabilization of GHG in this scenario stabilizes the temperature rise by the EC. The projected temperature shows a similar spatial distribution across the country for higher global warming scenarios as well. The projected temperature rises (>28°C) over these hotspots, and it is highest under RCP85. The temperature rise is much more intense at EC as compared to MC under these RCPs (Figure S2d–g). The projected temperature shows an escalation by 1–2°C during the MC, which further increases to 1–3°C by EC (Figure 6c,d). The rise in temperature at MC under RCP8.5 is 1–2°C (Similar to RCP4.5), while the highest temperature is projected during the EC where most parts of the country will experience a temperature increase of more than 4°C (Figure 6e,f), particularly over the islands of Sumatra, Java and Kalimantan.

4.3 | Change in the climate indices (nature of rainfall and temperature)

The climate indices are examined in this section to understand the nature and behaviour of the rainfall and temperature at MC and EC with respect to the historical period. The number of wet days (WDs), heavy rainfall days (rainfall >20 mm/day), warm spell and heatwave periods are examined for future changes.

4.3.1 | Wet days

WDs are defined as the day when the rainfall received is more than 1 mm/day. It is found that the WD varies between 100 and 350 across Indonesia during the historical period (Figure S3a). The Sumatra Island, Kalimantan and northern parts of Papua Island experience a higher number of WDs (150–350 days) with the highest over the mountains. While Java Island and the southern part of Papua Island have comparably fewer WDs (50–150). This means that the whole Indonesian region gets precipitation above 1 mm for most days of the year. Figure 7 shows that the projected WDs will decline at MC and EC under all three RCPs as compared to the historical values. It varies between 150 and 350 under RCP2.6 (Figure S3b,c) and the projected decline is highest under RCP2.6 around 50 days for both MC and EC (Figure 7a,b). The highest number

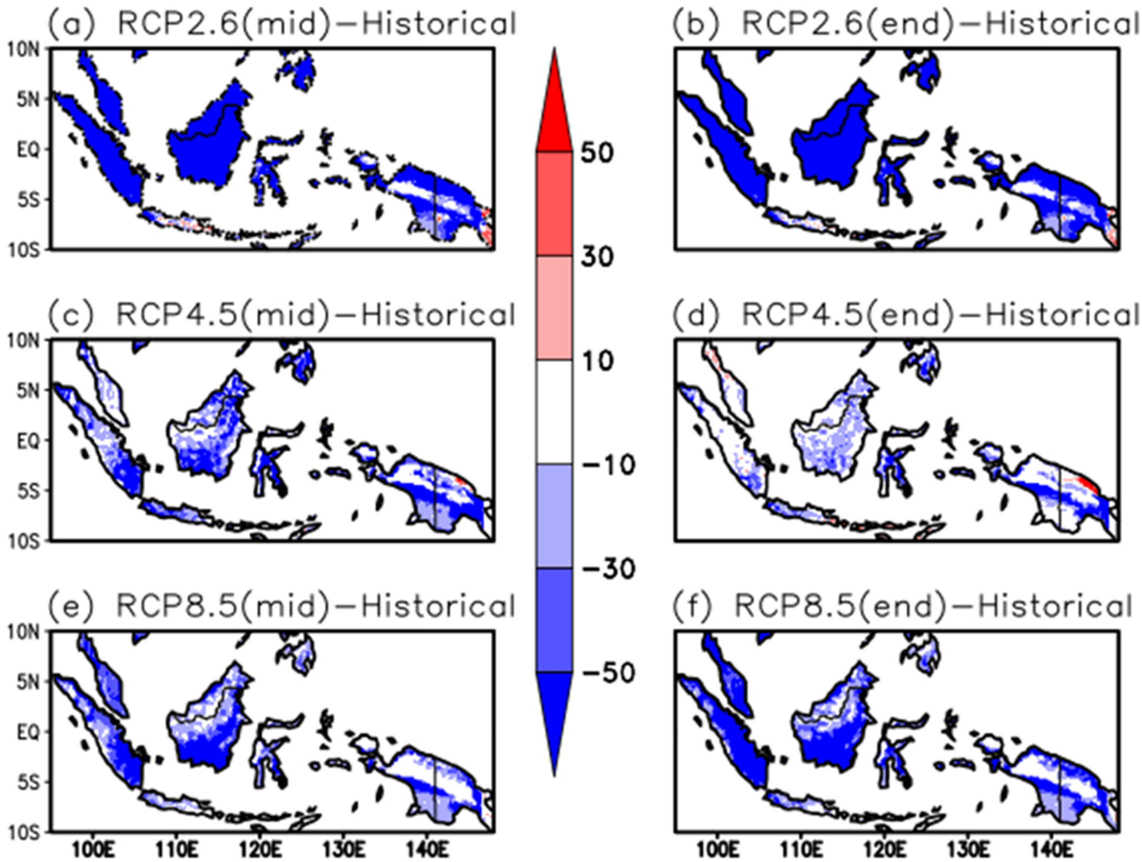

FIGURE 7 The difference in wet days per annum over Indonesia for the mid and end of the century under RCP2.6, RCP4.5 and RCP8.5 with respect to the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

of WDs are experienced in the mountain regions. The WD count further increases to more than 250 across the Indonesian landmass under RCP45 and RCP8.5 (Figure S3d–g). A similar decline in WDs by 10–30 is projected under RCP4.5 (Figure 7c,d). There has been a similar decline in projected WDs in the MC (30 days) which further decreases at the EC (50 days) under RCP8.5 with respect to the historical periods (Figure 7e,f).

4.3.2 | Heavy precipitation days (rainfall >20 mm/day)

The days where the rainfall exceeds 20 mm/day are termed as heavy precipitation days (HPD, hereafter). The spatial presentation of HPD over Indonesia is provided for the historical period and different climate projections (Figure S4). The historical data reflects that Indonesia experiences HPD in the range of 1–10 days, while highlands areas are more prone to heavy precipitation with count exceeding 50 HPD (Figure S4a). This can be attributed to the ability of RCMs to resolve the topography leading to higher rainfall (Maharana & Dimri, 2014a). The HPD is projected to increase by 5–15 days across Indonesia in MC and EC as compared to the historical period under RCP2.6 (Figure 8a,b), while the same is more than 50 across the study domain under RCP4.5 (Figure S4b–e). The HPDs are increasing in MC and EC under both scenarios (RCP2.6 and RCP4.5) with similar spatial structures. The increase of HPD is more around the highlands of Sumatra, Kalimantan and Papua. Under the RCP4.5 scenario, it is projected to increase by more than 15 days in most parts of the country (Figure 8c,d). Interestingly under RCP8.5 Scenario, there is almost no change in the HPD across the country with a slight increase over Kalimantan Island in EC (Figure 8e,f and Figure S4f,g).

A similar increase in rainfall and its extremes in RCP4.5 as compared to RCP8.5 over several places in southeast Asia (Thailand, Myanmar and Malaysia) and tropical American regions has been also reported (Bhowmick et al., 2019; Costa et al., 2022; Rahmat et al., 2022; Shrestha & Roachanakanan, 2021). The possible reason for the relatively lesser rainfall extreme under RCP8.5 may be attributed to the increasing water-holding capacity of the atmosphere following the Clausius–Clapeyron relationship.

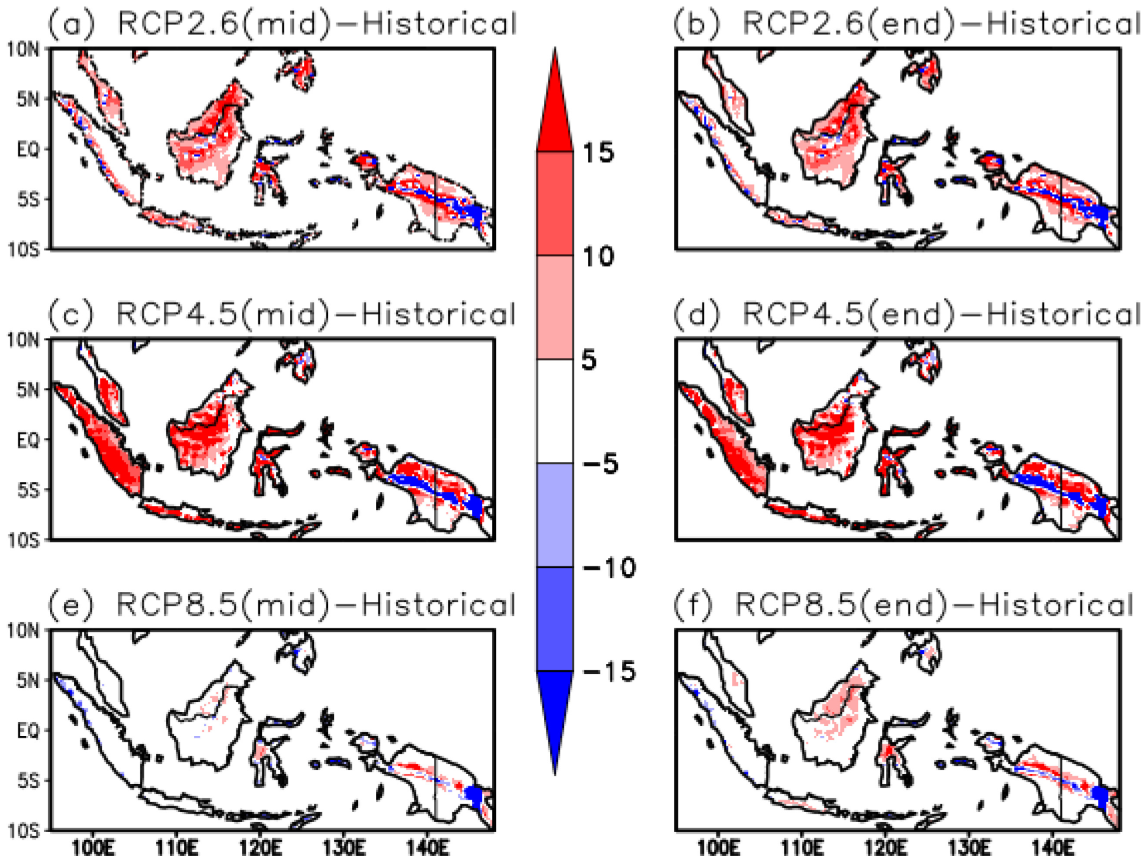

FIGURE 8 The difference of heavy precipitation days per annum (rainfall more than 20 mm/day) over Indonesia for the mid and end of the century under RCP2.6, RCP4.5 and RCP8.5 with respect to the historical period (1976–2005). [Colour figure can be viewed at wileyonlinelibrary.com]

4.3.3 | Heatwave spells

A heatwave spell is defined as the day when the daily maximum temperature of a day exceeds its climatological average by 5°C for 5 consecutive days. The spatial distribution of the number of heatwave spells per annum for different time slices and RCPs are presented (Figure 9). The historical time has no record of the heatwaves over Indonesia (Figure 9a). This can be attributed to the geographical location of the country which experiences the equatorial climate that does not fluctuate much. The global temperature rise with the increase in GHG emission has the potential to increase the number of heatwave spells, which are evident from the projected climate (Figure 9b–g). The optimistic scenario (RCP2.6), where the GHG are stabilized in the early part of the century, projects one heatwave per annum over a few parts of Indonesia in both MC and EC, mostly confined over the coastlines of Indonesia (Figure 9a,b). Under the RCP4.5 scenario, a similar rise of one heatwave spell is projected. However, these differ from RCP2.6 in terms of spatial coverage within Indonesia where the highlands are also impacted by heatwaves (Figure 9c,d). A similar pattern of increase of the heatwave spells is projected under the RCP8.5 scenario for MC. Four heatwave spells are projected at the EC over some areas on the islands of Java, Sumatra and Kalimantan. This clearly indicates that the heatwave spells are increasing in the higher warming scenarios.

4.3.4 | Warm spells

A warm spell is defined as the days when the mean temperature exceeds the 90th percentile range of the reference period for 5 consecutive days. The Indonesian regions experience 1–2 warm spells during the historical period (Figure 10a). The rising GHG concentration in the early part of RCP2.6 increases the global temperature, which is reflected as increase in 5 warm spells at MC and EC (Figure 10b,c). Furthermore, under the RCP4.5 scenario, there was a decrease in warm spells to 3–4 spells over the highlands, while other regions have more than 5 warm spells (Figure 10c). Interestingly, the warm spells are further projected to decline to 2–3 spells at EC (Figure 10d). This could be attributed to the merger of multiple warm spells into a smaller number of spells with longer duration. This leads to a decline in the number of

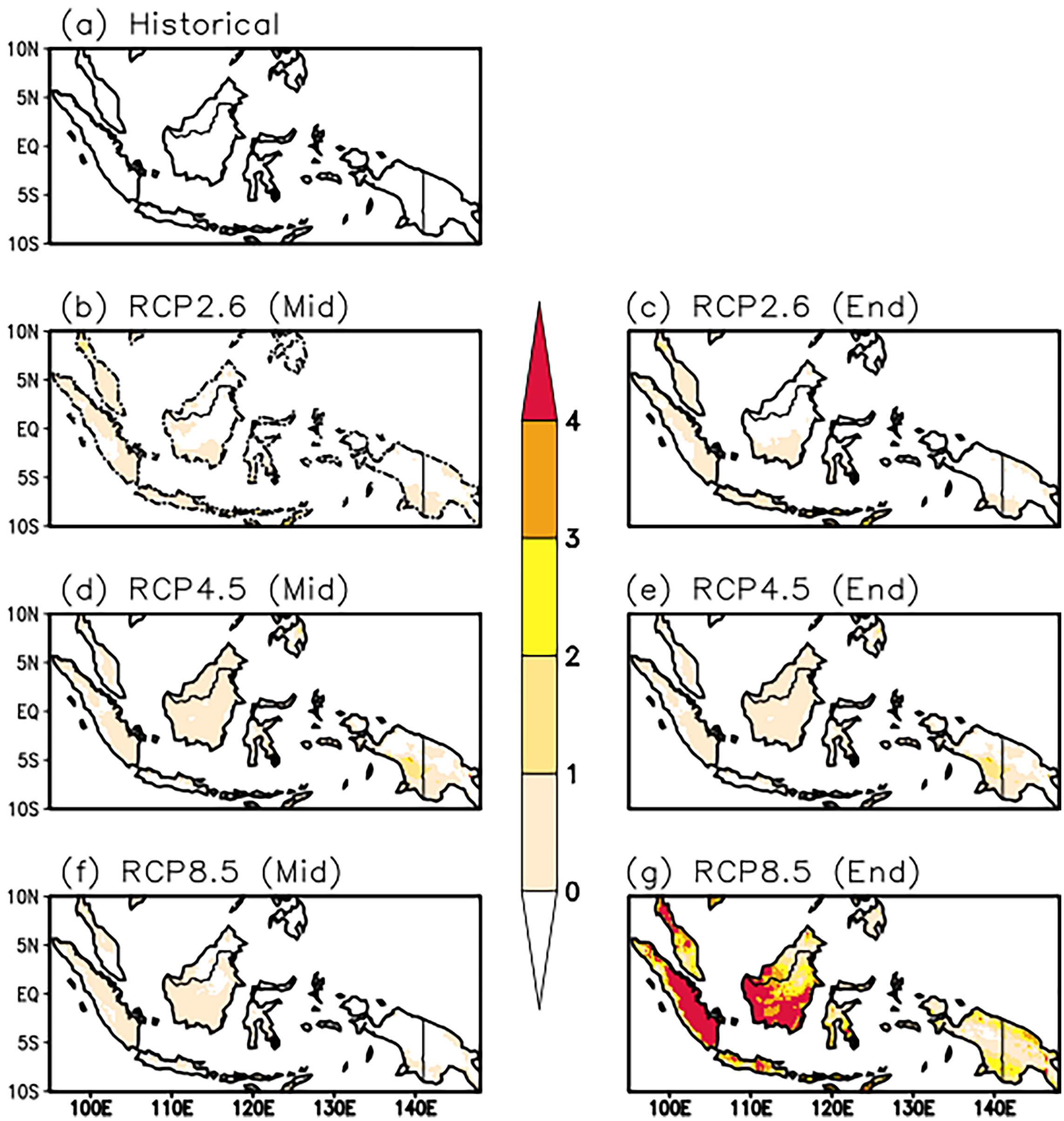

FIGURE 9 The Heatwave wave spells per annum over Indonesia for historical period (1976–2005) and the mid and end of the century under RCP2.6, RCP4.5 and RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com]

warm spells under the high-emission scenario. Similarly, under the RCP8.5 scenario, 5 warm spells in the MC reduce to 1–2 at EC.

4.4 | Impact of climate change on nutmeg production over Banda Island of Maluku Province

The Maluku province of Indonesia is well-known for producing high-quality nutmegs along with other spices. Recently, the government of Indonesia is making efforts to intensify the production of spices on Banda Island. Nutmeg production depends upon various factors such as crop factors, climate and harvested area. Therefore, there is an urgent need to develop strategies to address these factors to maintain a good yield in the future; otherwise, thousands of state revenues and farmers' livelihoods will be threatened (Rehatta et al., 2021). The impact of the climatic variables (rainfall and temperature) on the annual nutmeg production over Banda Neira Island is examined in this section. The nutmeg production along with the seasonal temperature and rainfall is presented (Figures S5 and S6). The annual nutmeg production shows variability in recent years (1980–2020) with an increase in the last decade (Figure S5). It has increased at a rate of 3.89% per year. The average production during this study period is 20,682 tonnes/year. It is observed that the production experienced a considerable

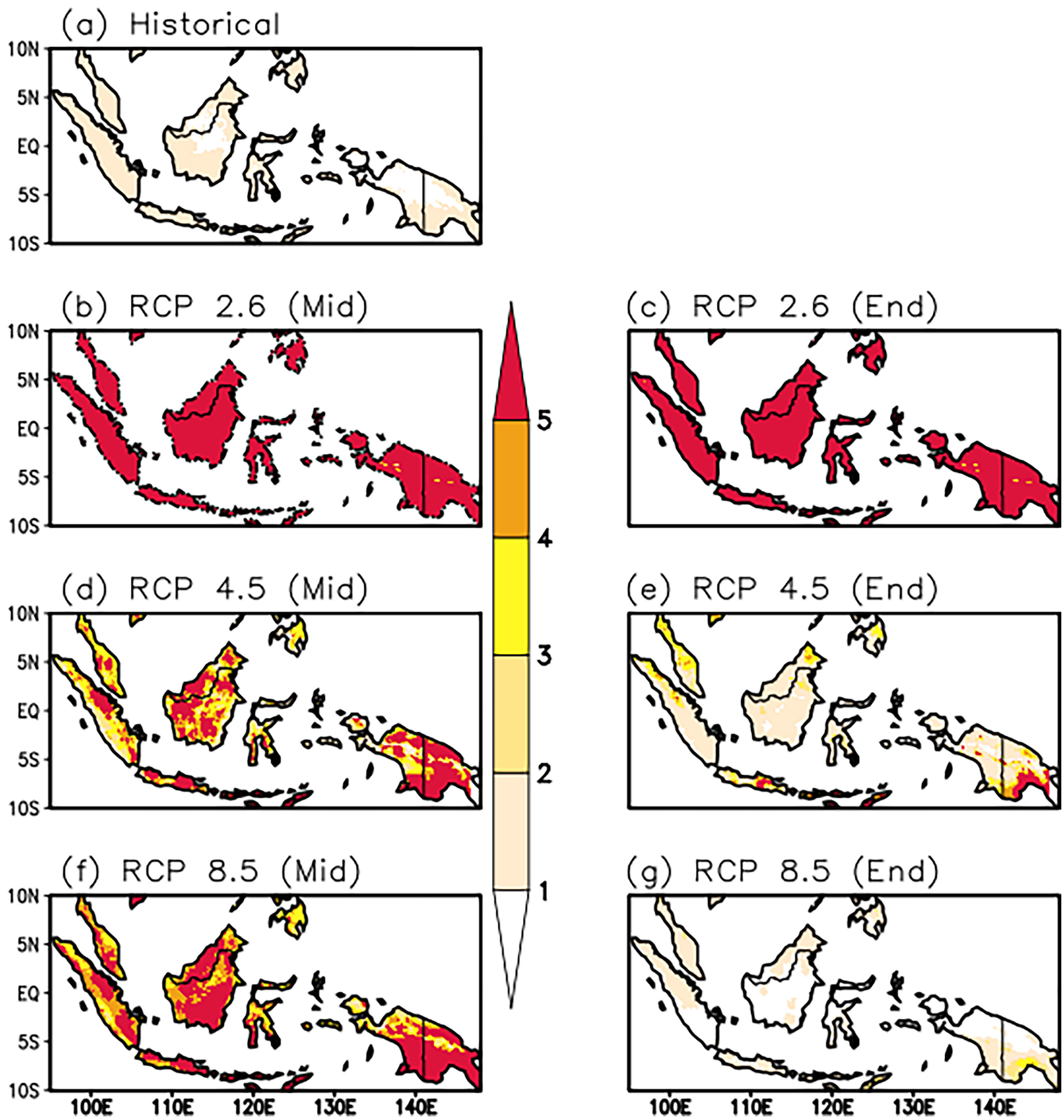

FIGURE 10 The warm spells per annum over Indonesia for the historical period (1976–2005) and mid and end of the century under RCP2.6, RCP4.5 and RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com]

decline during 2004 and 2005. A sharp rise in production is observed from 2012 to 2016, but this began to experience a decline thereafter in recent times. Among the climatic variables, the rainfall over Banda Island is not consistent and varies between 200 and 1520 mm during the period 1992–2011 (Figure S6). The highest precipitation is recorded during 2008 while a significant decline is found during 1997 and 1999. Unlike rainfall, the seasonally averaged temperature does not show much variability. The temperature ranges from 22 to 24.5°C. The less temperature variability over Indonesia can be attributed to its proximity to the equator (Figure 1).

The linear relationship of rainfall and temperature with nutmeg production is also examined using linear regression method. The following regression equations (Equation 1, Rainfall ~ Production and Equation 2, Temperature ~ Production) provide the relationship between the rainfall and temperature with the production.

$$y = 1.3775x + 15{,}240 \quad (1)$$

$$y = 4835.8x - 93{,}407 \quad (2)$$

where y is the dependent variable (production), x is the independent variable (precipitation or temperature). The regression equation (Equation 1) reflects that the behaviour of precipitation is favouring nutmeg production in recent years. Equation 2 depicts that the mean temperature has a very significant impact on production. The higher the temperature, the higher the yield, provided it lies within the range of favourable temperature. The temperature over Banda Neira Island is close to the favourable temperature required for maximum production, which is between 24 and 26°C. Therefore, production is increasing in the recent time. Further, the combined impact of rainfall and temperature on nutmeg production is examined using multiple linear regression. The model provides the relation between the dependent variable (production) with the independent climatic variables such as temperature and precipitation.

$$y = ax1 + bx2 + c \tag{3}$$

where y is the dependent variable (production), $x1$ is the independent variable 1 (precipitation), $x2$ is the independent variable 2 (temperature) and the coefficients a, b and c of the above multiple regression equation are derived using the following formula.

$$a = \left[\left(\Sigma x_2{}^2\right)(\Sigma x_1 y) - (\Sigma x_1 x_2)(\Sigma x_2 y)\right] / \left[\left(\Sigma x_1{}^2\right)\left(\Sigma x_2{}^2\right) - (\Sigma x_1 x_2)^2\right] = 0.99$$

$$b = \left[\left(\Sigma x_1{}^2\right)(\Sigma x_2 y) - (\Sigma x_1 x_2)(\Sigma x_1 y)\right] / \left[\left(\Sigma x_1{}^2\right)\left(\Sigma x_2{}^2\right) - (\Sigma x_1 x_2)^2\right] = 4804.3$$

$$c = y - a\overline{X}_1 - b\overline{X}_2 = 93{,}781$$

where 'y' is the annual nutmeg production time series, $x1$ is the annual precipitation time series, $x2$ is the annual temperature time series, $\overline{X}_1$ is the mean of the rainfall time series for the historical period and $\overline{X}_2$ is the mean of the temperature time series for the historical period.

From the derived values of the coefficients, the temperature is found to be a more dominant variable that impacts the production as compared to rainfall in influencing the production.

The nutmeg production forecast is obtained for the historical period, MC and EC under all the three RCPs considered in the study using Equation 3 (Table S1). The forecasted mean production during the historical period is 16,953.7 tonnes/year which is less than the actual value of 20,682 tonnes/year. The forecast/prediction shows a sharp rise in the mean production of the nutmeg during MC and EC with a mean production ranging from 43,911.7 (RCP2.6) to 53,404.6 (RCP8.5). However, this does not seem realistic as it is difficult to have more than 2-fold production under circumstances where the available cultivated land is not increasing being an island. Therefore, dynamically produced (simulated) temperature and rainfall pattern is further examined from the extracted data over Banda Neira Island to understand its nature under different climate change scenarios and to explain whether it supports/opposes the statistical forecast of the nutmeg production.

TABLE 2 Projected nature of rainfall pattern over Banda Island.

Periods	Wet days	Heavy rainfall events (>20 mm/day)
RCP26_Mid	234	65
RCP26_End	213	58
RCP45_Mid	67	27
RCP45_End	78	26
RCP85_Mid	201	30
RCP85_End	164	29

The projected WDs are examined for MC and EC under different RCPs (Table 2). Under RCP2.6, it varies from 213 to 234. Interestingly, this drastically declines to 67–78 and again rises to 164–201 under RCP4.5 and RCP8.5, respectively. This indicates that there is uncertainty in presenting the WDs under different RCPs. The optimum number of WDs for the best growth of nutmeg lies between 100 and 160. When the projected numbers of WDs are examined, it is found that the projected WDs are not in favour of the higher nutmeg production under any of the RCPs considered in the study. The HPDs are also projected to increase with respect to the historical period where it ranges between 1 and 10. This is projected to increase under all RCPs. Heavy rainfall events can harm plant growth.

The simulated temperature over Banda Neira Island for the historical and different periods under various RCPs are presented in a box plot (Figure 11). This reflects that the simulated mean temperature rises from 27.5°C (historical period) to 31.5°C (at the EC under RCP8.5). The projected temperature exceeds the optimal temperature range of 24–26°C under all RCPs. The analysis suggests that the nature of dynamically produced climatic parameters (simulated temperature and rainfall) will not be in favour of nutmeg production in the future over Banda Neira Island. Therefore, the forecasted values of nutmeg production through the linear regression model does not get support from the dynamically produced variable and hence the forecasted value can be rejected. The unfavourable climatic condition can impact plant growth and can decrease production (Gornall et al., 2010; Müller et al., 2021; Shikha et al., 2019; Yang et al., 2017), which cannot be accurately predicted by the linear regression model used in this study. The rising temperature escalates respiration and transpiration leading to an increase in water consumption (Kirschbaum, 2004; Urban et al., 2017) and

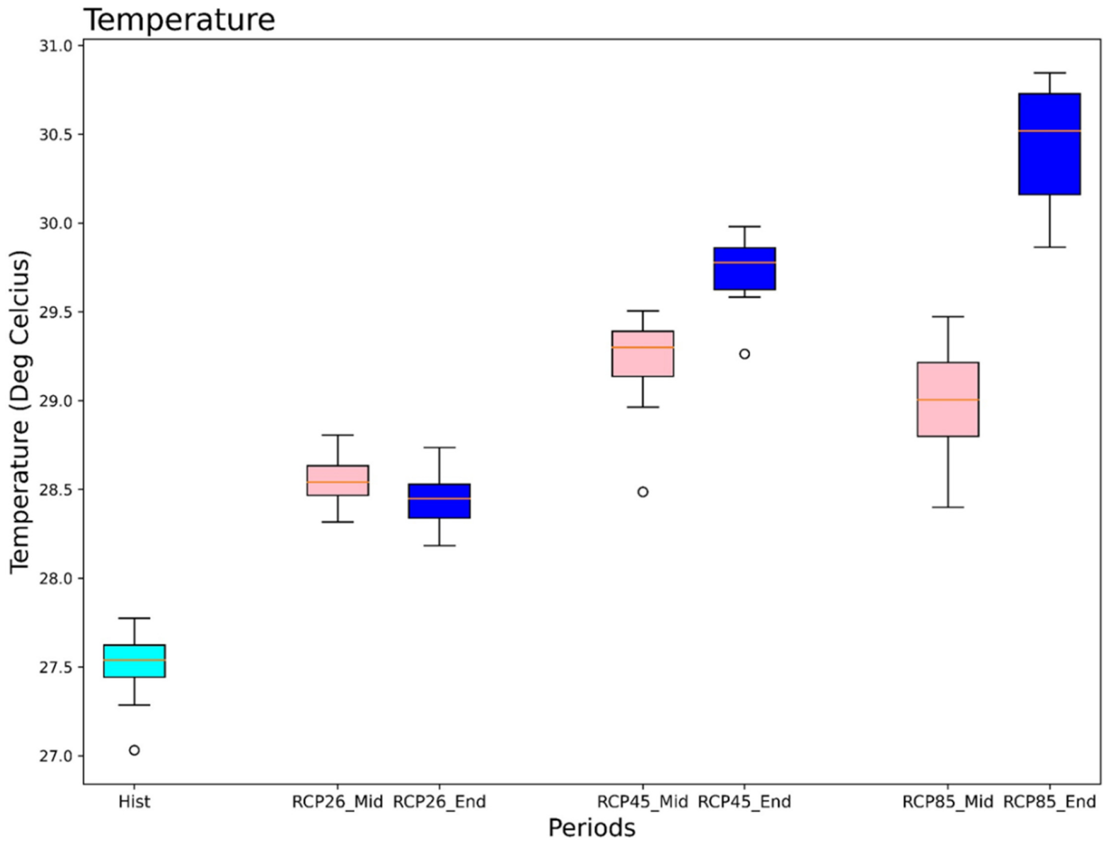

FIGURE 11 The box plot of the simulated temperature over Banda Neira island for model ensembles for historical and mid and end of the century under RCP2.6, RCP4.5 and RCP8.5. [Colour figure can be viewed at wileyonlinelibrary.com]

also accelerates the ripening of fruit and seeds, which reduces the quality of the yields.

A similar decline in projected crop production has also been found using dynamic crop models. Many studies that use dynamical crop models agree with the increasing climate uncertainty and the associated decline in projected crop production (Gornall et al., 2010; Müller et al., 2021). Müller et al. (2021) employed multiple agricultural models to examine the impact of climate change on crop yield and reported that it will result in a reduction in crop production under both CMIP5 and CMIP6 forcings. The crop yield projections are dependent upon the interplay of the temperature and CO_2 fertilization effect (Gornall et al., 2010; Shikha et al., 2019; Yang et al., 2017). Shikha et al. (2019) found that the rising temperature will be harmful to cotton production in the future. Apart from that, the rising uncertainty in the rainfall variability will make the central Indian region relatively less suitable and the northern parts of India will have a higher potential for cotton production (Shikha et al., 2022). The crop models reflect a decline in wheat crop production in China due to increasing extremes of both heat and water stress (Challinor et al., 2018; Yang et al., 2017). A similar decline in projected rice yield across various agro-climatic regions of India has also been reported (Singh et al., 2017).

5 | SUMMARY AND CONCLUSIONS

The present study examined the changing climate in Indonesia using the outputs from different high-resolution RCMs under CORDEX-CORE framework. We further seek to understand the impact of climate change on nutmeg production over Banda Neira Island, located in the Maluku province of Indonesia. Nutmeg originated in Indonesia and contributes significantly to the country's annual gross domestic product. Indonesia experiences two major seasons: the rainy period (October–March) and the dry period (April–September). Nutmeg cultivation is carried out during the rainy season, and thus our analyses focus on this season only. The study examines historical and projected climate data under three different RCPs (RCP2.6, RCP4.5 and RCP8.5) obtained from multiple GCM–RCM combinations.

The present study examines two important parameters, rainfall and temperature, for two periods under different climate change scenarios with special reference to the mean and changing nature of the parameters. Most of the model experiments are able to replicate the observed pattern of rainfall and temperature over Indonesia, while the ensemble of model experiments reproduces the pattern with the least bias. Furthermore, PDFs indicate that the distribution is better represented in the ensemble compared to the individual model experiments. Therefore, only the model ensembles are used for the climate change analysis. The distribution of rainfall shows high uncertainty in MC and EC for different RCPs with the maximum (minimum) increase projected for RCP4.5 (RCP8.5), resulting in the highest rainfall over mountainous regions. This can be attributed to the higher resolution of RCMs which better resolve the topography and represent the orographic rainfall more accurately. Projected temperatures are seen to rise from MC to EC under all RCPs, with the highest increase observed under RCP8.5.

The study also examines the impact of changing climate on nutmeg production over Banda Neira Island. The optimum temperature for the highest nutmeg production is between 25 and 26°C. While 100–160 wet days are considered ideal. A linear regression model, built using observed data from the historical period, suggests that both rainfall and temperature, individually as well as in combination, favour nutmeg production, with the temperature being the dominant factor. The model forecast predicts a significant increase in mean nutmeg production from 20,682 tonnes/year in the historical period to 53,404.6 tonnes/year by EC. The study further examines the dynamically projected climatic parameters from high-resolution climate models to understand climate suitability and to verify the accuracy of the statistical forecast. The projected temperature over Banda Neira Island is observed to be consistently increasing from the historical period (27.5°C) to its maximum during EC under RCP8.5 (31.5°C). The number of projected warm spells is increasing from the historical period (1–2) to EC under RCP2.6 (∼5) across Indonesia. Interestingly, it declines under high-emission scenarios (RCP4.5 and RCP8.5) to around 3. The decline in the count can be attributed to the merging of small-length warm periods into fewer but longer spells in the relatively warmer world. Also, the occurrence of heatwaves over certain regions of Indonesia is on a constant rise. The rise in mean temperature above 26°C, increasing warm spells and heatwaves will have a combined adverse impact on nutmeg production in the future. The study also examined the behaviour of rainfall through the projected number of WDs, which is highly uncertain under different scenarios. It is much higher during RCP2.6 (213–234) and RCP8.5 (164–201), while it declines significantly under RCP4.5 (67–78). Further, the number of projected HPDs are also clearly escalating from the historical period (1–10) to different RCPs (26–65). So overall, the projected WDs are not in favour of an increase in nutmeg production in the future, irrespective of whether it rises or decreases. The increase in HPDs will also not be suitable for nutmeg plant, which may impact the plant at a different stage of its growth by increasing the uncertainty and vulnerability. Overall, the changes in the rainfall and temperature patterns and their behaviour will have a harmful impact on nutmeg production as these climatic parameters are deviating from a suitable climate that favours high nutmeg production. It has also been documented that nutmeg production would decrease if the temperature exceeds the suitable temperature range (Indonesian ministry of Agriculture, 2016).

The changing climate greatly increases the vulnerability of the nutmeg plant, affecting production by impacting cropping patterns, planting times and the quality of the product. This situation is alarming for those engaged in the agriculture sector and for food security. Rising temperature induces a more extreme climate which ultimately reduces nutmeg production. Therefore, global GHG emissions must be curbed through strict laws and policies with proper implementation at global, regional and local levels. Global treaties like the Paris Climate Agreement, along with others, must be strongly enforced to avoid the worst scenarios.

AUTHOR CONTRIBUTIONS

Conceptualization: Pyarimohan Maharana and Nuralfin Anripa. *Methodology, software, validation, formal analysis and investigation*: Nuralfin Anripa, A. Kumar and Pyarimohan Maharana. *Writing, review and editing*: A. P. Dimri with all the authors.

ACKNOWLEDGEMENT

The authors would like to thank the WCRP and the ESGF (https://www.esgf-data.dkrz.de/projects/esgf-dkrz) for freely providing the CORDEX-CORE simulations for this research.

FUNDING INFORMATION

The authors did not receive any external funding for this work.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data will be available upon request.

ORCID

Nuralfin Anripa https://orcid.org/0000-0002-1588-3139
Pyarimohan Maharana https://orcid.org/0000-0003-3175-8714
A. P. Dimri https://orcid.org/0000-0002-7832-8669

REFERENCES

Arora, N.K. (2019) Impact of climate change on agriculture production and its sustainable solutions. *Environmental Sustainability*, 2(2), 95–96. Available from: https://doi.org/10.1007/s42398-019-00078-w

Barnwal, P. & Kotani, K. (2013) Climatic impacts across agricultural crop yield distributions: an application of quantile regression on rice crops in Andhra Pradesh, India. *Ecological Economics*, 87, 95–109. Available from: https://doi.org/10.1016/j.ecolecon.2012.11.024

Bhowmick, M., Sahany, S. & Mishra, S.K. (2019) Projected precipitation changes over the south Asian region for every 0.5°C increase in global warming. *Environmental Research Letters*, 14(5), 054005. Available from: https://doi.org/10.1088/1748-9326/ab1271

Bukovsky, M.S. & Mearns, L.O. (2020) Regional climate change projections from NA-CORDEX and their relation to climate sensitivity. *Climatic Change*, 162(2), 645–665. Available from: https://doi.org/10.1007/s10584-020-02835-x

Challinor, A.J., Müller, C., Asseng, S., Deva, C., Nicklin, K.J., Wallach, D. et al. (2018) Improving the use of crop models for risk assessment and climate change adaptation. *Agricultural Systems*, 159, 296–306. Available from: https://doi.org/10.1016/j.agsy.2017.07.010

Costa, A.A., Guimarães, S.O., Sales, D.C., das Chagas Vasconcelos, F., Junior, Marinho, M.W.S., Pereira, J.M.R. et al. (2022) Precipitation extremes over the tropical Americas under RCP4.5 and RCP8.5 climate change scenarios: results from dynamical downscaling simulations. *International Journal of Climatology*, 43, 787–803. Available from: https://doi.org/10.1002/joc.7828

D'Agostino, A.L. & Schlenker, W. (2016) Recent weather fluctuations and agricultural yields: implications for climate change. *Agricultural Economics*, 47(S1), 159–171. Available from: https://doi.org/10.1111/agec.12315

Giorgi, F. (2019) Thirty years of regional climate modeling: where are we and where are we going next? *Journal of Geophysical Research-Atmospheres*, 124(11), 5696–5723. Available from: https://doi.org/10.1029/2018JD030094

Giorgi, F., Coppola, E., Solmon, F., Mariotti, L., Sylla, M.B., Bi, X. et al. (2012) RegCM4: model description and preliminary tests over multiple CORDEX domains. *Climate Research*, 52, 7–29. Available from: https://doi.org/10.3354/cr01018

Giorgi, F. & Gutowski, W.J., Jr. (2015) Regional dynamical downscaling and the CORDEX initiative. *Annual review of environment and resources*, 40, 467–490. Available from: https://doi.org/10.1146/annurev-environ-102014-021217

Giorgi, F., Jones, C. & Asrar, G.R. (2009) Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organization (WMO) Bulletin*, 58(3), 175.

Gornall, J., Betts, R., Burke, E., Clark, R., Camp, J., Willett, K. et al. (2010) Implications of climate change for agricultural productivity in the early twenty-first century. *Philosophical Transactions of the Royal Society, B: Biological Sciences*, 365(1554), 2973–2989. Available from: https://doi.org/10.1098/rstb.2010.0158

Guntukula, R. & Goyari, P. (2020) Climate change effects on the crop yield and its variability in Telangana, India. *Studies in Microeconomics*, 8(1), 119–148. Available from: https://doi.org/10.1177/2321022220923197

Hadad, M.E.A., Randriani, E., Firman, C. & Sugandhi, T. (2006) Budidaya Tanaman Pala: Balai Penelitian Tanaman Rempah Dan Aneka Tanaman Industri, Parangkuda, pp. 1–38.

Harris, I., Osborn, T.J., Jones, P. & Lister, D. (2020) Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Scientific data*, 7(1), 109. Available from: https://doi.org/10.1038/s41597-020-0453-3

Hidup, K.L. (2004) Perubahan iklim global. Available at: http:/climatechange.menlh.go.id [Accessed on 20th April 2022].

Hunter, J.D. (2007) Matplotlib: a 2D graphics environment. *Computing in Science & Engineering*, 9(3), 90–95.

Indonesian Ministry of Agriculture. (2016). Outlook nutmeg: agricultural commodities in the plantation subsector. [Cited 2022 Aug 09]. Available from: http://epublikasi.setjen.pertanian.go.id

Iizumi, T. & Ramankutty, N. (2016) Changes in yield variability of major crops for 1981–2010 explained by climate change. *Environmental Research Letters*, 11(3), 034003. Available from: https://doi.org/10.1088/1748-9326/11/3/034003

IPCC. (2007) Climate change 2007: the scientific basis. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B. et al. (Eds.) *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, p. 946.

IPCC. (2013) Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. et al. (Eds.) *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, p. 1535.

Juroszek, P. & von Tiedemann, A. (2011) Potential strategies and future requirements for plant disease management under a changing climate. *Plant Pathology*, 60(1), 100–112. Available from: https://doi.org/10.1111/j.1365-3059.2010.02410.x

Kirschbaum, M.U.F. (2004) Direct and indirect climate change effects on photosynthesis and transpiration. *Plant Biology*, 6(3), 242–253.

Konduri, V.S., Vandal, T.J., Ganguly, S. & Ganguly, A.R. (2020) Data science for weather impacts on crop yield. *Frontiers in Sustainable Food Systems*, 4, 52. Available from: https://doi.org/10.3389/fsufs.2020.00052

Lesk, C., Rowhani, P. & Ramankutty, N. (2016) Influence of extreme weather disasters on global crop production. *Nature*, 529(7584), 84–87. Available from: https://doi.org/10.1038/nature16467

Lobell, D.B. & Field, C.B. (2007) Global scale climate-crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, 2(1), 014002. Available from: https://doi.org/10.1088/1748-9326/2/1/014002

Luttge, U. & Pitman, M.G. (Eds). (2011) Transport in Plants II, Part A, Cells. In: *Encyclopedia of Plant physiology*, New Series, Vol 2. Berlin: Springer-Verlag, pp. 284-316.

Maharana, P., Agnihotri, R. & Dimri, A.P. (2021) Changing Indian monsoon rainfall patterns under the recent warming period

2001–2018. *Climate Dynamics*, 57(9), 2581–2593. Available from: https://doi.org/10.1007/s00382-021-05823-8
Maharana, P. & Dimri, A.P. (2014a) Impact of initial and boundary conditions on regional winter climate over the Western Himalayas: a fixed domain size experiment. *Global and Planetary Change*, 114, 1–13. Available from: https://doi.org/10.1016/j.gloplacha.2013.12.011
Maharana, P. & Dimri, A.P. (2014b) Study of seasonal climatology and interannual variability over India and its subregions using a regional climate model (RegCM3). *Journal of Earth System Science*, 123(5), 1147–1169. Available from: https://doi.org/10.1007/s12040-014-0447-7
Maharana, P. & Dimri, A.P. (2016) Study of intraseasonal variability of Indian summer monsoon using a regional climate model. *Climate Dynamics*, 46(3), 1043–1064. Available from: https://doi.org/10.1007/s00382-015-2631-0
Maharana, P., Kumar, D., Das, S. & Tiwari, P.R. (2021) Present and future changes in precipitation characteristics during Indian summer monsoon in CORDEX-CORE simulations. *International Journal of Climatology*, 41(3), 2137–2153. Available from: https://doi.org/10.1002/joc.6951
Miao, C., Su, L., Sun, Q. & Duan, Q. (2016) A nonstationary bias-correction technique to remove bias in GCM simulations. *Journal of Geophysical Research-Atmospheres*, 121(10), 5718–5735. Available from: https://doi.org/10.1002/2015JD024159
Mohammed, K., Islam, A.S., Islam, G.M.T., Alfieri, L., Bala, S.K. & Khan, M.J.U. (2017) Extreme flows and water availability of the Brahmaputra River under 1.5 and 2°C global warming scenarios. *Climate Change*, 145(1–2), 159–175. Available from: https://doi.org/10.1007/s10584-017-2073-2
Müller, C., Franke, J., Jägermeyr, J., Ruane, A.C., Elliott, J., Moyer, E. et al. (2021) Exploring uncertainties in global crop yield projections in a large ensemble of crop models and CMIP5 and CMIP6 climate scenarios. *Environmental Research Letters*, 16(3), 034040. Available from: https://doi.org/10.1088/1748-9326/abd8fc
Nabat, P., Somot, S., Mallet, M., Sevault, F., Chiacchio, M. & Wild, M. (2015) Direct and semi-direct aerosol radiative effect on the Mediterranean climate variability using a coupled regional climate system model. *Climate Dynamics*, 44(3), 1127–1155. Available from: https://doi.org/10.1007/s00382-014-2205-6
Nagavciuc, V., Ionita, M., Perşoiu, A., Popa, I., Loader, N.J. & McCarroll, D. (2019) Stable oxygen isotopes in Romanian oak tree rings record summer droughts and associated large-scale circulation patterns over Europe. *Climate Dynamics*, 52(11), 6557–6568. Available from: https://doi.org/10.1007/s00382-018-4530-7
Nurdjannah, N. (2007) *Teknologi pengolahan pala*. Badan Penelitian Dan Pengembangan Pertanian. Balai Besar Penelitian Dan Pengembangan Pascapanen Pertanian, Badan, Penelitian dan Pengembangan Pertanian, Departemen Pertanian. pp. 1–54. Available from: http://pascapanen.litbang.pertanian.go.id/assets/buku_teknologi/juknis_pala.pdf
Oerke, E.C. (2006) Crop losses to pests. *The Journal of Agricultural Science*, 144(1), 31–43. Available from: https://doi.org/10.1017/S0021859605005708
Putra, I.D.G.A., Rosid, M.S., Sopaheluwakan, A. & Sianturi, Y.C.U. (2020) The CMIP5 projection of extreme climate indices in Indonesia using simple quantile mapping method. In: Wardana, A.N.I., Purwono, S., & Liem, P.H., (Eds.) *AIP Conference Proceedings*, Vol. 2223, 1. Yogyakarta, Indonesia: AIP Publishing, p. 050008. Available from: https://doi.org/10.1063/5.0000849
Rahmat, S.N., Hamid, H., Tukimat, N.N.A., Khastagir, A. & Al-Gheethi, A. (2022) Impacts of climate change on rainfall trends under RCP scenarios in Johor, Malaysia. *International Journal of Integrated Engineering*, 14(5), 272–280. Available from: https://doi.org/10.21203/rs.3.rs-673266/v1
Rai, P.K., Singh, G.P. & Dash, S.K. (2020) Projected changes in extreme precipitation events over various subdivisions of India using RegCM4. *Climate Dynamics*, 54(1), 247–272. Available from: https://doi.org/10.1007/s00382-019-04997-6
Rao, K.K., Patwardhan, S.K., Kulkarni, A., Kamala, K., Sabade, S. S. & Kumar, K.K. (2014) Projected changes in mean and extreme precipitation indices over India using PRECIS. *Global and Planetary Change*, 113, 77–90. Available from: https://doi.org/10.1016/j.gloplacha.2013.12.006
Ratna, S.B., Ratnam, J.V., Behera, S.K., Tangang, F.T. & Yamagata, T. (2017) Validation of the WRF regional climate model over the subregions of Southeast Asia: climatology and interannual variability. *Climate Research*, 71(3), 263–280. Available from: https://doi.org/10.3354/cr01445
Rehatta, H., Leatemia, J.A. & Laimeheriwa, S. (2021) The impact of climate variables on nutmeg (Mirystica fragrans HOUTT) production in Saparua Island, Central Maluku Regency. In: *IOP Conference Series: Earth and Environmental Science, International Conference on Small Islands Community: Momentum of Transformation of Small Islands Community in New Normal Era 12th December 2020*, Vol. 797. Maluku, Indonesia: IOP Publishing, p. 012025. Available from: https://doi.org/10.1088/1755-1315/797/1/012025
Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G. et al. (2011) RCP 8.5—a scenario of comparatively high greenhouse gas emissions. *Climatic Change*, 109(1), 33–57. Available from: https://doi.org/10.1007/s10584-011-0149-y
Schewe, J., Levermann, A. & Meinshausen, M. (2011) Climate change under a scenario near 1.5°C of global warming: monsoon intensification, ocean warming and steric sea level rise. *Earth System Dynamics*, 2(1), 25–35. Available from: https://doi.org/10.5194/esd-2-25-2011
Schleussner, C.F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E.M. et al. (2016) Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change*, 6(9), 827–835. Available from: https://doi.org/10.1038/nclimate3096
Shahi, N.K., Das, S., Ghosh, S., Maharana, P. & Rai, S. (2021) Projected changes in the mean and intra-seasonal variability of the Indian summer monsoon in the RegCM CORDEX-CORE simulations under higher warming conditions. *Climate Dynamics*, 57(5), 1489–1506. Available from: https://doi.org/10.1007/s00382-021-05771-3
Shikha, A., Dimri, A.P., Singh, K.K., Maharana, P. & Mina, U. (2022) Risk assessment and adaptation strategies for irrigated and rainfed cotton crop production under climate change. *Journal of Earth System Science*, 131(4), 267. Available from: https://doi.org/10.1007/s12040-022-01995-x
Shikha, A., Maharana, P., Singh, K.K., Dimri, A.P. & Niwas, R. (2018) Cotton crop in changing climate. *Current Science*,

115(5), 948–954. Available from: https://doi.org/10.18520/cs/v115/i5/948-954
Shikha, A., Singh, K.K., Dimri, A.P., Niwas, R. & Maharana, P. (2019) Model-based approach to study the response of Bt-cotton towards elevated temperature and carbon dioxide in the semi-arid region of Hisar. *Journal of Climate Change*, 5(2), 35–50. Available from: https://doi.org/10.3233/JCC190011
Shrestha, S. & Roachanakanan, R. (2021) Extreme climate projections under representative concentration pathways in the Lower Songkhram River Basin, Thailand. *Heliyon*, 7(2), e06146. Available from: https://doi.org/10.1016/j.heliyon.2021.e06146
Singh, P.K., Singh, K.K., Bhan, S.C., Baxla, A.K., Singh, S., Rathore, L.S. et al. (2017) Impact of projected climate change on rice (*Oryza sativa* L.) yield using CERES-rice model in different agroclimatic zones of India. *Current Science*, 112, 108–115. Available from: https://doi.org/10.18520/cs/v112/i01/108-115
Stevanović, M., Popp, A., Lotze-Campen, H., Dietrich, J.P., Müller, C., Bonsch, M. et al. (2016) The impact of high-end climate change on agricultural welfare. *Science Advances*, 2(8), e1501452. Available from: https://doi.org/10.1126/sciadv.1501452
Thomson, A.M., Calvin, K.V., Smith, S.J., Kyle, G.P., Volke, A., Patel, P. et al. (2011) RCP4.5: a pathway for stabilization of radiative forcing by 2100. *Climatic Change*, 109(1), 77–94. Available from: https://doi.org/10.1007/s10584-011-0151-4
Trenberth, K.E., Dai, A., Rasmussen, R.M. & Parsons, D.B. (2003) The changing character of precipitation. *Bulletin of the American Meteorological Society*, 84(9), 1205–1218. Available from: https://doi.org/10.1175/BAMS-84-9-1205
UNFCCC. (1992) *United Nations framework convention on climate change*. New York: United Nations, General Assembly, pp. 1–25 Available from: https://unfccc.int/resource/docs/convkp/conveng.pdf
Urban, J., Ingwers, M., McGuire, M.A. & Teskey, R.O. (2017) Stomatal conductance increases with rising temperature. *Plant Signaling & Behavior*, 12(8), e1356534.
van Vuuren, D.P., Stehfest, E., den Elzen, M.G., Kram, T., van Vliet, J., Deetman, S. et al. (2011) RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change*, 109(1), 95–116. Available from: https://doi.org/10.1007/s10584-011-0152-3
Wang, J., Yang, B.A.O., Ljungqvist, F.C. & Zhao, Y.A.N. (2013) The relationship between the Atlantic multidecadal oscillation and temperature variability in China during the last millennium. *Journal of Quaternary Science*, 28(7), 653–658. Available from: https://doi.org/10.1002/jqs.2658
Weedon, G.P., Balsamo, G., Bellouin, N., Gomes, S., Best, M.J. & Viterbo, P. (2014) The WFDEI meteorological forcing data set: WATCH forcing data methodology applied to ERA-Interim reanalysis data. *Water Resources Research*, 50(9), 7505–7514. Available from: https://doi.org/10.1002/2014WR015638
Wing, I.S., De Cian, E. & Mistry, M.N. (2021) Global vulnerability of crop yields to climate change. *Journal of Environmental Economics and Management*, 109, 102462. Available from: https://doi.org/10.1016/j.jeem.2021.102462
Yang, X., Tian, Z., Sun, L., Chen, B., Tubiello, F.N. & Xu, Y. (2017) The impacts of increased heat stress events on wheat yield under climate change in China. *Climatic Change*, 140, 605–620. Available from: https://doi.org/10.1007/s10584-016-1866-z
Yao, T., Yang, X., Xu, B., Zhao, H., Li, J., Li, Z. et al. (2017) Warming and wetting climate during last century revealed by an ice core in northwest Tibetan Plateau. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 487, 270–277. Available from: https://doi.org/10.1016/j.palaeo.2017.09.009
Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D.B., Huang, Y. et al. (2017) Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, 114(35), 9326–9331. Available from: https://doi.org/10.1073/pnas.1701762114

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Anripa, N., Kumar, A., Maharana, P., & Dimri, A. P. (2023). Climate change over Indonesia and its impact on nutmeg production: An analysis under high-resolution CORDEX-CORE regional simulation framework. *International Journal of Climatology*, *43*(10), 4472–4490. https://doi.org/10.1002/joc.8098