https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Review article: Past and future climate-related hazards in Indonesia

Vempi Satriya Adi Hendrawan[1], Adam Pamudji Rahardjo[1], Hanggar Ganara Mawandha[2], Edvin Aldrian[3], Abdul Muhari[4], Daisuke Komori[5,6]

[1] Department of Civil and Environmental Engineering, Universitas Gadjah Mada, Yogyakarta 55284, Indonesia
[2] Department of Agricultural Engineering and Biosystem, Universitas Gadjah Mada, Yogyakarta 55281, Indonesia
[3] Agency for Research and Innovation BRIN, Jakarta 153143, Indonesia
[4] National Disaster Management Authority, Jakarta 13120, Indonesia
[5] Green Goals Initiative, Tohoku University, Sendai 980–8572, Japan
[6] Graduate School of Environmental Studies, Tohoku University, Sendai 980–8579, Japan

Correspondence to: Vempi Satriya Adi Hendrawan (vempi@ugm.ac.id)

Abstract. Indonesia, one of the most populous countries, ranked fifth globally for climate-related hazards and disasters in the past five years. This study aims to assess historical trends, future projections, and potential implications of climate-related hazards in Indonesia. We synthesize literature, analyze historical datasets, and examine CMIP projections to assess the trend of extreme climate events and their potential effects on climate hazards. Results show that current records and studies predominantly highlight floods as the most common hazard in the tropical–humid region, followed by landslides, droughts, extreme weather, and wildfires. Historical evidence indicates an increasing threat of flood by intensifying amplitude and frequency of rainfall extremes by around 25%, especially in most northern parts of Indonesia (Kalimantan, northern Sumatera, parts of Sulawesi, and Papua), while the drought amplified by 60% over the country across the dry regions from southern Sumatera, Java to Nusa Tenggara. These trends are projected to persist under future climate scenarios (SSPs or RCPs). We found that urban factors like land subsidence and landuse change, particularly in cities like Jakarta, may worsen flood impacts in the future. Future studies should also examine rainfall-induced landslides and flash floods in other vulnerable areas, such as steep areas. Additionally, drought, often overlooked in this country, requires comprehensive research given its unique slow onset and its agricultural and societal effects. Global teleconnection mechanisms (ENSO, IOD, MJO) have intensified wet and dry hazards in recent decades and must be considered. A more integrated approach, combining cascading process models, impact assessments, early warning systems, and adaptive land-use practices, is essential to enhance resilience against climate hazards in Indonesia.

1 Introduction

Natural hazards have induced unprecedented levels of damage and loss of life over the years. The scale of losses from typical weather– and climate-related hazards and disasters has intensified over recent decades (IPCC, 2012). Between 2000 and 2023, approximately 1.42 million people lost their lives, and global financial losses exceeded at least USD 107 billion per year.

Disaster-related fatalities and economic losses as a proportion of GDP, in fact, tend to be higher in emerging economies (Botzen et al., 2019; McGlade et al., 2019). Over the past two decades, 90% of disaster deaths occurred in low– and middle–income countries (Chapagain et al., 2022; CRED, 2018). On the other hand, the rising trend in losses and damages over time could partly be due to improved reporting (De Groeve et al., 2013). Other key factors include increased exposure from population growth and higher assets at risk (IPCC, 2007; Peduzzi et al., 2009) and the growing impact of extreme weather and climate changes linked to human-induced climate change (Alexander et al., 2006; Donat et al., 2013; Seneviratne et al., 2012).

Since around 1950, an increase in extreme weather and climate hazards have been linked to human-driven climate change (IPCC, 2007, 2023), which is often associated with the rising impacts of climate-related disasters (Easterling et al., 2016; Huggel et al., 2013). A recent study estimates that climate change-related extreme events cost an additional USD 143 billion annually, with 63% of this attributed to human fatalities (Newman and Noy, 2023). With climate change, there is rising concern that economic and other forms of losses will continue to increase. Several global initiatives, including the Sendai Framework for Disaster Risk Reduction (2015–2030) (UNISDR, 2015), the Sustainable Development Goals, and the Paris Agreement on Climate Change have proposed the interconnectedness of disaster reduction, sustainable development, and climate action. Since disasters have repeatedly undermined poverty reduction efforts, particularly in developing nations, these countries are likely to experience the greatest impact from increasing climate-related risks (Formetta and Feyen, 2019; Huggel et al., 2013). Therefore, the latest framework emphasizes the need for coordinated policies and actions to mitigate disaster risks.

Disaster risk is a multifaceted concept that encompasses three key components (Hendrawan et al., 2023b; IPCC, 2007): i) hazard, which refers to natural events that can lead to loss of life, health impacts, property damage, and environmental degradation; ii) exposure, which includes human, economic, or environmental assets in hazard-prone areas; and iii) vulnerability, which is the degree to which people, assets, and the environment are susceptible to the effects of hazards (UNISDR, 2015). Disaster is the actual adverse outcome that occurs when the hazard interacts with exposed and vulnerable people or assets, leading to significant loss or damage. The difference lies in the hazard being the potential threat and the disaster being the realized consequence of that threat (Cutter, 2021). Research on hazard and disaster risks has expanded significantly worldwide, emphasizing the need for a regular synthesis of trends, challenges, and innovative approaches to disaster management, particularly in relation to climate and global changes, to ensure that vulnerable regions are not left behind (Aitsi-Selmi et al., 2015).

Indonesia, located on the Pacific Ring of Fire and at the intersection of three major tectonic plates, is particularly vulnerable to a wide range of natural hazards, including volcanic eruptions, earthquakes, and tsunamis (Kryspin-Watson et al., 2020). Additionally, climate-related hazards such as flooding, landslides, and droughts pose significant threats. The annual monsoon season brings frequent weather-related hazards, with large parts of the country affected each year (Djalante, 2018; Giannini et al., 2007). On the other hand, during Indonesia's dry season from May to October, around 18.8 million people were severely affected by drought-related events. It placed the country first among the top 10 most drought-impacted globally and ranked second globally in 2023 for disaster risk, following the Philippines (Auer Frege et al., 2023). Indonesia is also currently the

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

world's fourth most populous country. Between 2019 and 2023, approximately 6.6 million people were impacted by climatic hazards, including floods (68% of affected individuals), droughts (31%), and other extreme weather events (Indonesia Disaster Data and Information, 2024a), since Indonesia was the fifth in the number of recorded climate-related disaster events during the period, after the US, China, India, and the Philippines (EM-DAT: The Emergency Events Database).

Moreover, the ongoing urbanization and unmanaged land use change have been prominent factors increasing exposure and vulnerability of the country to disasters. As of 2022, almost 58% of Indonesia's population resides in urban areas, which are highly vulnerable to disaster threats. This figure is projected to rise to more than 70% by 2045 (Roberts et al., 2019). For instance, in the Greater Jakarta Area, excessive land use conversion and groundwater extraction have worsened flood risks since the area is crossed by 13 rivers and faces frequent riverbank overflow during the monsoon season. Rapid urban growth, inadequate drainage systems, and unregulated land use have all contributed to the city's increased vulnerability to floods (Budiyono et al., 2016; Januriyadi et al., 2018). A study analyzing inland water flooding in the suburban city of Tangerang found that while 71% of flooding cases were explained by topographical conditions, 29% were influenced by human activities, reinforcing the role of urban development in flood risk exacerbation (Djamres et al., 2021). These facts underscore the urgent need for effective disaster risk reduction strategies in Indonesia.

This paper presents the latest understanding of climate change and its influence on hazards that can trigger natural disasters in Indonesia. In addition to reviewing scientific literature on how climate change affects the risk of climate-related hazards in the region, this study draws on historical datasets and the latest projections from the Intergovernmental Panel on Climate Change (IPCC), particularly those based on studies using the current Coupled Model Intercomparison Project (CMIP) (IPCC, 2022). Our focus is on extreme climate events related to precipitation and temperature anomalies and their implications, including floods, droughts, extreme temperatures, storms, wildfires, and wet mass movements (i.e., landslides). Understanding climate hazards is crucial for proactive risk management, as disaster characteristics remain highly dynamic and unpredictable over time (Cutter, 2021).

Therefore, the objectives of this study are to (1) synthesize findings on climate hazards and their trends in Indonesia based on previous studies and reports, (2) assess past climate-related hazards and disaster events, (3) examine trends in climate change–induced hazards, and (4) delineate key climate hazards and identify regions likely to be exposed in the future to guide mitigation and adaptation efforts. The findings of this study contribute to climate risk assessment, disaster preparedness, and policymaking in Indonesia. By identifying trends and potential impacts, this research supports the development of effective mitigation and adaptation strategies to enhance resilience against climate hazards.

2 Method

2.1 Literature review

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

In this study, we review current studies focusing on historical trends and climate change projection or modeling and its effect on natural hazards, especially hydro-meteorological hazards. First, for literature reviews, we adopted a protocol introduced by (Moher et al., 2009), which is basically used to analyze literature systematically. The methodology includes several steps and processes, illustrated in Fig. 1. Scopus was selected as the database because of its wide range of publications on construction materials with a period limit of up to 5 November 2024. The systematic search query used was as follows: ("climate change" OR "global warming" OR "climate model") AND ("CMIP" OR "CMIP5" OR "CMIP6") AND ("natural disaster" OR "disaster") AND ("hydrometeorology" OR "hydro–meteorology" OR "precipitation" OR "rainfall" OR "rain" OR "water") AND ("impact" OR "loss" OR "losses" OR "damage" OR "risk" OR "hazard" OR "vulnerability" OR "capacity" OR "exposure") AND TITLE–ABS–KEY(Indonesia) AND (LIMIT–TO (LANGUAGE, “English"))

After identification through a search with the above query, the selection processes were conducted comprising two stages: 1) screening and 2) eligibility. First, titles and abstracts were reviewed to exclude obviously irrelevant studies. The search yielded 93 papers published with no duplicates. Then we screened titles and abstracts for relevance, which led to the exclusion of 25 papers, then the total number of papers passing this screening was 68 papers. Afterward, the remaining articles underwent a full–text review to determine their eligibility regarding the discussion inclusion based on the hazard types defined here (Table 1). This full–text review led to the exclusion of almost half of the previously sorted papers; thus, the final collection comprised 35 papers.

Then, we classified papers based on disaster topics based on EM–DAT (Emergency Events Database), as shown in Table 1 (EM-DAT: The Emergency Events Database). Figure 1 illustrates the relationship between various weather and climate hazard triggers or climatic extreme events as well as their associated impacts, highlighting the role of climate change in amplifying or mitigating these hazards. The climate drivers include extreme dry conditions, extreme temperature, extreme wind, and extreme precipitation, each leading to specific hazards, namely drought, wildfires, storm surges, river floods, and landslides. Notably, extreme precipitation contributes to both river flooding and rapid–onset events like flash floods and debris flows. In terms of classification based on EMDAT, floods and wet mass movements (i.e., landslides) are classified as hydrological disasters caused by water movement. Storm surges and storms are both hydrological and meteorological, as they arise from atmospheric conditions like high winds, heavy rainfall, and sea level changes, often linked to severe weather systems. Droughts and wildfires are climatological disasters driven by prolonged dry conditions or weather anomalies. Here, we include the studies concerning more about the weather and climate hazard triggers which are mainly rooted in temperature and rainfall extremes as the most common climatic impact driver (CID) in the current climate change assessment (IPCC, 2023).

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

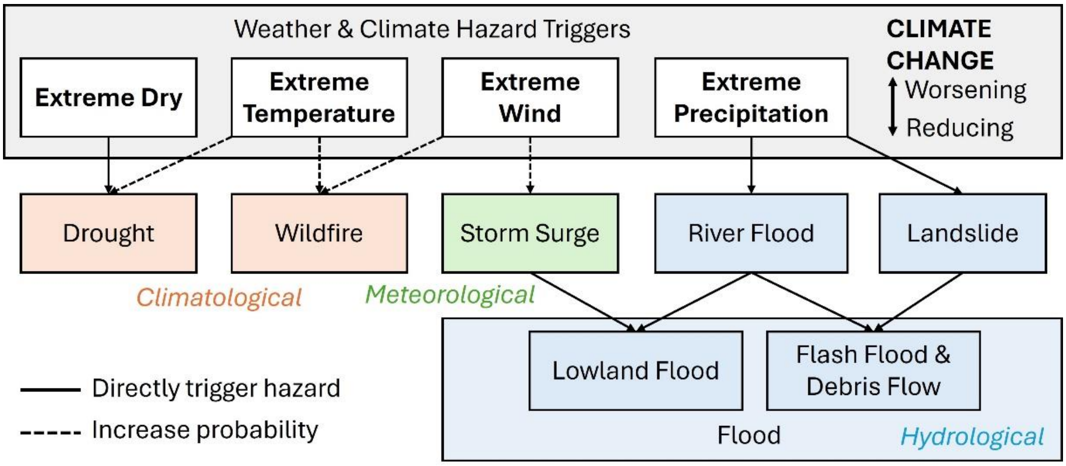

Figure 1 Weather and climate hazard triggers are influenced by climate change and the cascade hazards. These triggers result in hazards such as drought, wildfire, storm surge, river flood, flash flood, debris flow, and landslides, with worsening or reducing effects linked to climate change.

Table 1 Disaster types in this study and their EMDAT classification.

No.	Disaster	Type
1	Flood	Hydrological
2	Wet mass movement, Landslide	Hydrological
3	Storm surge, Storm	Hydrological, meteorological
4	Drought	Climatological
5	Wildfire	Climatological
6	Temperature and/or rainfall extremes (T/R extremes)	–

2.2 Country climate hazard trend

We analyze trends in hazard occurrences across Indonesia from 2000 to 2024, focusing on selected climate-related hazard types. The data were sourced from the national disaster database DIBI (Indonesia Disaster Data and Information, 2024b), which includes detailed records such as location, data, and the impacts (fatality, number of people suffered, house affected, etc.). We categorize the events by type, as shown in Table 1, including floods (including debris flows), landslides, droughts, and coastal hazards like storm surges and tidal waves. Additionally, we also include extreme weather events comprising strong winds, heavy rainfall, and extreme temperatures. We examine its temporal trends based on a number of recorded events, fatalities, etc., to assess the frequency and severity of each hazard type accumulatively. The analysis also considers regional variations by mapping the spatial distribution of selected disaster occurrences, highlighting some locations that have ever experienced major disasters and showing their general vulnerability to specific types of hazards.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

2.3 Climatic extreme indices

The increasing frequency and intensity of natural hazards are intrinsically linked to future temperature projections and extreme events (Moore et al., 2015; Seneviratne et al., 2012). For instance, rising temperatures, coupled with reduced precipitation in certain regions, may escalate evapotranspiration rates, intensifying drought conditions. Meanwhile, increasing extreme rainfall events may exacerbate flash floods, debris flows, and landslides. Areas with lower elevations may face compounded risks from intensified river floods (fluvial floods), urban floods (pluvial floods), and coastal flooding due to sea–level rise and extreme wind (e.g., storm surge). Furthermore, the combination of high temperatures and prolonged dry spells can trigger more frequent and severe wildfires.

Based on the IPCC, future climate-related hazards can be approached using indices: extreme indices and climatic impact drivers (CID) (IPCC, 2022). Extreme indices are rather representations of climatic hazards based on basic statistical distribution parameters (frequency, percentile), such as that set by the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) (Zhang et al., 2011). CIDs are indices currently used in the latest IPCC reports (IPCC, 2023), defined as physical climate parameters based on actual conditions that may have impacts on the elements of society or the environment (Ruane et al., 2022). Previous studies have used both indices and can be used as a proxy for climate–related hazards that then turn into disaster risks when they are combined with exposure and vulnerability (IPCC, 2007).

In this study, we used several extreme indices based on mean and extreme temperature and precipitation as adverse events that drive impacts. The use of extreme indices is recommended by the World Meteorological Organization (WMO) and has been used by previous studies, allowing comparison among results (Heim, 2015; Peterson et al., 2001). Here, we discuss trends in historical and projected temperature extremes using parameters: annual mean temperature (T) and maximum daily maximum temperature, while for the precipitation extreme, we use total precipitation (PR), maximum 1-day precipitation (day), Consecutive Dry Days (CDD), and Standardized Precipitation Index (6–month aggregation) (McKee et al., 1993; Zhang et al., 2011). Here, all indices are computed annually while some results may also discuss seasonal change and trend.

2.4 Historical trend and future projection

For the historical assessment, we observed both mean temperature (T) and total precipitation (PR) from CRU TS (version 4.04) (Harris et al., 2020) and the regional dataset available for Asia, APRODHITE (Yatagai et al., 2012) under IPCC database (https://interactive-atlas.ipcc.ch/). CRU TS provides reliable and quality–controlled global gridded data over a long period, while APHRODITE offers high–resolution precipitation data based on dense station networks over Asia. These datasets have been widely used in previous studies and have been proven for their performance. We used the parameter of trend °C and mm/day per decade, respectively, during 1980–2010 on an annual basis.

Moreover, we assessed several extreme indices as a proxy of future hazard impact drivers (Zhang et al., 2011). We used the Maximum of maximum temperatures (TXx) as a proxy of heat wave or warm spell events, while for precipitation, we assessed total precipitation (PR), maximum 1-day precipitation (RX1day), and Consecutive Dry Days (CDD). Parameters of PR and

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

CDD are basically used to represent the projected water resources availability and drought events, while RX1day represents the extreme daily precipitation (Zhang et al., 2011). We employed an ensemble of the most available General Circulation Models or GCMs (32 models) (see Supplementary Table S1) under CMIP6 and the downscaled regional climate model based on the CORDEX Southeast Asia (CORDEX SEA) (Tangang et al., 2020) under the SSP5–8.5 scenario and RCP4.5, respectively (Supplementary Table S2). We calculated relative changes of the parameters during the last decade, 2081–2100, relative to the baseline period 1981–2010.

3 Results

3.1 Literature review

We have analyzed selected literature in terms of the trend of the topic and its number over time. Figure 2 of line and bar plots depict the trend in publication output on the topic started from 2014 to 2024 that have been through the screening process (total of 35 papers). The bar graph represents the number of papers published annually, showing a fluctuating pattern and a slightly gradual rise beginning from the last current years by 2022 and 2023. The line graph shows the cumulative publication count, which consistently rises, reflecting overall growth. It should be noted that the total number of accumulative papers was recorded by the cutoff date used in this literature study. Thus, the current 2024 and the upcoming years are expected to be increasing.

Moreover, the pie chart in Figure 2 shows the proportion of hazard types defined in Table 1. It indicates that predominant papers dealt with temperature and rainfall (hereafter T/R extremes) (57% or 20 papers in total), followed by floods regardless of the subtype of floods (17%), drought and wildfire (11%), and landslides (3%). The T/R extremes have basically discussed the historical and future trends of extreme and mean temperature and rainfall indices. They used output from some historical data and future projection simulation based on CORDEX Southeast Asia, CMIP5, and CMIP6 over several scenarios. Meanwhile, the other remaining paper observed or simulated future floods, droughts, wildfires, and landslide hazards. In addition, it is worth noting that one hazard type, which is storm surge or wave, was not found in the included papers in this literature review. Yet, we discussed such coastal hazards in this paper according to other related studies (see results and discussion). Moreover, the temporal growth of the topic and their topic distribution suggests research areas that have grown their presence in academic discourse, punctuated by the relative rise of the whole topic discussed and their proportions. This demonstrates the importance and need for future efforts to address the potential risks from such hazards.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

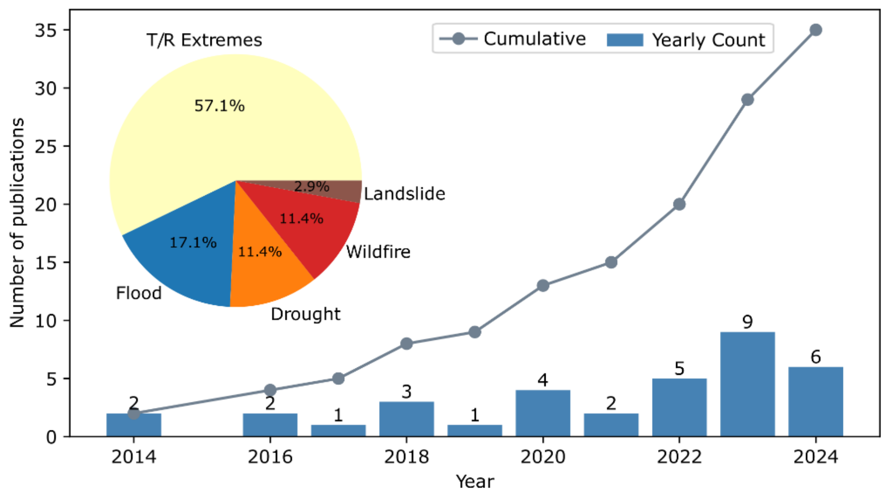

Figure 2 Number of published papers included in the literature review by year, along with a pie chart illustrating the proportion of hazard types covered in the papers.

3.2 Country climate hazard trend

Figure 3 illustrates the trend of disaster occurrences across Indonesia from starting of the records in 2000 to 2024 by disaster types: floods (including flash floods and debris flow), landslides, and droughts. Here, we also include extreme weather hazard type based on the dataset as it includes strong winds, heavy rain, or extreme temperatures. Note that coastal hazards (e.g., storm surges, coastal abrasion, tidal waves) are only available through DIBI as of 2024; therefore, we do not include them in this analysis. The graph reveals a significant increase in the frequency of recorded disasters, particularly floods and landslides, in the past two decades. Floods dominate the recorded events, accounting for approximately 34.1% of all disasters, followed by extreme weather (27.5%), landslides (20.3%), wildfires (11.3%), and droughts (6.7%). The trend is shown in Figure 3 partly reflects improved reporting and awareness, it also highlights a real increase driven by factors such as climate change and land–use changes.

Floods consistently represent a significant share of events throughout the period, with their frequency steadily increasing, particularly after 2010. Extreme weather events exhibit a sharp rise in recent years, becoming one of the dominant hazard types by 2023. Landslides emerge more prominently after 2010, showing rapid growth and contributing the largest proportion of events in the later years. Wildfire events fluctuate but show an upward trend overall, with notable peaks in certain years. Droughts remain relatively stable and contribute the smallest proportion compared to the other hazards. Droughts have had more records, especially during strong El Niño years, such as during the current 2023–2024. This data highlights the growing dominance of floods, extreme weather, and landslides over time, reflecting changing environmental and climatic conditions as well as varying regional vulnerabilities to these hazards.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

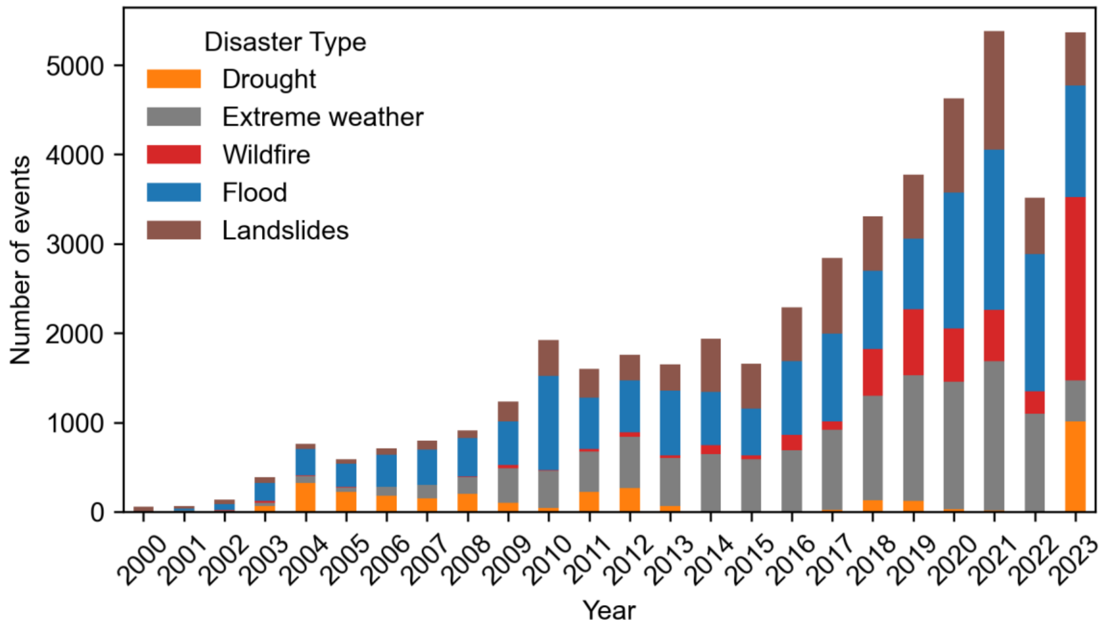

Figure 3 Trends in the annual number of recorded natural hazard events (2000–2023) categorized by hazard type (drought, extreme weather, wildfire, flood, and landslides) obtained from the national disaster database DIBI (Indonesia Disaster Data and Information, 2024b)**. Coastal hazards (e.g., storm surge, abrasion, tidal waves) are only available in DIBI (2024) and are excluded from this analysis. It should be noted that the increasing trend may reflect both actual increases in hazard occurrences and improved reporting systems over time.**

Figure 4 provides a map of Indonesia, marking selected major disaster hotspots and the locations of significant climate-related events recorded in the current 15 years (2010–2024), derived from the national disaster database DIBI (Indonesia Disaster Data and Information, 2024b). Notable events include the Sentani flash flood (2019), which caused 105 fatalities and damaged 1,804 houses, and the Wasior flash flood (2010), resulting in 107 fatalities and 987 houses affected, and Pesisir Selatan (2024, 25 fatalities, 32,000 houses affected). Indramayu (2014) experienced severe flooding, with 18 fatalities and 62,200 houses affected, while East Kutai (2022) saw flooding impacting 48,700 homes. Additional significant floods include those in Rokan Hilir (2023, 13,300 houses affected) and Kupang (2021, 13 fatalities, 12,000 houses affected). Droughts, such as in Sukabumi (2023), caused a water deficit of 121,000 liters, and East Sumba (2023) damaged 5,925 hectares of crops. Wildfires in Jambi (2015, 19,528 hectares) and West Aceh (2017, 3,053 hectares) highlight Indonesia's susceptibility to fire-related hazards. Landslides in Banjarnegara (2014, 99 fatalities) and Natuna (2023, 43 fatalities, 100 houses affected) further demonstrate the region's risk. Extreme storms in Bojonegoro (2019, 3,000 houses affected) add to the list of severe hazards.

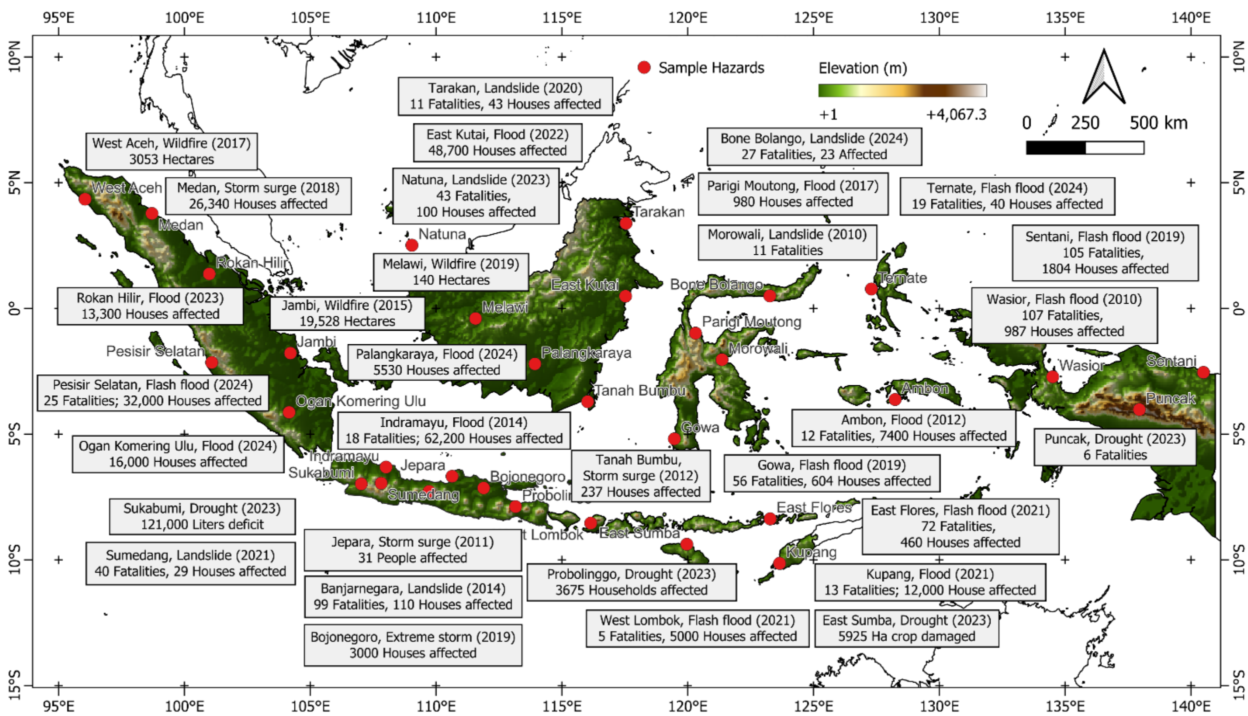

Figure 4 Spatial distribution of significant natural hazards in Indonesia (2010–2024) based on data from the DIBI database (Indonesia Disaster Data and Information, 2024b)**. The elevation gradient in the background shows the elevation based on DEM from HydroSHEDS (https://www.hydrosheds.org/).**

Floods and landslides are among the most hazardous natural disasters in Indonesia, comprising 33.2% and 36.3% of the total casualties, respectively (see Supplementary Figure S1). In particular, floods dominate the impacts with the most numbers of people missing (73.6% of the total), injured (92.2%), displaced (97.2%), and houses damaged (69%). Among flood types, flash floods are particularly catastrophic, likely resulting in the highest number of fatalities due to their sudden onset and intensity. Moreover, drought mostly suffered societies 31.8% of total people suffered from natural hazards in the country. Droughts primarily affect the southern regions of Indonesia, from Java to East Nusa Tenggara. Java, Indonesia's agricultural heartland, has faced drought-induced water stress during El Niño years (Supari et al., 2018). Wildfires are most common in Sumatra and Kalimantan, frequently triggered by land–clearing activities. Meanwhile, extreme weather recorded mostly features a strong wind with extreme storms impacting houses by 48.3% of total moderately damaged houses. Extreme weather events also mark a significant number of records after the flood, with 27.5% of total events.

3.3 Extreme Indices based on IPCC

We summarize the possible impacts of various climate-related hazards triggered by rising temperatures and extreme weather based on current reports and previous research aligned with IPCC (Table 2). Each entry outlines observed patterns, future

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

projections, and associated consequences supported by the reviewed references. Further discussions are provided in the subsequent sections.

Table 2 Overview of the associated climate-related hazards in Indonesia with temperature and rainfall extreme parameters and key references used in this study. Note that storm surges are not specifically discussed in reviewed papers.

Triggered Hazards	Cases and key findings	Remarks	References
Flood and landslides	Increased rainfall intensity and frequency observed in northern Indonesia (e.g., Kalimantan, Sumatra). Projections under high–emission scenarios signify more extreme wet days and shorter return periods for rainfall events. studies highlight that heavy rainfall–triggered landslides are also common in steep and mountainous areas including in Java.	Possible amplified flood risks, particularly in northern parts, due to intensification of rainfall and climate teleconnection patterns like MJO and ENSO.	(An et al., 2023; Fan et al., 2022; Hariadi et al., 2023; Hendrawan et al., 2024; Kurniadi et al., 2023; Liang et al., 2022; Meehl and Tebaldi, 2004; Mubarrok and Jang, 2022; Ngai et al., 2017; O'Neill et al., 2016; Supari et al., 2017, 2020; Tangang et al., 2018; Watterson, 2020)
Drought and wildfire	Southern regions (e.g., East Java, Bali, and Nusa Tenggara) show increasing consecutive dry days trends historically and into the future, especially during dry seasons. Drying is intensified by negative ENSO phases. Warming trends historically observed, with significant increases in maximum daily temperature (0.18–0.24 °C per decade) or exceeding 30°C across most of Indonesia (under SSP5–8.5). Mean future warming projections range from 1°C (low emissions) to 5°C (high emissions) by 2100. Warming trends may enhance the risks of wildfire, especially in drier regions and extensive land–clearing regions such as Sumatera and Kalimantan.	Drought risks are more pronounced in the south due to prolonged dry periods and reduced rainfall intensity. Increasing heat stress, wildfire risks, and impacts on agriculture due to higher evapotranspiration and extreme warm spells in the regions.	
Compound disasters and other hazards (e.g., extreme weather)	Southern regions show mixed drying and wetting patterns, with fewer rainy days but higher average daily rainfall during rainy days. Studies also emphasized the higher threat of compound risks of hot and dry weather in the dry region hotspots.	Increased the potential drier in dry seasons and wetter in wet seasons in the country and amplified simultaneous risk of hot–dry weather.	

3.3.1 Precipitation extremes

Historical

In terms of precipitation extremes, the evidence for significant changes in heavy rainfall events is highly varied over regions. It's been robust that the variable trends across Indonesia show increases in some areas and decreases in others (Alexander et al., 2006). Our analysis based on observational gridded data (CRU and APHRODITE) in Figure 5 shows a drying trend across Indonesia from 1950 to 2014, indicated by decreasing total precipitation. This trend is most pronounced in the southern regions, as also reported by previous studies based on both observations and GCMs (Hariadi et al., 2023; Tangang et al., 2018). In particular, the increase in Consecutive Dry Days (CDD) and the decrease in annual total precipitation are profound in southern regions, particularly in Java (East Java), as reported by (Hendrawan et al., 2024) and Nusa Tenggara, considered Indonesia's

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

driest provinces. Rainfall patterns in southern Indonesia are closely linked to El Niño during the peak dry season from June to August and the early rainy season from September to November (Aldrian and Dwi Susanto, 2003; Watterson, 2020). This evidence emphasizes the recorded drought events across the hotspot regions, as previously discussed (Indonesia Disaster Data and Information, 2024b).

On the other hand, a previous study (An et al., 2023) pointed out that Northern Indonesia, including regions such as northern Sumatra and Kalimantan, shows a dominance of precipitation intensity, while southern regions exhibit a mixed influence of intensity and frequency. A number of heavy rainfall days (R20mm) is more frequent (> 30 days) in the northern part of Indonesia, such as northern Kalimantan, West and Central Java, and central Papua (Hariadi et al., 2023). Whereas, over the archipelago, the change of total rainfall from extremely heavy precipitation days (> 95th percentile) (R95pTOT) ranges from +15 to +25%. Higher R95pTOT values (20–25%) also appear in Nusa Tenggara and the southern and northern regions of Papua. High SDII values indicating the average rainfall intensity on rainy days (around 12 mm) are seen in Java, Borneo, Nusa Tenggara, and central Papua. For those regions, high SDII with low R95pTOT values correlates with more frequent heavy rainfall events. Meanwhile, in Nusa Tenggara, high values of both SDII and R95pTOT result from a limited number of rainy days, as expressed by high CDD (Kurniadi et al., 2023). These highlight regional variations in rainfall patterns across Indonesia, with generally northern regions showing an increasing trend in rainfall intensity, while southern regions exhibit both drying and wetting signals isolated in each season. These extremes have been shown to trigger significant floods, for example, in Kalimantan, Sumatera, Papua, and parts of Java, and drought hazards in Nusa Tenggara during the current decade.

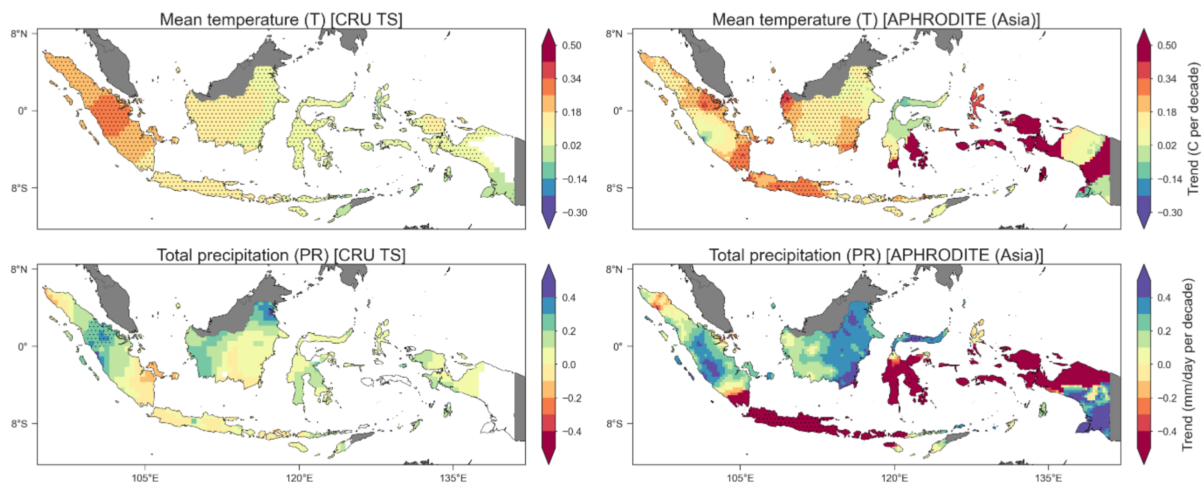

Figure 5 The trend of mean temperature (°C) and total precipitation (mm/day) per decade from CRU TS and APRHODITE Observations (1980–2015, annual scale). Dot hatching highlights regions where at least two–thirds of models agree on the sign of the trend, indicating statistically significant changes.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Future projections

The future projection by previous studies (Ngai et al., 2022; Supari et al., 2020; Tangang et al., 2020) based on bias–corrected CORDEX SEA simulations generally show similar patterns to that of the historical period simulations. Dry extremes, measured by consecutive dry days (CDD), continue to increase in the south and decrease in the north during the wet season while showing a nationwide increase during the dry season (Kurniadi et al., 2024), including the northern Kalimantan and Sumatera, may experience increased Consecutive Dry Days throughout the year during winter monsoon (Dec–Feb) by up to 64%. These imply the threat of drought in the prominent dry regions of southern Indonesia (i.e., Java, East Java in particular, Bali, and Nusa Tenggara), which is also highly influenced by drying due to the negative phase of the El Niño–Southern Oscillation (ENSO) or the El Nino events (An et al., 2023).

In contrast, the study projected a consistent rise in wet extremes (R95pTOT and maximum 5-day total precipitation) during the wet season across much of Indonesia (Ngai et al., 2022; Supari et al., 2020). The extreme wet days (R95pTOT) are projected to be a slight increase in Papua and a slight decrease in the Indonesian region, especially Java. This signal is estimated to be stronger during Boreal Summer (Jun–Aug), where during this drier season, the R95pTOT is expected to be decreasing, especially in Java and Nusa Tenggara. Future scenarios suggest that the intensification of Climate Teleconnection Patterns (CTPs), such as the Madden–Julian Oscillation (MJO) and ENSO, will likely shorten the return period for extreme rainfall events, amplifying flood risks in already vulnerable regions, particularly in northern parts like Kalimantan and Sumatra under high–emission scenarios (Liang et al., 2022; Mubarrok and Jang, 2022).

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

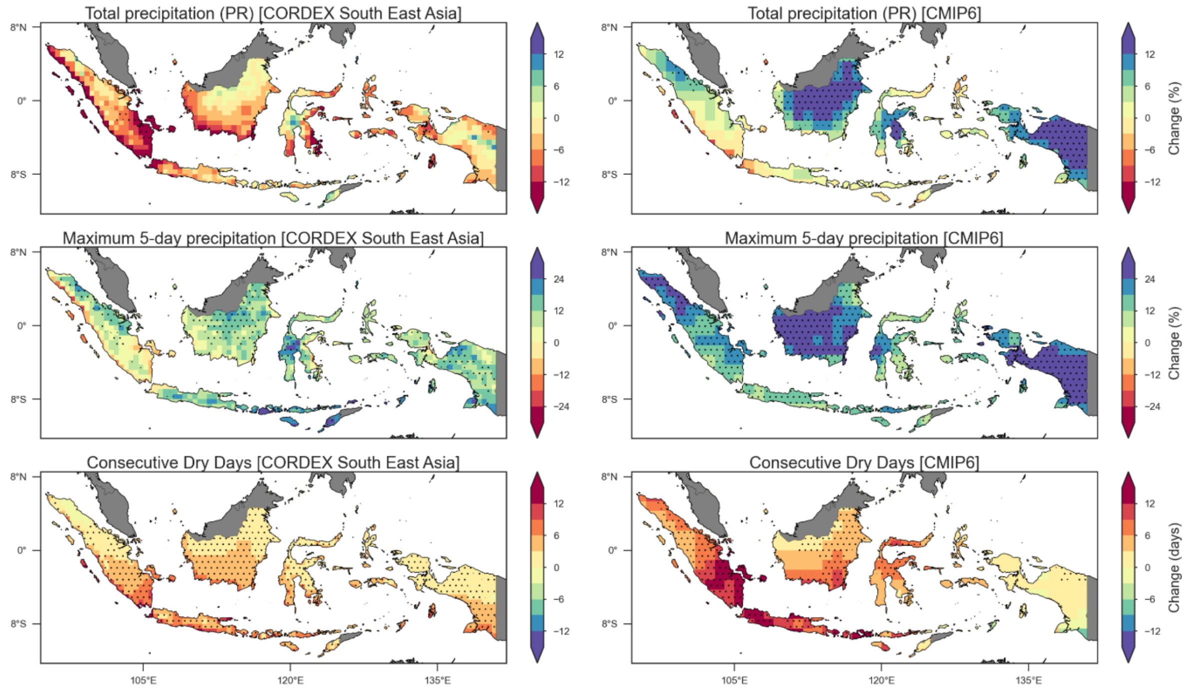

Figure 6 Future projections of Total Precipitation, Maximum 5-day Precipitation, and Consecutive Dry Days for 2080–2100 relative to the 1980–2010 baseline. (a) Results from Regional Climate Models (RCMs) under CORDEX Southeast Asia (10 models) and (b) Global Climate Models (GCMs) under CMIP6 (33 models). Regions with statistically significant changes, where at least two–thirds of models agree on the direction of the trend, are marked with dot hatching.

3.3.2 Temperature extremes

Historical

Continuous measurements from numerous meteorological stations in Indonesia provide strong evidence for a significant warming trend recorded in the past five decades revealed from earlier IPCC studies (Alexander et al., 2006; Meehl and Tebaldi, 2004; Seneviratne et al., 2012). Higher populated regions, such as Java, Sumatra, and Kalimantan, have been experiencing significant temperature extremes change (IPCC, 2023). A study (Supari et al., 2017) using 88 meteorological stations data over Indonesia (1983–2012) reported that the annual mean and annual maximum daily maximum temperature (TXx) increased significantly by 0.18–0.24 °C per decade, indicated by 90% of stations with increased maximum temperature (46% significant). In addition, a local study (Sugianto et al., 2020) also evidenced that air temperature in Semarang City has increased by 0.2 °C per decade over 48 years (1970–2017). Figure 5 shows another historical record based on two grided data (CRU and APHRODITE) that demonstrates a distinct spatial pattern of temperature changes, except those in Java and other southern Indonesian (e.g., Nusa Tenggara), which show more spatial coherence. Another study (Fan et al., 2022) based on Southeast Asia gridded data (SA–OBSv2.0) generally agrees with the spatial pattern temperature change from APHRODITE data, which shows a spatially uniform historical increase of TXx over most of Sumatera, Borneo, and Java during 1981–2017, while the

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

eastern Papua and parts of Nusa Tenggara show insignificant changes (or slightly cooling). This steady rise in temperatures mean and extreme aligns with broader projections of increasing warm spells across Indonesia and the region of Southeast Asia.

Future projections

In regard to the future projections, it is evident from the IPCC global climate models that the warming trend will persist in future years. We analyzed the results of up to 29 models within Indonesia, indicating that Indonesia's average and extreme temperature could rise by 1–5°C by 2100, as shown in Figure 7, varying due to scenarios and climate model estimates. We observe that the future daily maximum temperature changes over 2090–2100 (median and 10^{th}– 90^{th} percentile) are 1.08°C (0.56°C–1.80°C), 1.90°C (1.30°C–2.60°C), and 3.55°C (2.53°C–5.17°C) for SSP1–2.6, SSP2–4.5, and SSP5–8.5, respectively, compared to that during historical period of 1980–2100. In absolute values, these changes are equal to 29.91°C, 30.71°C, and 32.52°C for respectively each scenario compared to 28.80°C during the baseline period. Such pronounced warming would inevitably increase the risk of warm spells, wildfire, and drought, particularly for agriculture (due to increasing evapotranspiration). In terms of warm spells, most models have agreed on the increase in the frequency and/or duration of warm spells on an annual timescale in Indonesia (Meehl and Tebaldi, 2004; O'Neill et al., 2016).

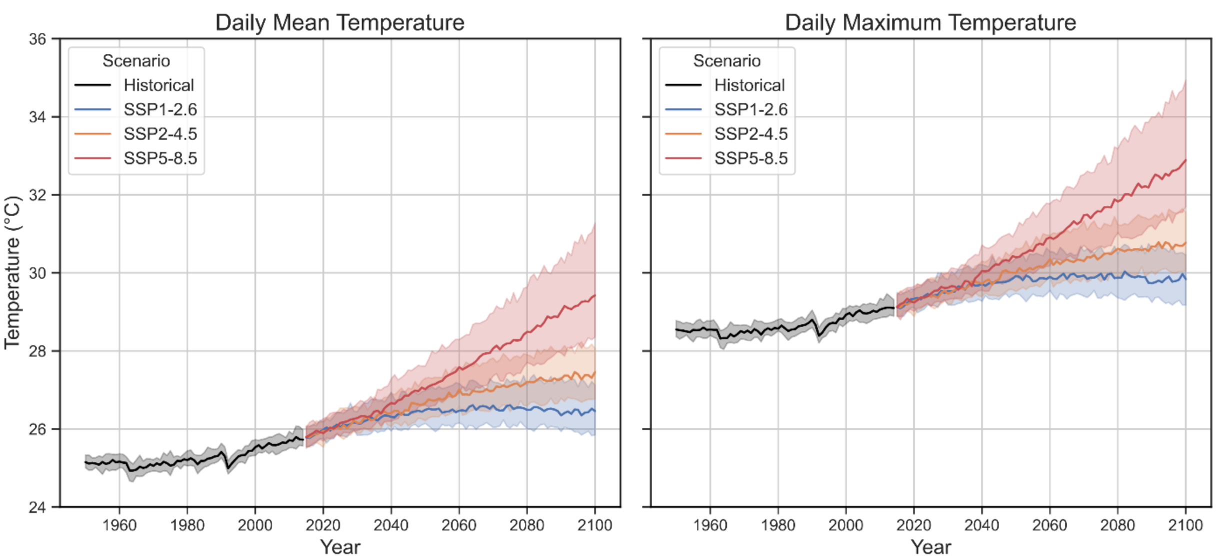

Figure 7 Projected average daily mean and maximum surface air temperatures for the historical period and future scenarios (SSP1–2.6, SSP2–4.5, SSP3–8.5) from 1950 to 2100 over Indonesia. Estimates are based on CMIP6 simulations, utilizing ensembles of up to 29 General Circulation Models (GCMs), with the number of models varying depending on availability for each scenario.

3.4 Climate–related hazards trend in Indonesia

The prominent evidence of increasing climate extreme events driven by changes in both precipitation and temperature due to climate change may have serious consequences to the amplified risks from natural hazards as evidenced in the reports, especially in prone countries such as Indonesia (IPCC, 2007; Legg, 2021; Seneviratne et al., 2012). These shifts in climate patterns have led to more frequent and severe adverse climate events. Here, based on the papers selected, we review such

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

studies and cases to underscore the urgency of addressing the challenges in the future. Table 3 summarizes the key findings from previous studies reviewed concerning the natural hazards and disaster trends to impact Indonesia under the influence of climate change, highlighting relevant studies, their methodological approaches, and key findings. We will further discuss them in detail in the subsequent sections.

Table 3 Overview of climate–related hazards in Indonesia obtained from literature reviews, including the methodological approaches, key findings, and references highlighting uncertainties and risks associated with each hazard type.

Hazards	Cases and key findings	Remarks	References
Flood	Numerous studies using GCMs, SSPs, and RCPs predict a rise in flood risks in Jakarta (180% to 402%) due to climate change, land subsidence, and urban development—significant uncertainties in projections of extreme precipitation and flood risk. Simulation studies for Java Island highlight future flood extents exceeding historical levels under high–emission scenarios.	Hazard projections remain highly uncertain due to complex interactions between future urban expansion, extreme precipitation patterns, and other urban development factors.	(Budiyono et al., 2016; Farid et al., 2023; Januriyadi et al., 2018; Mishra et al., 2018; Priyambodho et al., 2022; Willner et al., 2018)
Landslide	A projection estimated a 131%–137% rise in landslide casualty risks by 2031–2060, driven by extreme precipitation and population exposure in Indonesia. Past events highlight flash floods triggered by natural dams collapsing due to landslides. Case studies include among the deadliest hazards: Bahorok (2003), Kalijompo (2006), and Palu earthquake cascade events (2018).	The increasing intensity of extreme precipitation, combined with Indonesia's seismic activity and steep terrain, heightens the risk of cascading hazards of landslides and flash floods.	(Tunas et al., 2020; Wang et al., 2023; Zain et al., 2021)
Storm Surge, Storm	ENSO–driven changes (El Nino, La Nina) may intensify wind patterns and wave heights in Indonesia. Wave and storm surge dynamics remain understudied under climate change scenarios, but ENSO events are projected to increase in intensity, altering wave generation and propagation.	Given the limited research on storm surges and wave dynamics, further studies are essential, particularly in the context of rising sea levels and increasing coastal vulnerability.	(Odériz et al., 2024; Semedo et al., 2013)
Drought (and extreme temperature)	Increasing drought risks are found in some regions, such as the Solo and Barito River Basins, with projections of over 50% high–risk areas by 2050. El Nino events have historically caused 93% of droughts in Indonesia, leading to significant rainfall deficits and crop failures. Rain–fed agriculture remains highly sensitive to rainfall variability, particularly during wet seasons, highlighting the vulnerability of agricultural systems to future droughts. Studies highlight significant increases in air temperature and heatwave frequency across Indonesia. Projections under high–emission scenarios anticipate heatwaves in the country, similar to Russia's 2010 event becoming biannual by century's end. Urban areas	Droughts are often overlooked in Indonesia due to their slow onset and relatively low immediate impact, despite their long–term consequences. Extreme temperature: Despite Indonesia's humid climate, prolonged heat extremes are becoming more frequent, particularly in	(Barkey et al., 2019; Farahnaz et al., 2020; Ferijal and Fauzi, 2024; Gusyev et al., 2016; Hasegawa et al., 2016) (Russo et al., 2014; Setiawati et al., 2021; Sun et al., 2023)

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

	face exacerbated risks due to the UHI effect and rising UTCI, demanding urgent adaptation measures.	urban areas, exacerbating heat stress and energy demands.	
Wildfire	Forest fires are driven by prolonged droughts and rising temperatures. ENSO is strongly linked to severe fire events (1997, 2006, 2015). Future projections show a 25% rise in severe droughts and high fire risks in Southern Sumatra and Borneo. Compounding effects of temperature–driven fire susceptibility even during wetter periods.	Wildfires are increasingly temperature–driven, highlighting the need for temperature–specific management strategies, even in non–drought years.	(Chen et al., 2016; Fernandes et al., 2017; Lam et al., 2024; Lestari et al., 2014; Rendana et al., 2023)
Compound disasters and other hazards (e.g., extreme weather)	Increasing compound hazards, e.g., simultaneous dry and wet extremes, are projected with higher global warming scenarios. Machine learning predicts significant risks of combined drought and forest fire hazards, especially in Kalimantan.	There is an urgent need for integrated hazard modeling that accounts for compound and multi–faceted risks.	(Heo et al., 2023; Vogel et al., 2020)

3.4.1 Flood

A previous study (Budiyono et al., 2016) projected a median increase in flood risk in Jakarta of 180%, driven by climate change, land subsidence, and land use changes, with land subsidence contributing the most significantly to this rise. Based on ensemble 40 GCMs-RCPs, the study found that climate change impacts on extreme 1-day precipitation up to 2050 are highly uncertain in the basins of Jakarta. Median projections indicate around -19% (decrease), respectively, with minimal variation across return periods, but a wide range and large percentile spread reveal significant uncertainty, even in the direction of change. In terms of flood risk, this study suggested that within a "baseline + extreme precipitation" scenario alone, the percent change of risk can even decrease –46% (–94% to +104% of the 5^{th}–95^{th} percentile).

In contrast, a later study (Januriyadi et al., 2018) using a different approach to asset value estimates projected a 322–402% increase in flood risk by 2050 under combined scenarios of climate change and urban development, suggesting a more dramatic rise in flood risk in Jakarta (Mishra et al., 2018). This increase was partly due to a slight increase of daily extreme precipitation (bias–corrected 8 GCM ensemble) by around 17% (median) with yet high uncertainty with a range of 5% within the decrease sign. Another study (Farid et al., 2023) simulated flood hazards for Java Island based on six bias–corrected CMIP6 models under SSP climate scenarios by the end of the century. Their study showed that future flood extents exceeded historical 100–year return levels, especially in Jakarta and Central Java, whilst maintaining high uncertainties and higher emission scenarios for far future periods. In addition, (Willner et al., 2018) also pointed out that Java is the region most impacted by future floods. East Java (Jawa Timur) is projected to see a significant rise in affected population numbers up to 300,000 (199,000 to 705,000 of 16.7^{th}– 83.3^{rd} percentile), highlighting a pressing need for enhanced adaptation measures.

The findings reveal significant uncertainty in flood risk projections for Jakarta due to inconclusive changes in extreme precipitation over GCMs as well as observations (i.e., bias correction approach), leading to outcomes ranging from decreased to increased flood hazards. These uncertainties add to the complexities of risk assessments drawn from hazard estimation (data, modeling, assumptions), exposure and vulnerability parameters (e.g., asset valuation, flood damage curves), and the feedback of future urban development (Priyambodho et al., 2022).

3.4.2 Landslide

There is limited study on the topic related to landslides in this study's review. Among limited studies, a projection global–scale study (Wang et al., 2023) revealed that Indonesia is one of the fifth countries after China, Afghanistan, India, and the Philippines, with high landslide casualty risks under climate change scenarios. The study estimated Indonesia may have an average of 380 casualties annually during 2031–2060 and 370 during 2066–2095 under the SSP2–4.5 scenario, marking increases of 137% and 131%, respectively, compared to the 1971–2000 period. This heightened risk is driven by Indonesia's mountainous terrain, frequent extreme precipitation, and high population exposure, all of which are expected to worsen due to climate change. This finding is also suggested by another study (Hendrawan et al., 2024) that the potential of intensifying landslides In Java as the increase of extreme daily rainfall in mountainous regions at the end of the century.

Landslides in Indonesia, triggered by extreme rainfall, often lead to flash floods by forming natural dams in rivers (Zain et al., 2021). When these dams collapse under pressure, debris–laden floods rush downstream, causing severe erosion and widespread destruction. Previous studies highlighted several disaster events, including Bahorok Catchment (2003), Kalijompo and Kalipakis Catchments (2006), Wasior Catchment (2010), and Nasiri Catchment (2012) (Zain et al., 2021). A flash flood is generally triggered by heavy rainfall (100–300 mm over three days) with the combination of steep slopes (>40°) and soil movement causing landslides that block rivers. The fractured geological structure may weaken slope stability, resulting in debris–laden floods. In addition, a study (Tunas et al., 2020) pointed out the impacts of the 2018 Palu earthquake (magnitude 7.5) on landslides and subsequent flash floods in the Bangga River Basin, Sulawesi, Indonesia.

These studies highlighted that Indonesia may face significant and escalating landslide risks driven by climate change (e.g., increasing extreme precipitation) as well as seismic activity. This also highlights an urgent need for comprehensive mitigation strategies to address cascading hazards like flash floods and rising exposure due to land use change and increasing population.

3.4.3 Storm surge and wave

While the direct influence of climate change on storm surges and waves in Indonesia is complex, the increasing intensity and frequency of ENSO events, exacerbated by climate change, potentially impact these phenomena (Semedo et al., 2013). Studies have shown that a warming climate can intensify ENSO events, leading to more pronounced El Niño and La Niña phases (Cai et al., 2015). During El Niño, for instance, Indonesia often experiences drier conditions and reduced rainfall, which can indirectly affect ocean currents and wind patterns, influencing wave generation and propagation. Conversely, La Niña events can lead to increased rainfall and stronger winds, potentially contributing to larger waves and storm surges (Chang et al., 2020; Supari et al., 2018). The findings of a previous study (Odériz et al., 2024) highlight the specific impact of ENSO on wind patterns and wave conditions in Indonesia, particularly during the DJF season. These events lead to a concurrent increase in wind, wind–sea, and swell from the east (E direction) by approximately +1%, +6%, and up to +7%, respectively. There is

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

currently very limited research on the specific interactions between climate change and its impacts on storm surges and wave dynamics in Indonesia, highlighting the need for further in–depth studies.

3.4.4 Drought

Several local studies projected drought risk in parts of Indonesia. The drought risk is expected to intensify, as well as impacting rice production during critical growing seasons. From local river basin studies (Gusyev et al., 2016; Hasegawa et al., 2016), it was indicated there would be an increase in meteorological to socioeconomic drought severity up to 16% of the dam inflow in the Solo River basin during the end of the century (RCP8.5). Another basin–scale study (Farahnaz et al., 2020) projected a significant increase in drought risk in the Barito River Basin by 2050. Drought–prone areas with medium and high–risk levels are expected to cover more than 50% of the basin, with high–risk areas expanding compared to the earlier projection (2031–2035). Using the Keetch–Byram Drought Index (KBDI), the study highlights the strong relationship between prolonged dry periods and wildfire occurrences, especially in southern Kalimantan.

The study (Hohl et al., 2021) also highlighted that extreme drought frequency and severity are projected to increase in the near future (2016–2040) based on the Standardized Precipitation Index. They demonstrated a clear connection between rainfall shortages and fluctuations in agricultural production, especially during the wet season (typically from January to April). In the wet season, rain–fed irrigation supports most of the rice cultivation, making it highly sensitive to rainfall variability (Hendrawan et al., 2023a; Irawan et al., 2023). Another study (Barkey et al., 2019) based on hydrological modeling projected a significant increase in drought–prone areas by 2030 (under RCPs). The increase, particularly within the karst regions, which are expected to face low water retention, adversely affects both agricultural lands and unique biodiversity in Bantimurung Bulusaraung National Park. Another study (Ferijal and Fauzi, 2024) emphasized the role of seasonal patterns in exacerbating drought in the Aceh region based on the observed historical period 1982–2022. They observed that total precipitation decreased by 13% from March to August (dry period), with a slight increase in the dry day fraction, whereas annual rainfall during the current period increased by 14% compared to the earlier period (1982–2000). These increasing future droughts in several local areas in Indonesia evidenced the vulnerability region's economic activity (e.g., agriculture), underscoring the need for robust drought management strategies in the country.

Historically, El Niño has been associated with 93% of droughts in Indonesia (Quinn et al., 1987). Previous studies reported that drought events in Indonesia were associated with El Nino occurrences, especially in major El Nino events such as 1997–1998, 2002–2003, and 2013–2014. These drought events also triggered crop yield drops over the years, such as El Nino 1973 and 1992, triggering average annual rainfall of only approximately 67% of the average, which caused a yield decline of around half (Amien et al., 1996; Hendrawan et al., 2023a; Naylor et al., 2001)

3.4.5 Wildfire

In Indonesia, biomass burning, primarily from shifting cultivation practices, causes haze disasters that impact the country and neighboring regions. The spread of forest fires, particularly evident in October in Sumatra, is largely driven by prolonged droughts during the dry season (May to October) (Field et al., 2009). A previous study (Lestari et al., 2014) assessed fire

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

hazards in both historical and future projections based on GCM simulations under CMIP5 in Indonesia. They found that current anthropogenic warming has weakened the Walker Circulation associated with tropical ocean warming, increasing the likelihood of severe drought over the past 50 years. This phenomenon is strongly linked to El Niño events, particularly the Eastern Pacific El Niño, which contributed to severe wildfire events in southern Kalimantan (Borneo) and the surrounding islands of Sumatra and Papua in 1997, 2006, and 2015 (Chen et al., 2016). The future projection shows a rise in severe drought events by approximately 25% over 2001–2050 relative to 1951–2000. Another study (Rendana et al., 2023) using a meteorological drought index also estimated an increase in high fire risk areas in Ogan Komering Ilir, Southern Sumatra, of around 14% and 30% during 2021–2040 and 2041–2060, respectively.

Furthermore, in accordance with (Chen et al., 2016), previous studies (Lam et al., 2024) also suggested that warming eastern Pacific SST anomalies, particularly during March–May, can predict drought conditions with a lead time of several months, serving as an early warning trigger. ENSO remains a primary driver, and high–emission scenarios (e.g., SSP585) project an intensified link between SST anomalies and drought, with drought indicators, such as the maximum number of consecutive dry days, expected to increase significantly in Indonesian Borneo by 2061–2100 (Lam et al., 2024). Additionally, studies highlight that rising temperatures are increasingly driving fire probability in Indonesia, even under wetter–than–average conditions (Fernandes et al., 2017). While drought conditions are one of the primary drivers, wildfire risk can escalate during wetter seasons with anomalously high temperatures. Higher evapotranspiration in warm, moist conditions accelerates soil moisture depletion, intensifying fire susceptibility.

Despite increasing tropical mean rainfall north of the equator (Lestari et al., 2014), other regions of Indonesia may experience drier conditions, especially during boreal summer (June–August), under various climate scenarios. Rising temperatures and shifting El Niño increase wildfire risk even in wetter years, with projections of more frequent droughts and raised wildfire susceptibility. Together, these findings emphasize the need for fire management strategies that account for both drought and temperature–related risks, underscoring a future compounding fire hazard across Indonesia. Wildfire management strategies should also account for temperature–driven fire risks even in non–drought years (Fernandes et al., 2017).

3.4.6 Temperature extremes

By the end of the century, under high emission scenarios, warm spells as intense as Russia's 2010 summer heatwave may occur in Indonesia as often as every two years (Russo et al., 2014). Such projections are reinforced by recent findings that under the SSP1–2.6 scenario, the Maritime Continent, including much of Indonesia, experiences approximately 150 days of heatwaves, with the longest lasting around 11 days. The SSP5–8.5 scenario projects an extreme increase, with heatwave frequency surpassing 300 days and durations extending up to 90 days by the end of the 21st century (Sun et al., 2023). In urban areas, this risk is further magnified by the urban heat island (UHI) effect. According to (Setiawati et al., 2021), projections for Indonesian cities Medan, Surabaya, and Denpasar show a substantial increase in the Universal Thermal Climate Index (UTCI) under future land–cover and climate change scenarios (RCP8.5). The UTCI in these cities could rise by up to 3.1 °C (during 2018–2042 compared to 1981–2015) without extensive greening measures, leading to exacerbated health risks, increased

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

energy demands for cooling, and greater vulnerability to heat stress. These studies collectively highlight the urgent need for climate adaptation and urban planning measures to mitigate rising temperatures in Indonesia.

3.4.7 Compound hazards

Based on the extreme percentile, a previous study (Vogel et al., 2020) projected Indonesia to face increasingly frequent and intense compound dry and wet extremes. For instance, at +2°C, dry and wet extreme events could intensify, with up to three occurrences in the same month every 20 years. At +3°C, Indonesia becomes a hotspot for extremes, experiencing up to 10 months of clustered hot and wet events per 20 years, along with more than four instances of these extremes co–occurring within the same week. The study (Heo et al., 2023) based on a machine learning approach projected significant risks of drought (22.6%) and forest fires (21.7%), with 2.6% of the compound drought and forest fire hazards. These risks are expected to rise under both RCP–SSP2–4.5 and RCP–SSP5–8.5 scenarios. Among the five provinces studied, West Kalimantan had the highest risk of forest fires (33.02%), while South Kalimantan faced the greatest risk of drought (67.3%) and the combined impact of both hazards (7.1%). In the worst–case scenario (RCP–SSP5–8.5 in 2080), West Kalimantan's Forest fire risk increases to 33.51%, South Kalimantan's drought risk rises to 74.01%, and the combined risk escalates to 16.34%.

4 Discussion

This study provides a thorough of the current trend of climate–related hazards in Indonesia, demonstrating how extreme weather events become more frequent and intense under current and future scenarios. We reveal significant increases in the frequency and severity of climate–related hazards in Indonesia. Flood risk, for instance, is projected to rise dramatically in urban areas such as Jakarta, up to ~400% by 2050 due to the combined effects of climate change and urban development (Budiyono et al., 2016; Januriyadi et al., 2018). These projections are supported by climate model outputs showing intensified extreme rainfall events and reduced return periods for significant precipitation (Farid et al., 2023; IPCC, 2023; Priyambodho et al., 2022). Drought risks are expected to escalate, with projections indicating over 50% of high–risk areas in key river basins in most populated regions (i.e., Java) by mid–century (Gusyev et al., 2016). Historical analyses reveal that 93% of drought events in Indonesia are highly associated with El Nino phases, underscoring the role of climate teleconnections in modulating regional climate extremes (Quinn et al., 1987). Fire risk, amplified by rising temperatures and prolonged dry spells, is projected to increase by 25% in southern Sumatra and Kalimantan (Chen et al., 2016; Rendana et al., 2023). The annual maximum daily maximum temperature (TXx) trends, increasing by 0.18–0.24°C per decade, reinforces the possible aggravating drought–heat extremes, modulating substantial future impacts on agriculture and ecosystems.

This study aligned with regional and global findings but provided more granular insights into Indonesia's unique setting. Here, we emphasize several regions within the archipelago responding differently to climate changes in terms of hazard occurrences based on the generated map using rainfall parameter projection in the future. Using K–means clustering, we classified regions into three categories, as shown in Figure 8. Further details on the clustering methodology and parameters can be found in the Extended Method (Supplementary). Figure 8 illustrates the clustered zones based on two layers: 1) projected changes in rainfall

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

extremes and drought conditions across Indonesia for 2081–2100 under SSP5–8.5, relative to 1981–2010, based on CMIP6 model outputs for Consecutive Dry Days (CDD) and 2) the maximum 5-day precipitation (RX5day). Zone one (blue) characterizes regions with expected increasing drought with relatively "no change" rainfall extremes, comprising drier regions of southern Sumatera, Java, and small parts of Kalimantan and Sulawesi. Zone two (orange) indicates regions with at least no change in drought risks yet rising rainfall extremes. This zone is expected to have more heavy rainfall in the future, triggering wet hazards such as floods and landslides. Zone three (green) comprises the rest of the country, mostly islands in Maluku and parts of northern Kalimantan and Papua. This zone is expected to have moderate climate hazards in the future, both extreme rainfall and drought.

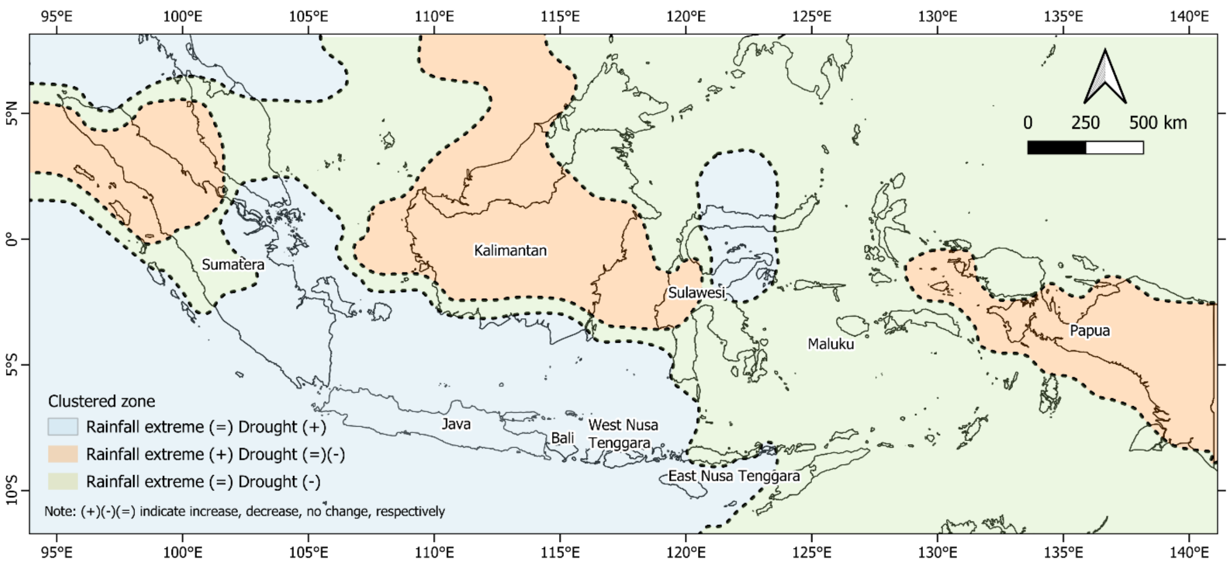

Figure 8 Clustered regions in Indonesia based on projected changes in rainfall extremes and drought conditions for the period 2081–2100 under SSP5–8.5, relative to 1981–2010. Data derived from CMIP6 projections (32 models) for Consecutive Dry Days (CDD) and Maximum 5-day precipitation (RX5day). Positive (+), negative (–), and neutral (=) signs indicate increase, decrease, and no change, respectively. Please refer to the Extended Method (Supplementary) for the details of the clustering method.

The common extreme rainfall will be at least the same or increase over the archipelago (shown by all zones in Figure 8); we emphasize the potentially exacerbated drying risks due to climate change in southern Sumatera, Java, and Nusa Tenggara, especially Bali and West Nusa Tenggara (and small parts of southern Kalimantan and Sulawesi), where reduced rainfall is expected to impact agriculture, the environment, and society disproportionately, which may be worsened by compounding heat stress. The drying threats have been even more dangerous when coinciding with El Nino, such as that in the 2023 drought, which affected 18.75 million people between June to September in Indonesia (IFRC, 2023), and these are expected to heighten in the future (Cai et al., 2015). The research regarding drought in the country is often underestimated, probably due to its relative insignificance in terms of fatality and scale compared to other hazards, such as floods, earthquakes, and tsunamis, according to recent disaster records (Indonesia Disaster Data and Information, 2024b). In addition, its typical slow onset and low magnitude given in the humid tropical country hinder its importance, especially given the dominance of wet farming (i.e., rice) across the rice bowl regions such as Java and Sumatera.

On the other hand, regarding the undeniable impact of the fatalities and damages caused by the flood, we figure out the complex variability among the projections from numerous studies indicating the challenges of modelling complex flood hazard systems, in particular under changing climate and dynamic urban development scenarios. For instance, a previous study reported that land subsidence contributes the largest percentage (126%) to increasing flood risk in Jakarta by 2030, extremely surpassing the effect of land use change, climate change, and sea level rise (out of 180% changes considering all factors) (Budiyono et al., 2016). Another study (Takagi et al., 2016) even projected that without intervention, parts of North Jakarta could be permanently inundated by 2050. In addition, previous studies and the IPCC reports determined that the increase of extreme precipitation is more uncertain across regions and scenarios than that of temperature, not excluding Indonesia (IPCC, 2023), making the attribution of extreme rainfall in amplifying the risk of flood much inconclusive. Furthermore, the differing assumptions and methods also underscore the need for more studies and standardized approaches in future assessments. Considering these gaps and the consequences of flooding in the country, many more historical flood attribution studies focus on determining the role of different factors, such as climate change and urban developments, in influencing the occurrence and severity of floods, compared to their natural variability. Once this understanding is established, future projections of flood hazards can be more accurately assessed, enabling better preparedness and mitigation strategies.

Moreover, many disasters in Indonesia are strongly linked to precipitation extremes, including both excessive rainfalls leading to floods and landslides, as well as prolonged dry spells contributing to drought and wildfires. The study (Aldrian and Djamil, 2008) identifies an increasing imbalance in the annual rainfall pattern, characterized by intensified wet–season precipitation and prolonged dry spells. This shift has heightened the risk of extreme weather events, including floods during the wet season and droughts during the dry season. The finding pattern aligns with the well–established climate change phenomenon, often summarized as ‘dry gets drier, and wet gets wetter’ (Trenberth, 2011). This study also underscores the crucial consideration of the cascading climate risks, for example, the interplay among the global climate oscillation (ENSO, MJO, IOD) driving temperature and rainfall anomaly, which induce drought, warm spells, storm surges to leading ranging impacts (Kurniadi et al., 2021; Lam et al., 2024; Supari et al., 2018).

Furthermore, this study reveals that a critical but overlooked issue in disaster studies and databases in Indonesia is the increasing threat posed by coastal hazards, i.e., storm surges, tidal waves, and sea level rise. These hazards are linked with the fact that previous studies reported Jakarta has been recognized as one of the fastest–sinking cities globally, with land subsidence rates reaching up to 280 mm/year between 1982 and 2010 (Abidin et al., 2011) and persisting at 20 mm/year in some areas (Nicholls et al., 2021). This rapid land sinking may intensify coastal flooding risks much sooner than what sea level rise projections alone would suggest. As sea levels continue to rise—estimated at 3.9 ± 0.4 mm/year globally—low–lying coastal cities experiencing subsidence will face compounded coastal hazards (Nicholls et al., 2021). Furthermore, Jakarta

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

and other coastal cities in Indonesia are highly exposed to storm surges and tidal flooding, which are expected to worsen under future climate change scenarios. Given these pressing challenges, this present study suggests that further research and more comprehensive data collection on coastal hazards and land subsidence are urgently needed.

Developing predictive models for hazards is imperative to achieve disaster risk reduction by targeting more effective adaptation and mitigation measures. This study implies that the other components of risk, namely vulnerability (i.e., resilience) and exposure, play important roles in shaping disaster risks and impacts. For instance, according to disaster reports from 2000–2024 (Indonesia Disaster Data and Information, 2024b), the fatality rate of flash floods and landslides per event is at 0.34 and 0.31, respectively, notably high, while extreme weather, wildfires, and droughts have much lower rates, below 0.05. This study reveals that the trend of climatic drivers of flood and landslide disasters (i.e., rainfall extremes) is likely to increase over the country, especially in Northern Sumatera, Kalimantan, Sulawesi, and Papua (An et al., 2023; Hariadi et al., 2023). A previous study also stressed the expected increase of rainfall extremes in highland areas, signifying the intensifying risk of landslides and flash floods in the future (Hendrawan et al., 2024). Additionally, more than 50% of Indonesia's terrain is vulnerable to landslides due to its mountainous landscape, high rainfall intensity, and ongoing land–use changes (Karnawati et al., 2013). This gives a further urge to study related vulnerability and exposure trends, particularly for such fast onset hazards. Prioritizing measures to address those frequent and disastrous hazards can significantly reduce overall disaster-related fatalities in the country, thus minimizing economic losses and building more resilient communities, ultimately improving the effectiveness of disaster risk reduction.

Lastly, future research should focus on refining these approaches by incorporating higher–resolution data and multi-scenario ensembles. Integrating advanced modeling techniques to understand better mechanisms underlying floods, droughts, landslides, storm surges, and urban heat while also addressing compound risks could mark substantial contributions to disaster management. The use of machine learning for hazard prediction offers promising opportunities to enhance accuracy and early warning capabilities. Furthermore, detailed longitudinal studies are needed to track the evolution of hazards and understand cascading effects, such as floods triggering landslides or droughts exacerbating wildfires, which remain underexplored. Building on these insights will be key to improving predictive models and informing adaptive strategies tailored to Indonesia's complex and dynamic risk landscape.

This study underscores the critical importance of adopting integrated strategies to address the compounding effects of natural hazards and disasters in Indonesia. Adaptation measures such as enhancing early warning systems, improving land–use practices, strengthening infrastructure, and fostering community–based disaster risk management are essential for reducing vulnerabilities. Mitigation efforts, including sustainable environmental practices and disaster–resilient urban planning, are equally critical for minimizing long–term risks. As the frequency and complexity of climate-related disasters increase, fostering collaboration between researchers, policymakers, and communities will be vital. Together, these efforts can help build a resilient Indonesia capable of effectively mitigating and adapting to future hazards.

5 Conclusion

This study highlights Indonesia's exposure to intensifying climate hazards, with region-specific vulnerabilities under climate projections. We highlight those northern areas covering major islands, such as Kalimantan, Sumatra, and Papua, are projected to face more frequent extreme rainfall events, driving flood risks, while southern regions, including Java and Nusa Tenggara, are increasingly susceptible to prolonged droughts due to higher consecutive dry days. We also provide clustering analysis of rainfall extremes and drought metrics, revealing distinct zones of hazard overlap and emphasizing the need for tailored regional adaptation strategies.

The findings underscore significant gaps in hazard modeling, particularly the high variability in flood projections driven by uncertainties in extreme precipitation trends and urban dynamics. In urban areas like Jakarta, land subsidence remains a dominant driver of flood risks, necessitating integrated approaches combining hydrological and socio-economic modeling. Meanwhile, drought's underestimated impacts on water resources and agriculture highlight the urgency for improved monitoring and adaptive water management in southern agricultural regions, particularly in the Indonesian rice bowl of Java. Technical advancements are also needed in integrating teleconnections (e.g., ENSO, IOD, MJO) into climate projections to better capture compound hazards and cascading risks. Future research should prioritize refining localized hazard assessments and standardizing methodologies to address these uncertainties. Further studies may also address the most significant hazards affecting most losses and damages in the country, such as flash floods and landslides, while adaptive measures, including dynamic land-use planning and resilient infrastructure development, must be implemented urgently to mitigate the escalating impacts.

6 Code availability

Code is available from the authors upon request.

7 Data availability

CRU, APHRODITE, CORDEX SEA, and CMIP6 on climate parameters and extreme indices are publicly available via https://interactive-atlas.ipcc.ch/. Indonesian disaster dataset is available through Indonesian Disaster Data and Information (DIBI) https://dibi.bnpb.go.id/.

8 Author contributions

VSAH: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. **APR**: Resources, Validation, Investigation, Writing – Review & Editing, Supervision. **HGM**:

Funding Acquisition, Conceptualization, Data Curation, Writing – Review & Editing, Visualization, Project Administration. **EA**: Writing – Review & Editing. **AM**: Writing – Review & Editing. **DK**: Writing – Review & Editing, Supervision.

9 Competing interests

The authors declare that they have no conflict of interest.

10 Financial supports

This work was funded by the Universitas Gadjah Mada (6541/UN1.P1/PT.01.03/2024).

11 References

Abidin, H. Z., Andreas, H., Gumilar, I., Fukuda, Y., Pohan, Y. E., and Deguchi, T.: Land subsidence of Jakarta (Indonesia) and its relation with urban development, Natural Hazards, 59, 1753–1771, https://doi.org/10.1007/s11069-011-9866-9, 2011.

Aitsi-Selmi, A., Egawa, S., Sasaki, H., Wannous, C., and Murray, V.: The Sendai Framework for Disaster Risk Reduction: Renewing the Global Commitment to People's Resilience, Health, and Well-being, International Journal of Disaster Risk Science, 6, 164–176, https://doi.org/10.1007/s13753-015-0050-9, 2015.

Aldrian, E. and Djamil, Y. S.: Spatio-temporal climatic change of rainfall in East Java Indonesia, International Journal of Climatology, 28, 435–448, https://doi.org/10.1002/joc.1543, 2008.

Aldrian, E. and Dwi Susanto, R.: Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature, International Journal of Climatology, 23, 1435–1452, https://doi.org/10.1002/joc.950, 2003.

Alexander, L. V., Zhang, X., Peterson, T. C., Caesar, J., Gleason, B., Klein Tank, A. M. G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D. B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M., and Vazquez-Aguirre, J. L.: Global observed changes in daily climate extremes of temperature and precipitation, Journal of Geophysical Research Atmospheres, 111, 1–22, https://doi.org/10.1029/2005JD006290, 2006.

Amien, I., Rejekiningrum, P., Pramudia, A., and Susanti, E.: Effects of interannual climate variability and climate change on rice yield in Java, Indonesia, Water Air Soil Pollut, 92, 29–39, https://doi.org/10.1007/BF00175550, 1996.

An, D., Eggeling, J., Zhang, L., He, H., Sapkota, A., Wang, Y. C., and Gao, C.: Extreme precipitation patterns in the Asia–Pacific region and its correlation with El Niño-Southern Oscillation (ENSO), Sci Rep, 13, https://doi.org/10.1038/s41598-023-38317-0, 2023.

Auer Frege, I., Bradshaw, S., Dijkzeul, D., and others: World Risk Report 2023: Focus: Diversity, Bündnis Entwicklung Hilft, Berlin, 2023.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Barkey, R., Nursaputra, M., and Mappiase, M. F.: Assessing drought vulnerability using climate change models around Bantimurung Bulusaraung National Park, Indonesia, in: IOP Conference Series: Earth and Environmental Science, https://doi.org/10.1088/1755-1315/270/1/012007, 2019.

Indonesia Disaster Data and Information: https://dibi.bnpb.go.id/, last access: 24 November 2024a.

Indonesia Disaster Data and Information: https://dibi.bnpb.go.id/, last access: 31 December 2024b.

Botzen, W. J. W., Deschenes, O., and Sanders, M.: The economic impacts of natural disasters: A review of models and empirical studies, https://doi.org/10.1093/reep/rez004, 1 August 2019.

Budiyono, Y., Aerts, J. C. J. H., Tollenaar, D., and Ward, P. J.: River flood risk in Jakarta under scenarios of future change, Natural Hazards and Earth System Sciences, 16, 757–774, https://doi.org/10.5194/nhess-16-757-2016, 2016.

Cai, W., Santoso, A., Wang, G., Yeh, S.-W., An, S.-I., Cobb, K. M., Collins, M., Guilyardi, E., Jin, F.-F., Kug, J.-S., Lengaigne, M., McPhaden, M. J., Takahashi, K., Timmermann, A., Vecchi, G., Watanabe, M., and Wu, L.: ENSO and greenhouse warming, Nat Clim Chang, 5, 849–859, https://doi.org/10.1038/nclimate2743, 2015.

Chang, C. P., Li, T., and Yang, S.: Seasonal Prediction of Boreal Winter Rainfall over the Western Maritime Continent during ENSO, Journal of Meteorological Research, 34, 294–303, https://doi.org/10.1007/s13351-020-9181-z, 2020.

Chapagain, D., Bharati, L., and Borgemeister, C.: Declining vulnerability but rising impacts: the trends of climatic disasters in Nepal, Reg Environ Change, 22, https://doi.org/10.1007/s10113-022-01903-5, 2022.

Chen, C. C., Lin, H. W., Yu, J. Y., and Lo, M. H.: The 2015 Borneo fires: What have we learned from the 1997 and 2006 El Niños?, Environmental Research Letters, 11, https://doi.org/10.1088/1748-9326/11/10/104003, 2016.

EM-DAT: The Emergency Events Database: https://www.emdat.be/.

CRED, U.: Economic losses, poverty & disasters, 2018.

Cutter, S. L.: The Changing Nature of Hazard and Disaster Risk in the Anthropocene, Ann Am Assoc Geogr, 111, 819–827, https://doi.org/10.1080/24694452.2020.1744423, 2021.

Djalante, R.: Review article: A systematic literature review of research trends and authorships on natural hazards, disasters, risk reduction and climate change in Indonesia, Natural Hazards and Earth System Sciences, 18, 1785–1810, https://doi.org/10.5194/nhess-18-1785-2018, 2018.

Djamres, E. K. D., Komori, D., and Kazama, S.: Topographical Characteristics of Frequent Inland Water Flooding Areas in Tangerang City, Indonesia, Frontiers in Water, 3, https://doi.org/10.3389/frwa.2021.661299, 2021.

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., Willett, K. M., Aguilar, E., Brunet, M., Caesar, J., Hewitson, B., Jack, C., Klein Tank, A. M. G., Kruger, A. C., Marengo, J., Peterson, T. C., Renom, M., Oria Rojas, C., Rusticucci, M., Salinger, J., Elrayah, A. S., Sekele, S. S., Srivastava, A. K., Trewin, B., Villarroel, C., Vincent, L. A., Zhai, P., Zhang, X., and Kitching, S.: Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset, Journal of Geophysical Research Atmospheres, 118, 2098–2118, https://doi.org/10.1002/jgrd.50150, 2013.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Easterling, D. R., Kunkel, K. E., Wehner, M. F., and Sun, L.: Detection and attribution of climate extremes in the observed record, Weather Clim Extrem, 11, 17–27, https://doi.org/10.1016/j.wace.2016.01.001, 2016.

Fan, Y., Li, J., Zhu, S., Li, H., and Zhou, B.: Trends and variabilities of precipitation and temperature extremes over Southeast Asia during 1981–2017, Meteorology and Atmospheric Physics, 134, https://doi.org/10.1007/s00703-022-00913-6, 2022.

Farahnaz, N., Kuntoro, A. A., Syahril, M., and Kusuma, B.: Statistical Downscaling for the Projection of the Keetch Byram Drought Index in the Barito Basin, 10, 2020.

Farid, M., Sihombing, Y. I., Kuntoro, A. A., Adityawan, M. B., Syuhada, M. M., Januriyadi, N. F., Moe, I. R., and Nurhakim, A.: Development of flood hazard index under climate change scenarios in Java Island, Progress in Disaster Science, 20, https://doi.org/10.1016/j.pdisas.2023.100302, 2023.

Ferijal, T. and Fauzi, A.: Analysis of Local Climate Change Impacts on the Rainfall Patterns and Dry Spells in Banda Aceh and Aceh Besar, Indonesia, International Journal of Design and Nature and Ecodynamics, 19, 947–954, https://doi.org/10.18280/ijdne.190324, 2024.

Fernandes, K., Verchot, L., Baethgen, W., Gutierrez-Velez, V., Pinedo-Vasquez, M., and Martius, C.: Heightened fire probability in Indonesia in non-drought conditions: The effect of increasing temperatures, Environmental Research Letters, 12, https://doi.org/10.1088/1748-9326/aa6884, 2017.

Field, R. D., Van Der Werf, G. R., and Shen, S. S. P.: Human amplification of drought-induced biomass burning in Indonesia since 1960, Nat Geosci, 2, 185–188, https://doi.org/10.1038/ngeo443, 2009.

Formetta, G. and Feyen, L.: Empirical evidence of declining global vulnerability to climate-related hazards, Global Environmental Change, 57, https://doi.org/10.1016/j.gloenvcha.2019.05.004, 2019.

Giannini, A., Robertson, A. W., and Qian, J. H.: A role for tropical tropospheric temperature adjustment to El Niño-Southern Oscillation in the seasonality of monsoonal Indonesia precipitation predictability, Journal of Geophysical Research Atmospheres, 112, 1–14, https://doi.org/10.1029/2007JD008519, 2007.

De Groeve, Tom., Poljansek, Karmen., Ehrlich, Daniele., and European Commission. Joint Research Centre. Institute for the Protection and the Security of the Citizen.: Recording disaster losses : recommendations for a European approach., Publications Office, 2013.

Gusyev, M., Hasegawa, A., Magome, J., Sanchez, P., Sugiura, A., Umino, H., Sawano, H., and Tokunaga, Y.: Evaluation of water cycle components with standardized indices under climate change in the Pampanga, Solo and Chao phraya basins, Journal of Disaster Research, 11, 1091–1102, https://doi.org/10.20965/jdr.2016.p1091, 2016.

Hariadi, M. H., van der Schrier, G., Steeneveld, G. J., Ratri, D. N., Sopaheluwakan, A., Tank, A. K., Aldrian, E., Gunawan, D., Moine, M. P., Bellucci, A., Senan, R., Tourigny, E., Putrasahan, D. A., and Linarka, U. A.: Evaluation of extreme precipitation over Southeast Asia in the Coupled Model Intercomparison Project Phase 5 regional climate model results and HighResMIP global climate models, International Journal of Climatology, 43, 1639–1659, https://doi.org/10.1002/joc.7938, 2023.

Harris, I., Osborn, T. J., Jones, P., and Lister, D.: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset, Sci Data, 7, 1–18, https://doi.org/10.1038/s41597-020-0453-3, 2020.

Hasegawa, A., Gusyev, M., and Iwami, Y.: Meteorological drought and flood assessment using the comparative SPI approach in Asia under climate change, Journal of Disaster Research, 11, 1082–1090, https://doi.org/10.20965/jdr.2016.p1082, 2016.

Heim, R. R.: An overview of weather and climate extremes - Products and trends, https://doi.org/10.1016/j.wace.2015.11.001, 2015.

Hendrawan, V. S. A., Kim, W., and Komori, D.: Crop response pattern to several drought timescales and its possible determinants: A global-scale analysis during the last decades, Anthropocene, 43, https://doi.org/10.1016/j.ancene.2023.100389, 2023a.

Hendrawan, V. S. A., Komori, D., and Kim, W.: Possible factors determining global-scale patterns of crop yield sensitivity to drought, PLoS One, 18, 1–20, https://doi.org/10.1371/journal.pone.0281287, 2023b.

Hendrawan, V. S. A., Mawandha, H. G., Sakti, A. D., Karlina, Andika, N., Shahid, S., and Jayadi, R.: Future exposure of rainfall and temperature extremes to the most populous island of Indonesia: A projection based on CORDEX simulation, International Journal of Climatology, 44, 3529–3547, https://doi.org/10.1002/joc.8537, 2024.

Heo, S., Park, S., and Lee, D. K.: Multi-hazard exposure mapping under climate crisis using random forest algorithm for the Kalimantan Islands, Indonesia, Sci Rep, 13, https://doi.org/10.1038/s41598-023-40106-8, 2023.

Hohl, R., Jiang, Z., Tue Vu, M., Vijayaraghavan, S., and Liong, S. Y.: Using a regional climate model to develop index-based drought insurance for sovereign disaster risk transfer, Agricultural Finance Review, 81, 151–168, https://doi.org/10.1108/AFR-02-2020-0020, 2021.

Huggel, C., Stone, D., Auffhammer, M., and Hansen, G.: Loss and damage attribution, https://doi.org/10.1038/nclimate1961, August 2013.

IFRC: DREF OPERATION Indonesia: Drought Response 2023, 2023.

IPCC: Climate Change 2007: Impacts, Adaptation and Vulnerability, 2007.

IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by: Field, C. B., Barros, V., Stocker, T. F., and Dahe, Q., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 1–582 pp., https://doi.org/10.1017/CBO9781139177245, 2012.

IPCC: Climate Change 2022: Impacts, Adaptation and Vulnerability, Cambridge University Press, Cambridge, UK and New York, USA, 3–33 pp., 2022.

IPCC: Climate Change 2023: Synthesis Report, in: The Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: H. Lee and J. Romero, IPCC, Geneva, Switzerland, 35–115, 2023.

Irawan, A. N. R., Komori, D., and Hendrawan, V. S. A.: Correlation analysis of agricultural drought risk on wet farming crop and meteorological drought index in the tropical-humid region, Theor Appl Climatol, 153, https://doi.org/10.1007/s00704-023-04461-w, 2023.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Januriyadi, N. F., Kazama, S., Moe, I. R., and Kure, S.: Evaluation of future flood risk in asian megacities: A case study of Jakarta, Hydrological Research Letters, 12, 14–22, https://doi.org/10.3178/hrl.12.14, 2018.

Karnawati, D., Maarif, S., Fathani, T. F., and Wilopo, W.: Development of socio-technical approach for landslide mitigation and risk reduction program in Indonesia, ASEAN Engineering Journal, 2, 22–49, 2013.

Kryspin-Watson, J., Vun, Y. J., Stanton-Geddes, Z., and Semadeni, G. S.: Strengthening the Disaster Resilience of Indonesian Cities: A Policy Note, 2020.

Kurniadi, A., Weller, E., Min, S. K., and Seong, M. G.: Independent ENSO and IOD impacts on rainfall extremes over Indonesia, International Journal of Climatology, 41, 3640–3656, https://doi.org/10.1002/joc.7040, 2021.

Kurniadi, A., Weller, E., Kim, Y. H., and Min, S. K.: Evaluation of Coupled Model Intercomparison Project Phase 6 model-simulated extreme precipitation over Indonesia, International Journal of Climatology, 43, 174–196, https://doi.org/10.1002/joc.7744, 2023.

Kurniadi, A., Weller, E., Salmond, J., and Aldrian, E.: Future projections of extreme rainfall events in Indonesia, International Journal of Climatology, 44, 160–182, https://doi.org/10.1002/joc.8321, 2024.

Lam, T., Catto, J. L., Barciela, R., Harper, A. B., Challenor, P., and Arribas, A.: Quantifying causal teleconnections to drought and fire risks in Indonesian Borneo, International Journal of Climatology, 44, 2087–2105, https://doi.org/10.1002/joc.8442, 2024.

Legg, S.: IPCC, 2021: Climate change 2021 The Physical Science Basis, Interaction, 49, 44–45, 2021.

Lestari, R. K., Watanabe, M., Imada, Y., Shiogama, H., Field, R. D., Takemura, T., and Kimoto, M.: Increasing potential of biomass burning over Sumatra, Indonesia induced by anthropogenic tropical warming, Environmental Research Letters, 9, https://doi.org/10.1088/1748-9326/9/10/104010, 2014.

Liang, S., Wang, D., Ziegler, A. D., Li, L. Z. X., and Zeng, Z.: Madden–Julian Oscillation-induced extreme rainfalls constrained by global warming mitigation, NPJ Clim Atmos Sci, 5, https://doi.org/10.1038/s41612-022-00291-1, 2022.

McGlade, J., Bankoff, G., Abrahams, J., Cooper-Knock, S. J., Cotecchia, F., Desanker, P., Erian, W., Gencer, E., Gibson, L., Girgin, S., and others: Global assessment report on disaster risk reduction 2019, 2019.

McKee, T., Doesken, N., and Kleist, J.: The relationship of drought frequency and duration to time scales, in: Proc. 8th Conf. on Applied Climatology, 179–183, 1993.

Meehl, G. A. and Tebaldi, C.: More intense, more frequent, and longer lasting heat waves in the 21st century, Science (1979), 305, 994–997, https://doi.org/10.1126/science.1098704, 2004.

Mishra, B. K., Rafiei Emam, A., Masago, Y., Kumar, P., Regmi, R. K., and Fukushi, K.: Assessment of future flood inundations under climate and land use change scenarios in the Ciliwung River Basin, Jakarta, J Flood Risk Manag, 11, S1105–S1115, https://doi.org/10.1111/jfr3.12311, 2018.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Antes, G., Atkins, D., Barbour, V., Barrowman, N., Berlin, J. A., Clark, J., Clarke, M., Cook, D., D'Amico, R., Deeks, J. J., Devereaux, P. J., Dickersin, K., Egger, M., Ernst, E., Gøtzsche, P. C.,

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Grimshaw, J., Guyatt, G., Higgins, J., Ioannidis, J. P. A., Kleijnen, J., Lang, T., Magrini, N., McNamee, D., Moja, L., Mulrow, C., Napoli, M., Oxman, A., Pham, B., Rennie, D., Sampson, M., Schulz, K. F., Shekelle, P. G., Tovey, D., and Tugwell, P.: Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement, https://doi.org/10.1371/journal.pmed.1000097, 1 July 2009.

Moore, T. R., Matthews, H. D., Simmons, C., and Leduc, M.: Quantifying Changes in Extreme Weather Events in Response to Warmer Global Temperature, Atmosphere - Ocean, 53, 412–425, https://doi.org/10.1080/07055900.2015.1077099, 2015.

Mubarrok, S. and Jang, C. J.: Annual Maximum Precipitation in Indonesia and Its Association to Climate Teleconnection Patterns: An Extreme Value Analysis, Scientific Online Letters on the Atmosphere, 18, 187–192, https://doi.org/10.2151/SOLA.2022-030, 2022.

Naylor, R. L., Falcon, W. P., Rochberg, D., and Wada, N.: Using El Niño/Southern Oscillation climate data to predict rice production in Indonesia, Clim Change, 50, 255–265, https://doi.org/10.1023/A:1010662115348, 2001.

Newman, R. and Noy, I.: The global costs of extreme weather that are attributable to climate change, Nat Commun, 14, https://doi.org/10.1038/s41467-023-41888-1, 2023.

Ngai, S. T., Tangang, F., and Juneng, L.: Bias correction of global and regional simulated daily precipitation and surface mean temperature over Southeast Asia using quantile mapping method, Glob Planet Change, 149, 79–90, https://doi.org/10.1016/j.gloplacha.2016.12.009, 2017.

Ngai, S. T., Juneng, L., Tangang, F., Chung, J. X., Supari, S., Salimun, E., Cruz, F., Ngo-Duc, T., Phan-Van, T., Santisirisomboon, J., and Gunawan, D.: Projected mean and extreme precipitation based on bias-corrected simulation outputs of CORDEX Southeast Asia, Weather Clim Extrem, 37, https://doi.org/10.1016/j.wace.2022.100484, 2022.

Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., Hanson, S. E., Merkens, J.-L., and Fang, J.: A global analysis of subsidence, relative sea-level change and coastal flood exposure, Nat Clim Chang, 11, 338–342, https://doi.org/10.1038/s41558-021-00993-z, 2021.

Odériz, I., Losada, I. J., Silva, R., and Mori, N.: On the need to integrate interannual natural variability into coastal multihazard assessments, Sci Rep, 14, https://doi.org/10.1038/s41598-024-67679-2, 2024.

O'Neill, B. C., Tebaldi, C., Van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J. F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci Model Dev, 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016.

Peduzzi, P., Dao, H., Herold, C., and Mouton, F.: Assessing global exposure and vulnerability towards natural hazards: The Disaster Risk Index, Natural Hazards and Earth System Science, 9, 1149–1159, https://doi.org/10.5194/nhess-9-1149-2009, 2009.

Peterson, T., Folland, C., Gruza, G., Hogg, W., Mokssit, A., Plummer, N., and others: Report on the activities of the working group on climate change detection and related rapporteurs, World Meteorological Organization Geneva, 2001.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Priyambodho, B. A., Kure, S., Januriyadi, N. F., Farid, M., Varquez, A. C. G., Kanda, M., and Kazama, S.: Effects of Urban Development on Regional Climate Change and Flood Inundation in Jakarta, Indonesia, Journal of Disaster Research, 17, 516–525, https://doi.org/10.20965/jdr.2022.p0516, 2022.

Quinn, W. H., Neal, V. T., and Antunez De Mayolo, S. E.: El Niño occurrences over the past four and a half centuries, J Geophys Res Oceans, 92, 14449–14461, https://doi.org/https://doi.org/10.1029/JC092iC13p14449, 1987.

Rendana, M., Idris, W. M. R., Rahim, S. A., Abdo, H. G., Almohamad, H., Al Dughairi, A. A., and Albanai, J. A.: Current and future land fire risk mapping in the southern region of Sumatra, Indonesia, using CMIP6 data and GIS analysis, SN Appl Sci, 5, https://doi.org/10.1007/s42452-023-05432-6, 2023.

Roberts, Mark., Gil Sander, Federico., and Tiwari, Sailesh.: Time to act : realizing Indonesia's urban potential, World Bank Group, 305 pp., 2019.

Ruane, A. C., Vautard, R., Ranasinghe, R., Sillmann, J., Coppola, E., Arnell, N., Cruz, F. A., Dessai, S., Iles, C. E., Islam, A. K. M. S., Jones, R. G., Rahimi, M., Carrascal, D. R., Seneviratne, S. I., Servonnat, J., Sörensson, A. A., Sylla, M. B., Tebaldi, C., Wang, W., and Zaaboul, R.: The Climatic Impact-Driver Framework for Assessment of Risk-Relevant Climate Information, Earths Future, 10, https://doi.org/10.1029/2022EF002803, 2022.

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrao, H., Dunbar, M. B., Singleton, A., Montagna, P., Barbola, P., and Vogt, J. V.: Magnitude of extreme heat waves in present climate and their projection in a warming world, Journal of Geophysical Research Atmospheres, 119, 12,500-12,512, https://doi.org/10.1002/2014JD022098, 2014.

Semedo, A., Weisse, R., Behrens, A., Sterl, A., Bengtsson, L., and Günther, H.: Projection of global wave climate change toward the end of the twenty-first century, J Clim, 26, 8269–8288, https://doi.org/10.1175/JCLI-D-12-00658.1, 2013.

Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., Rusticucci, M., Semenov, V., Alexander, L. V., Allen, S., Benito, G., Cavazos, T., Clague, J., Conway, D., Della-Marta, P. M., Gerber, M., Gong, S., Goswami, B. N., Hemer, M., Huggel, C., van den Hurk, B., Kharin, V. V., Kitoh, A., Tank, A. M. G. K., Li, G., Mason, S., McGuire, W., van Oldenborgh, G. J., Orlowsky, B., Smith, S., Thiaw, W., Velegrakis, A., Yiou, P., Zhang, T., Zhou, T., and Zwiers, F. W.: Changes in Climate Extremes and their Impacts on the Natural Physical Environment, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, edited by: Field, C. B., Barros, V., Stocker, T. F., and Dahe, Q., Cambridge University Press, Cambridge, 109–230, https://doi.org/10.1017/CBO9781139177245.006, 2012.

Setiawati, M. D., Jarzebski, M. P., Gomez-Garcia, M., and Fukushi, K.: Accelerating Urban Heating Under Land-Cover and Climate Change Scenarios in Indonesia: Application of the Universal Thermal Climate Index, Front Built Environ, 7, https://doi.org/10.3389/fbuil.2021.622382, 2021.

Sugianto, D. N., Suryadi, Y., Wijayanti, H. S., and Afifah, D. N.: Identification of the Increase in the Air Temperature of the North Coast of Central Java as an Indicator of Climate Change: Semarang Station Climatology Data 1970-2017, 2020.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Sun, X., Ge, F., Chen, Q., Fraedrich, K., and Li, X.: How Striking Is the Intergenerational Difference in Exposure to Compound Heatwaves Over Southeast Asia?, Earths Future, 11, https://doi.org/10.1029/2022EF003179, 2023.

Supari, Tangang, F., Juneng, L., and Aldrian, E.: Observed changes in extreme temperature and precipitation over Indonesia, International Journal of Climatology, 37, 1979–1997, https://doi.org/10.1002/joc.4829, 2017.

Supari, Tangang, F., Salimun, E., Aldrian, E., Sopaheluwakan, A., and Juneng, L.: ENSO modulation of seasonal rainfall and extremes in Indonesia, Clim Dyn, 51, 2559–2580, https://doi.org/10.1007/s00382-017-4028-8, 2018.

Supari, Tangang, F., Juneng, L., Cruz, F., Chung, J. X., Ngai, S. T., Salimun, E., Mohd, M. S. F., Santisirisomboon, J., Singhruck, P., PhanVan, T., Ngo-Duc, T., Narisma, G., Aldrian, E., Gunawan, D., and Sopaheluwakan, A.: Multi-model projections of precipitation extremes in Southeast Asia based on CORDEX-Southeast Asia simulations, Environ Res, 184, https://doi.org/10.1016/j.envres.2020.109350, 2020.

Takagi, H., Esteban, M., Mikami, T., and Fujii, D.: Projection of coastal floods in 2050 Jakarta, Urban Clim, 17, 135–145, https://doi.org/10.1016/j.uclim.2016.05.003, 2016.

Tangang, F., Supari, S., Chung, J. X., Cruz, F., Salimun, E., Ngai, S. T., Juneng, L., Santisirisomboon, J., Santisirisomboon, J., Ngo-Duc, T., Phan-Van, T., Narisma, G., Singhruck, P., Gunawan, D., Aldrian, E., Sopaheluwakan, A., Nikulin, G., Yang, H., Remedio, A. R. C., Sein, D., and Hein-Griggs, D.: Future changes in annual precipitation extremes over Southeast Asia under global warming of 2°C, APN Science Bulletin, 8, https://doi.org/10.30852/sb.2018.436, 2018.

Tangang, F., Chung, J. X., Juneng, L., Supari, Salimun, E., Ngai, S. T., Jamaluddin, A. F., Mohd, M. S. F., Cruz, F., Narisma, G., Santisirisomboon, J., Ngo-Duc, T., Van Tan, P., Singhruck, P., Gunawan, D., Aldrian, E., Sopaheluwakan, A., Grigory, N., Remedio, A. R. C., Sein, D. V., Hein-Griggs, D., McGregor, J. L., Yang, H., Sasaki, H., and Kumar, P.: Projected future changes in rainfall in Southeast Asia based on CORDEX–SEA multi-model simulations, Clim Dyn, 55, 1247–1267, https://doi.org/10.1007/s00382-020-05322-2, 2020.

Trenberth, K. E.: Changes in precipitation with climate change, Clim Res, 47, 123–138, https://doi.org/10.3354/cr00953, 2011.

Tunas, I. G., Tanga, A., and Oktavia, S. R.: Impact of landslides induced by the 2018 palu earthquake on flash flood in bangga river Basin, Sulawesi, Indonesia, Journal of Ecological Engineering, 21, 190–200, https://doi.org/10.12911/22998993/116325, 2020.

UNISDR: Sendai framework for disaster risk reduction 2015– 2030, Sendai, 2015.

Vogel, M. M., Hauser, M., and Seneviratne, S. I.: Projected changes in hot, dry and wet extreme events' clusters in CMIP6 multi-model ensemble, Environmental Research Letters, 15, https://doi.org/10.1088/1748-9326/ab90a7, 2020.

Wang, X., Wang, Y., Lin, Q., and Yang, X.: Assessing Global Landslide Casualty Risk Under Moderate Climate Change Based on Multiple GCM Projections, International Journal of Disaster Risk Science, 14, 751–767, https://doi.org/10.1007/s13753-023-00514-w, 2023.

Watterson, I. G.: Influence of Sea Surface Temperature on Simulated Future Change in Extreme Rainfall in the Asia-Pacific, Asia Pac J Atmos Sci, 56, 349–366, https://doi.org/10.1007/s13143-019-00141-w, 2020.

https://doi.org/10.5194/egusphere-2025-584
Preprint. Discussion started: 10 June 2025

Willner, S. N., Levermann, A., Zhao, F., and Frieler, K.: Adaptation required to preserve future high-end river flood risk at present levels, 2018.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N., and Kitoh, A.: Aphrodite constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges, Bull Am Meteorol Soc, 93, 1401–1415, https://doi.org/10.1175/BAMS-D-11-00122.1, 2012.

Zain, A., Legono, D., Rahardjo, A. P., and Jayadi, R.: Review on Co-factors Triggering Flash Flood Occurrences in Indonesian Small Catchments, in: IOP Conference Series: Earth and Environmental Science, https://doi.org/10.1088/1755-1315/930/1/012087, 2021.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B., and Zwiers, F. W.: Indices for monitoring changes in extremes based on daily temperature and precipitation data, Wiley Interdiscip Rev Clim Change, 2, 851–870, https://doi.org/10.1002/wcc.147, 2011.