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Review article

Indonesia Climate Change: Observations and Future Projections in IPCC AR6 WG I and Beyond

Tosiyuki Nakaegawa[1,*], Takuro Kobashi[2]

[1] Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki, Japan; [2] Graduate School of Environmental Studies, Tohoku University, Japan

[*)] Correspondence: tnakaega@mri-jma.go.jp

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Abstract

This study aimed to comprehensively review and synthesize results specific to the Indonesian archipelago from the IPCC Sixth Assessment Report (AR6) Working Group I, "The Physical Science Basis." At the heart of the Indo-Pacific maritime continent, Indonesia's climate was undergoing significant anthropogenic alteration owing to complex atmospheric and oceanic processes. The review distilled pertinent observations, trends, and projections, while also offering a detailed analysis of the underlying physical science. The observed changes included a significant rise in tropospheric ozone since the 1990s, a persistent trend towards a La Niña-like state in the Pacific Walker Circulation, accelerated warming of surrounding tropical oceans, and increased multi-decadal variability in the Indonesian Throughflow. The regional water cycle was also intensifying, marked by an increase in rainfall extremes which occurred against a background of powerful climate variability modes such as El Niño-Southern Oscillation and Indian Ocean Dipole, contributing to severe events such as the 2015-2016 drought and fire crisis. Future projections assessed with high confidence pointed towards a decrease in annual mean precipitation with particularly severe drying of up to 30% projected for the summer months over key islands. These multifaceted changes have profound implications for Indonesia's environmental stability, socioeconomic development, and population well-being, underscoring the critical urgency for science-informed, targeted climate adaptation and mitigation strategies.

Keywords: Indonesia; Future Climate Changes; IPCC; AR6; WGI; Extreme.

1. Introduction

IPCC's Sixth Assessment Report (AR6) (IPCC, 2023) is said to represent the most comprehensive and up-to-date assessment of the physical science of climate change. The conclusions are unequivocal as human influence has warmed the atmosphere, ocean, and land, leading to widespread and rapid changes in the climate system. Although global scale metrics such as the rise in global mean surface temperature provide a crucial benchmark, a granular understanding of regional climate change is crucial for effective risk assessment and adaptation planning. Nowhere is this more critical than for Indonesia, the world's largest archipelagic state, whose population, economy, and unique biodiversity are exceptionally vulnerable to climate shifts. This is exemplified in the rise of tropospheric ozone, the shift of the Pacific Walker Circulation (Glossary in detail) to La Niña-like conditions (Glossary in detail), accelerated warming of the tropical oceans, and increased multidecadal variability in Indonesian Throughflow (ITF) (Glossary in detail).

This study synthesizes and analyses the specific results for Indonesia presented across the chapters of the AR6 WGI report (IPCC, 2021). Although grounded in the comprehensive assessment of AR6 WGI, the analysis further integrates critical results from recent and peer-reviewed literature published after AR6. These post-AR6 studies often provide higher-resolution insights, refine the understanding of complex processes, or validate early AR6 projections with new observational evidence, thereby enriching the detailed narrative of regional climate change. The objective is to construct a detailed narrative of climate change in the region, moving from observed historical trends in the atmosphere and oceans to the altered dynamics of the water cycle and extreme events, culminating in an assessment of future climate projections. By rephrasing and substantially elaborating on the core scientific statements cited in the report and recent advancements, this study aims to provide a deeper and more contextualized understanding of the physical basis of climate change in Indonesia, making the vast body of IPCC publications more accessible and relevant for regional stakeholders, scientists, and policymakers. This is to confirm that the IPCC AR6 is composed of three working groups. To avoid covering too many topics, this study focuses only on WG I. Therefore, the impacts, adaptation and vulnerability of WG II, as well as the mitigation of climate change of WG III are out of scope.

2. Research Methods

The initial search in IPCC AR6 WG I was conducted using the keyword "Indonesia", and the resulting sentence and reference information were subsequently extracted from the report. The term "Indonesia" was mentioned 80 times in the entire IPCC AR6 WG I, and 33 times in the main text, captions of tables and figures. A total of approximately 50 cited articles relevant to Indonesia have been collated and reviewed. The review process was used to select the articles that were to be included in the following summary.

Furthermore, recent post-AR6 studies have been searched using essential keywords with the addition of relevant keywords such as "changes", "future", and "historical" to the search terms "Indonesia" and "climate". Through Google Scholar, a scientific peer-reviewed literature search engine was used due to the comprehensive coverage of scientific articles. The articles cited in this study have undergone the peer-review process. In instances where the evaluation of a peer-reviewed article or grey literature proved challenging, the adoption of databases such as SCOPUS and Web of Science was recommended as these repositories exclusively contained journals that underwent rigorous evaluation. An exception to the peer review process was permitted for publications by Badan Meteorologi, Klimatologi, and Geofisika (BMKG), due to the crucial nature of the information provided by the governmental institute for the present article.

3. Observed Changes in the Atmospheric and Oceanic Systems

Indonesia's climate was intrinsically connected to the state of the vast atmospheric and oceanic systems that converged. AR6 presented clear evidence that these systems were undergoing fundamental changes, with direct and measurable impacts on the archipelago.

3.1. Atmospheric Composition: The Rise of Tropospheric Ozone

Tropospheric ozone (O3), a potent greenhouse gas, was also a key short-lived climate forcer. In contrast to the beneficial stratospheric ozone, it was detrimental to human health and ecosystems. Cooper *et al.* (2020) identified a strong and concerning trend of increasing tropospheric ozone since the mid-1990s (Figure 1). Based on a combination of commercial aircraft, ozone sonde, and satellite data, the report outlined that the most pronounced increases have occurred in the northern tropics (Gaudel *et al.,* 2020). Specifically, the region comprising Southern Asia and Indonesia had experienced decadal increases of 8% to 14% (3–6 ppbv), a rate significantly higher than that in the northern midlatitudes (2–7% per decade).

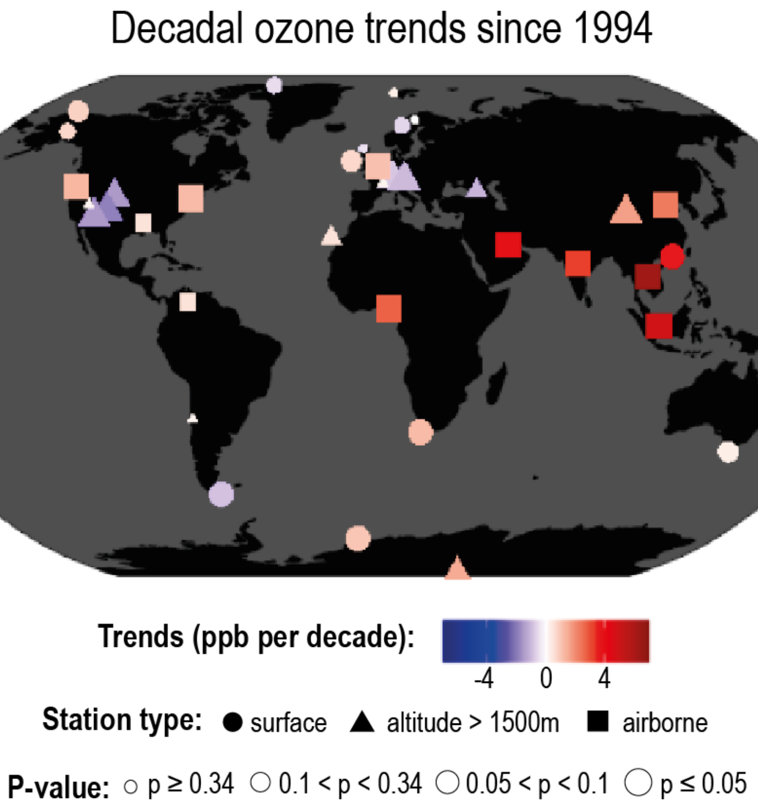

Figure 1. Decadal tropospheric ozone trends since 1994. Trends are shown at 28 remote and regionally representative surface sites (Cooper *et al.,* 2020) and in 11 regions of the lower free troposphere (650 hPa, about 3.5 km) as measured by In-Service Aircraft for a Global Observing System (IAGOS) above Europe, north-eastern USA, south-eastern USA, western North America, north-east China, South East Asia, southern India, the Persian Gulf, Malaysia/Indonesia, the Gulf of Guinea and northern South America (Gaudel *et al.,* 2020). High-elevation surface sites are >1500 m above sea level. All trends end with the most recently available year but begin in 1995 or 1994. (Figure 6 in IPCC AR6 WG1(IPCC, 2021)).

The drivers of this trend were complex and connected to rising anthropogenic emissions of precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) from industrial activities and transportation. However, widespread biomass burning was a critical driver in this region. To reinforce this point, recent studies have zeroed in on the outsized impact of these sources. Studies using advanced chemical transport models showed that emissions from forest and peatland fires a recurring issue in Indonesia were major regional sources of ozone precursors (Rosanka *et al.,* 2021). Furthermore, these fire emissions dominated regional atmospheric chemistry during severe drought years, leading to sharp spikes in surface ozone that posed significant health risks (Hein *et al.,* 2022).

3.2. Large-Scale Circulation: A Shifting Walker Circulation

The climate of the tropical Pacific, including Indonesia, was dominated by the Walker Circulation, an atmospheric pattern characterized by rising air over the warm Indo-Pacific and sinking air over the cooler eastern Pacific, which drove the trade winds. This pattern represented a significant long-term shift in the system (McGregor *et al.,* 2014). Observations showed rising sea level pressure over the eastern Pacific and falling pressure over Indonesia, which had strengthened Pacific trade winds. This observed strengthening which implied a systemic shift towards a more La Niña-like mean state, presented a significant puzzle for climate scientists.

Recent studies since IPCC AR6 showed that the Pacific Walker circulation (PWC) had shifted toward a stronger and more La Niña-like state, amplifying ascent and moisture over the Maritime Continent and producing wetter and warmer conditions across Southeast Asia. This evolving pattern increased the frequency and intensity of regional extremes (heavy rain, floods, and heatwaves) around Indonesia, while the equatorial Pacific became drier. Observations and high-resolution reanalysis (1940–2022) further showed that these changes were not fully explained by El Niño-Southern Oscillation (ENSO, see Glossary in detail) and could reflect forced changes plus internal variability, posing challenges for models and regional projections (Dong *et al.,* 2024).

3.3. Oceanic Dynamics: A Warming Realm and Variable Throughflow

The oceans surrounding Indonesia have been warming at an accelerated rate. The IPCC asserted that since 1950, tropical oceans have warmed faster than other regions with the most rapid warming observed in the tropical Indian and western Pacific Oceans. This area, often referred to as the Indo-Pacific Warm Pool, was the largest expanse of warm water on Earth and acted as the primary heat engine for the global atmosphere. Accelerated warming was driven by a combination of local atmosphere-ocean feedback mechanisms, the trends in Walker Circulation, and the dynamics of the ITF.

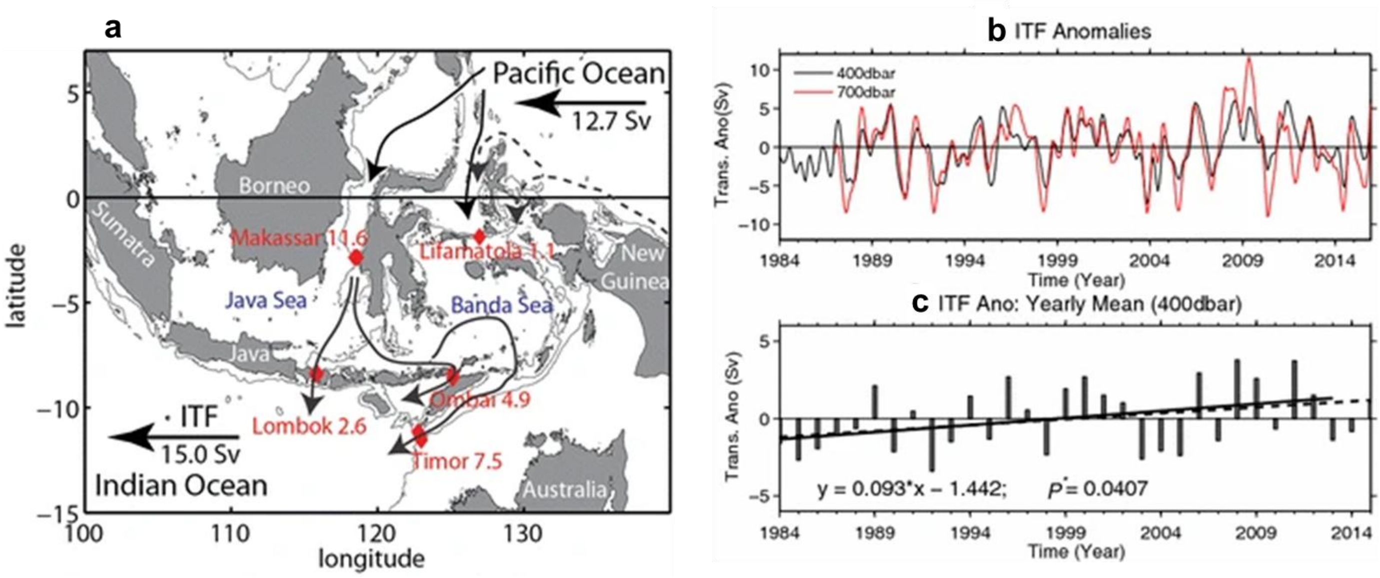

Figure 2. (a) Transport of the currents contributing to the Indonesian Throughflow via different passages. Transport of the currents contributing to the Indonesian Throughflow (ITF) via different passages through the Indonesian archipelago. The ITF transport anomalies estimated by IX1 XBT data. (b) Monthly time series of the ITF transport anomalies estimated by IX1 XBT temperature records and monthly T–S relationship, with reference depths of 400 and 700 m, respectively, from January 1984 to December 2015. (c) Annual mean ITF transport anomalies with a reference depth of 400 dbar, and the linear trends during 1984–2013, and during 1984–2015. The linear regression coefficients and 95% significance test are for the 1984–2013 period. (Figures 1 and 2 of Feng et al., 2018).

The ITF was a unique and globally significant network of ocean currents that acted as the only low-latitude conduit for water between major oceans, transporting vast quantities of warm, fresh water from the Pacific to the Indian Ocean through the Indonesian archipelago. This flow played a crucial role in regulating the heat and freshwater balance of both ocean basins and influences the global climate patterns. AR6 assessed that the ITF exhibited substantial variability on seasonal, interannual, and decadal timescales (Feng *et al.,* 2018; Figure 2).

Although some observational studies have reported an increasing trend in the geostrophic transport of approximately 1 Sverdrup (Sv) per decade between 1984 and 2013, the IPCC had high confidence that this recent increase was more inclined to be connected to multi-decadal scale variability (such as the Pacific Decadal Oscillation) rather than a persistent, long-term anthropogenic trend (Feng *et al.,* 2018), which was supported with high confidence by the IPCC (Fox-Kemper *et al.,* 2021; IPCC 2021).

A recent peer review outlined how the ITF modulated regional ocean warming and inter-ocean connectivity. A 2025 study (2009–2019) using reanalysis showed that ITF heat transport was tightly connected to ENSO, with La Niña strengthening flow and Banda Sea heat content, and El Niño (see Glossary in detail) weakening both (Pratama *et al.,* 2025). Additionally, modelling of ITF water in the Indian Ocean suggested that ITF pathways split between Atlantic and Pacific return routes—on average, more returning to the Atlantic—with transit times of 10–20 years (Atlantic) and 15–30 years (Pacific); vertical motion influences these routes (Guo *et al.,* 2023).

4. Alterations in the Water Cycle and Extreme Weather Events

The previously discussed shifts in large-scale atmospheric and oceanic systems were driving tangible changes in Indonesia's water cycle, leading to new rainfall patterns and the frequency and severity of extreme weather events.

4.1. Intensification of Rainfall Extremes

Observational data from weather stations across Indonesia provided clear evidence of a changing precipitation regime and led to more intense extremes (Supari *et al*., 2017). An analysis covering 1983–2012 confirmed that rainfall extremes intensified, particularly during the wet season (December–February). The Simple Daily Intensity Index (SDII), a measure of average precipitation on wet days, also significantly increased. Furthermore, the northern regions experienced a distinct wetting trend, with higher one-day rainfall maximums (RX1day) and more total precipitation from the wettest days (R99p). This showed that rain events were becoming more severe, a trend consistent with the physics of a warmer atmosphere holding more moisture and driving a more volatile water cycle. The regional observation correlated with the IPCC's broader assessment of intensifying rainfall extremes across much of Southeast Asia (Seneviratne *et al.,* 2021; IPCC 2021)

Recent studies have documented the intensification of rainfall extremes in Indonesia since the IPCC AR6. Publications have shown a significant upward trend in cloud liquid water content (CLWC) over 30-year intervals along the winter monsoon pathway in Indonesia. This increase in the CLWC, particularly during the December–February period, reflected the intensification of warm rain processes driven by the winter monsoon. These results underscored the critical role of the winter monsoon in shaping warm rain processes in Indonesia, with implications for extreme weather events such as flooding in land areas such as Jakarta (Harjupa and Nakakita, 2025). The observations were consistent with broader trends of increasing rainfall extremes in Southeast Asia, underscoring the need for enhanced monitoring and adaptive strategies to mitigate the impacts of these events.

4.2. Indonesia's Year-to-Year Climate Strongly Modulated by Powerful, Naturally Occurring Modes of Climate Variability

AR6 emphasized two critical phenomena, the Indian Ocean Dipole (IOD, see Glossary in detail) and ENSO, whose impacts were particularly severe when they occurred in concert. An east-west sea surface temperature gradient across the tropical Indian Ocean characterized the IOD. During a positive IOD event, waters off the coast of Sumatra became anomalously cool, leading to atmospheric subsidence and significantly reduced rainfall over Indonesia (As-syakur *et al.,* 2014; Nur'utami and Hidayat, 2016; Figure 3).

Conversely, negative IOD events led to warmer water and increased rainfall. The IPCC asserted that during the satellite era, this relationship was particularly effective, with positive IOD events reliably inducing substantial rainfall deficits. Paleoclimate reconstructions from corals and plant waxes provided a deeper context for the powerful and long-term influence. ENSO was the dominant driver of interannual climate variability on Earth, and the influence on Indonesia was profound. During El Niño events, the Walker Circulation weakened, and atmospheric convection shifted eastward, away from Indonesia. This led to widespread atmospheric subsidence, severe droughts, and a well-established increase in fire risk.

Critically, these impacts were often dramatically amplified when an El Niño event coincided with a positive IOD, creating conditions for Indonesia's most extreme drought and fire seasons. Extreme IOD events, such as positive phases, led to increased sea surface temperatures and sea-level rise along Indonesia's coasts, significantly in Java. These conditions intensified marine heatwaves and extreme sea-level rise events, posing substantial risks to coastal ecosystems and communities (Han *et al.,* 2022; Xie *et al.,* 2025; see Figure 4).

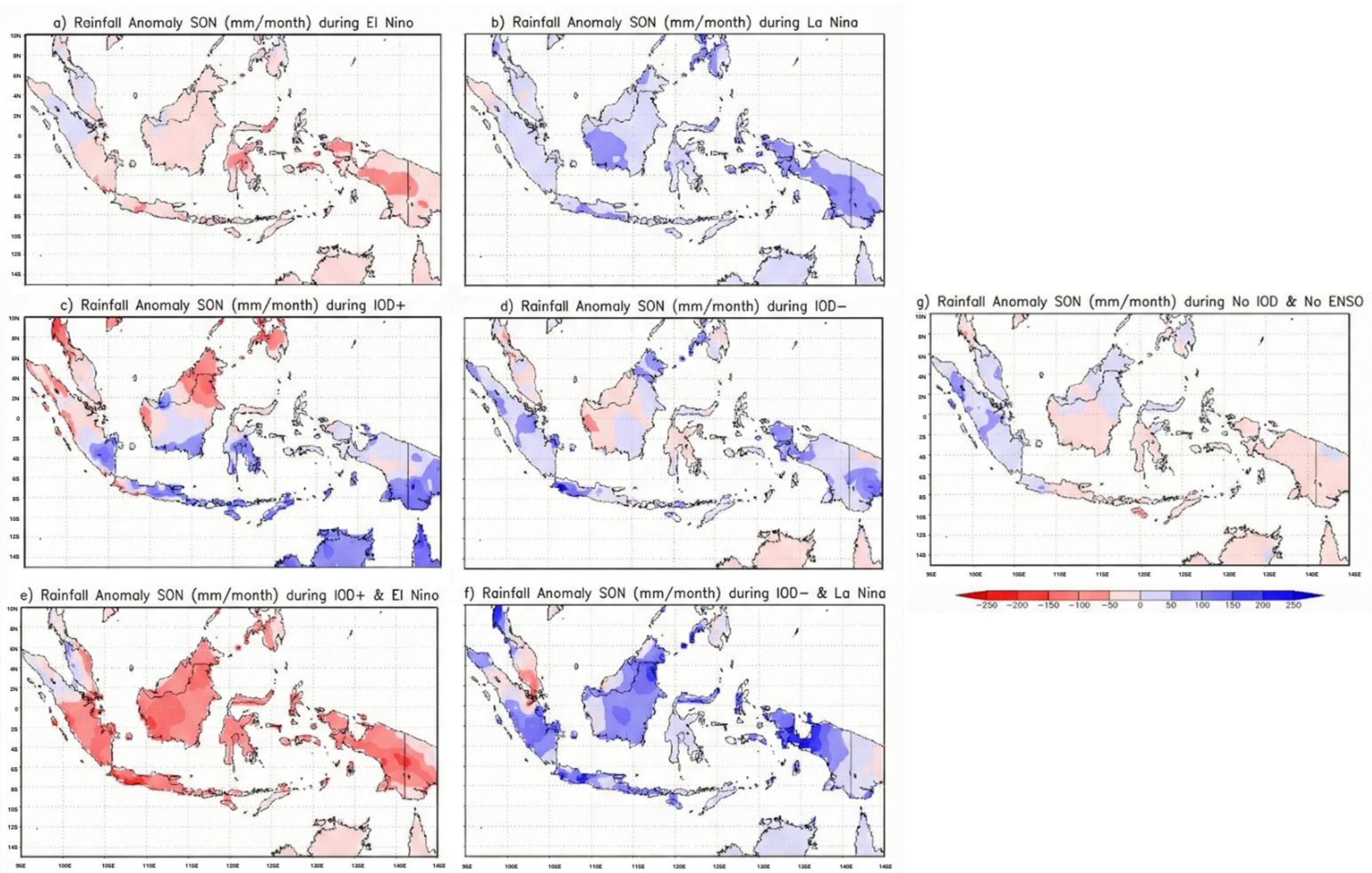

Figure 3. Composite of Indonesian Rainfall Anomaly (Contour; mm/month) During SON on (a) El Nino, (b) La Nina, (c) Positive IOD, (d) Negative IOD, (e) Positive IOD and El Nino, (f) Negative IOD and La Nina, and (g) No IOD and No ENSO. Positive (Negative) Value Shows the Increase (Decrease) in Rainfall. (Figure 2 of Nur'utami and Hidayat (2016)).

4.3. Case Study: The 2015–2016 Extreme El Niño and its Compounding Impacts

The extreme El Niño event of 2015–2016 served as a stark case study of the devastating consequences of these climate extremes in Indonesia. As outlined in the IPCC report, this event triggered a severe drought that was among the worst recorded. The arid conditions created a tinderbox environment, leading to catastrophic and extensive forest and peatland fires, particularly in Sumatra and Kalimantan (Field *et al.,* 2016).

The impacts were multifaceted and severe where the resulting "haze crisis" caused a major public health emergency across Southeast Asia and negatively affected the Indonesian economy. Ecologically, the fires destroyed vast areas of carbon-rich peatlands and rainforests, which were critical habitats for endangered species. This event also had global ramifications where the IPCC asserted that the global atmospheric CO_2 growth rate was particularly high in 2015, partly because of the droughts and fires.

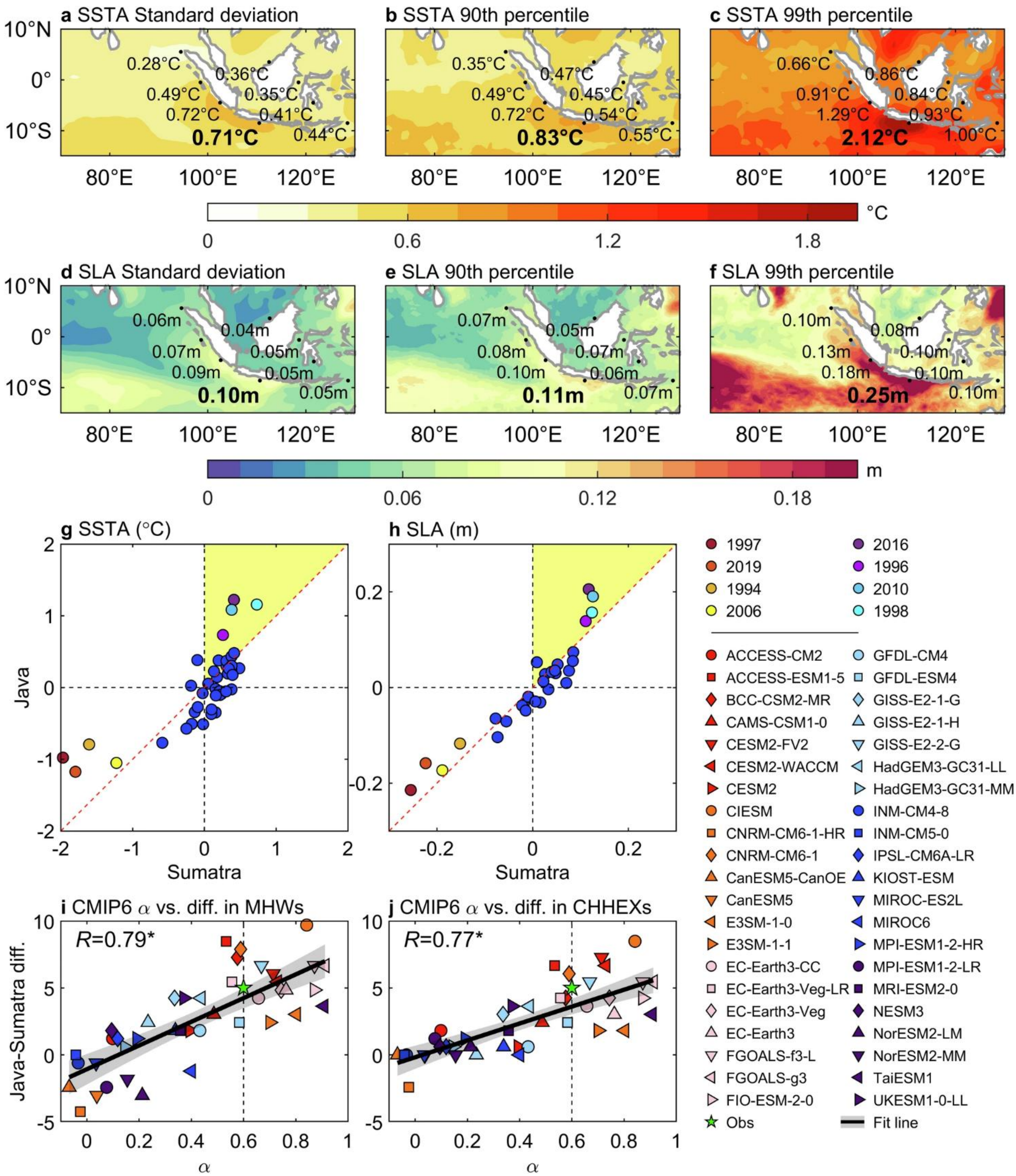

Figure 4. More Vulnerable Coastal Java than Sumatra to Marine Heatwaves (MHWs) and Compound Events of MHWs and Extreme Disasters (CHHEXs). (a) The Standard Deviation of Monthly SSTA on Each Grid. (b), (c) Same as (a), but for (b) the Upper 90th Percentile and (c) the 99th Percentile, Respectively. The Bold Temperature in Each Panel Is the Value of the Sample Site off Java, and Other Sample Sites Scattered Across the Indonesian Archipelago Are Also Shown for Comparison. (d), (e), (f) Same as (a–c), but for the Monthly Sea-Level Rise Anomaly (SLA) on Each Grid. (g) Scatterplots of SON-Mean Coastal SSTA off Java and Sumatra. The Red Dashed Line Marks the Ratio of 1:1. (h) Same as (g), but for Coastal SLA. The Yellow Shading Represents Values Along the Java Coast That Are Larger than Those Along the Sumatra Coast. (i) Scatterplots of the Difference in the Occurrences of Coastal MHWs (Java Minus Sumatra) with Respect to the Nonlinear Parameter α in Each CMIP6 Model. The Linear Fit (Black Solid Line) and Its Corresponding 95% Confidence Intervals (Grey Shading) Are Shown Together with the Correlation Coefficient R. An Asterisk Shows Statistical Significance Above the 95% Confidence Level by a Two-Tailed t-Test. The Unit of the y-Axis Has Been Converted into Occurrences per 100 Years. Also Shown Is the Observed Value (Green Star), Which Is Estimated by Directly Scaling 2 Times per 40 Years in the Recent Observing Period to 5 Times per 100 Years. (j) Same as (i), but for Coastal CHHEXs. (Figure 5 of Xie *et al.,* 2025).

Building on the lessons learned from the 2015–2016 disaster, recent publications moved beyond analysing past impacts to project how the risk of the compound events evolved in the future. Scientists were using climate models and land-use data to estimate fire risk under different global warming scenarios. These studies showed that even a modest increase in the frequency of strong El Niño events, combined with projected background drying, could substantially increase the annual area burned in Sumatra and Kalimantan by mid-century (Hariadi *et al.,* 2024; Figure 5). This forward-looking work was critical for planning long-term adaptation.

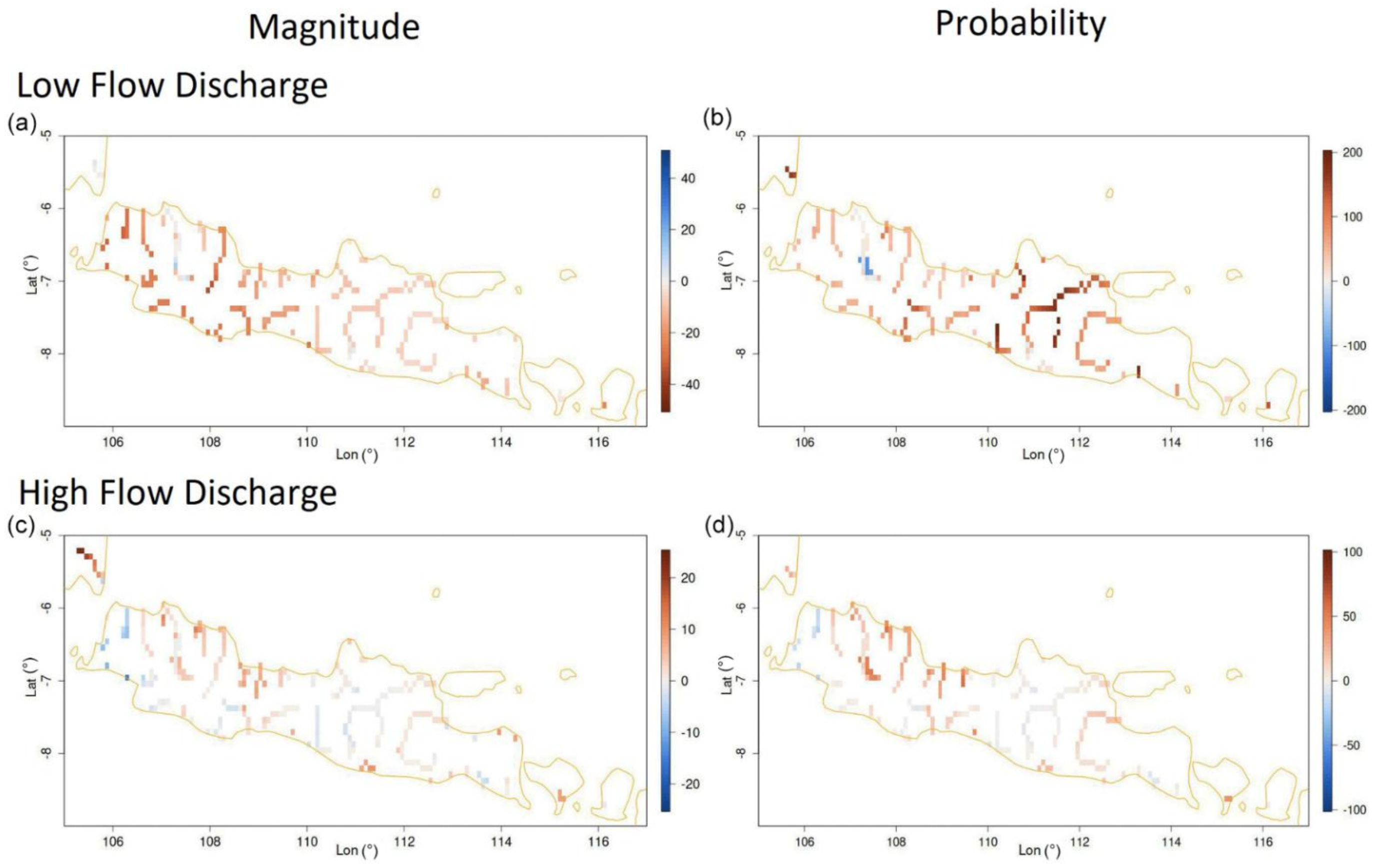

Figure 5. The change of extremely low (percentile 10) and extremely high (percentile 95) water discharge in the near future (2021–2050) compared to the historical period (1981–2010) over the Java region. (a) Low-flow magnitude change (%), (b) low-flow probability change (%), (c) high-flow magnitude change (%), and (d) high-flow probability change (%). (Figure 7 of Hariadi *et al.,* 2024).

5. Future Climate Projections and Anticipated Regional Impacts

Furthermore, the synthesis of climate models assessed by the IPCC projected a future for Indonesia that was significantly warmer and, critically, drier. These projections have profound implications for a nation's future. For future climate projections, evaluating model performance in reproducing historical climate (e.g., Hariadi et al., 2024) was essential because high reproducibility provided greater confidence in future projections.

5. 1. Projected Decrease in Mean Precipitation

Although some parts of continental Southeast Asia were projected to experience increases in annual rainfall, projections for the maritime continent were starkly different. The IPCC report stated with high confidence that the annual mean precipitation was inclined to decrease across Indonesia (Gutiérrez et al., 2021). Multiple lines of evidence from global and regional climate models supported this conclusion. The IPCC AR6 WGI report also stated, with high confidence, that annual mean precipitation was likely to decrease across Indonesia, a strong result from the interactive Atlas based on CMIP6 model ensembles (Gutiérrez *et al.,* 2021; IPCC, 2021, Atlas.SM.10).

Projections from the Coordinated Regional Climate Downscaling Experiment (CORDEX) initiative, which provided higher-resolution details, were particularly concerned about Indonesia's most populous and agriculturally important islands (Tangan *et al.,* 2020). These models showed a potential 20–30% decrease in mean rainfall during the key summer months of June, July, and August (JJA) by the end of the 21st century under higher emission scenarios. This projected drying was physically consistent with the projected increase in large-scale atmospheric subsidence over the region, which suppressed cloud formation and rainfall.

5.2. Intensifying Drought Risk and Heavy Rainfall

A direct consequence of decreased mean rainfall was an increased risk of drought. This was quantified in AR6 using metrics such as the Consecutive Dry Days (CDD, annual maximum number of consecutive days when daily precipitation < 1 mm) index (see Nakaegawa and Murazaki, (2022) and Murazaki *et al.* (2025) for detailed descriptions of climate metrics). The projections showed a clear drying trend for Indonesia based on an increase in CDD, even at a global warming level of 2°C (Tangan *et al.,* 2018; Figure 6). This trend was projected to intensify significantly under the 4°C warming scenario (Supari *et al.,* 2020), showing a future with more frequent, prolonged, and severe meteorological as well as agricultural droughts.

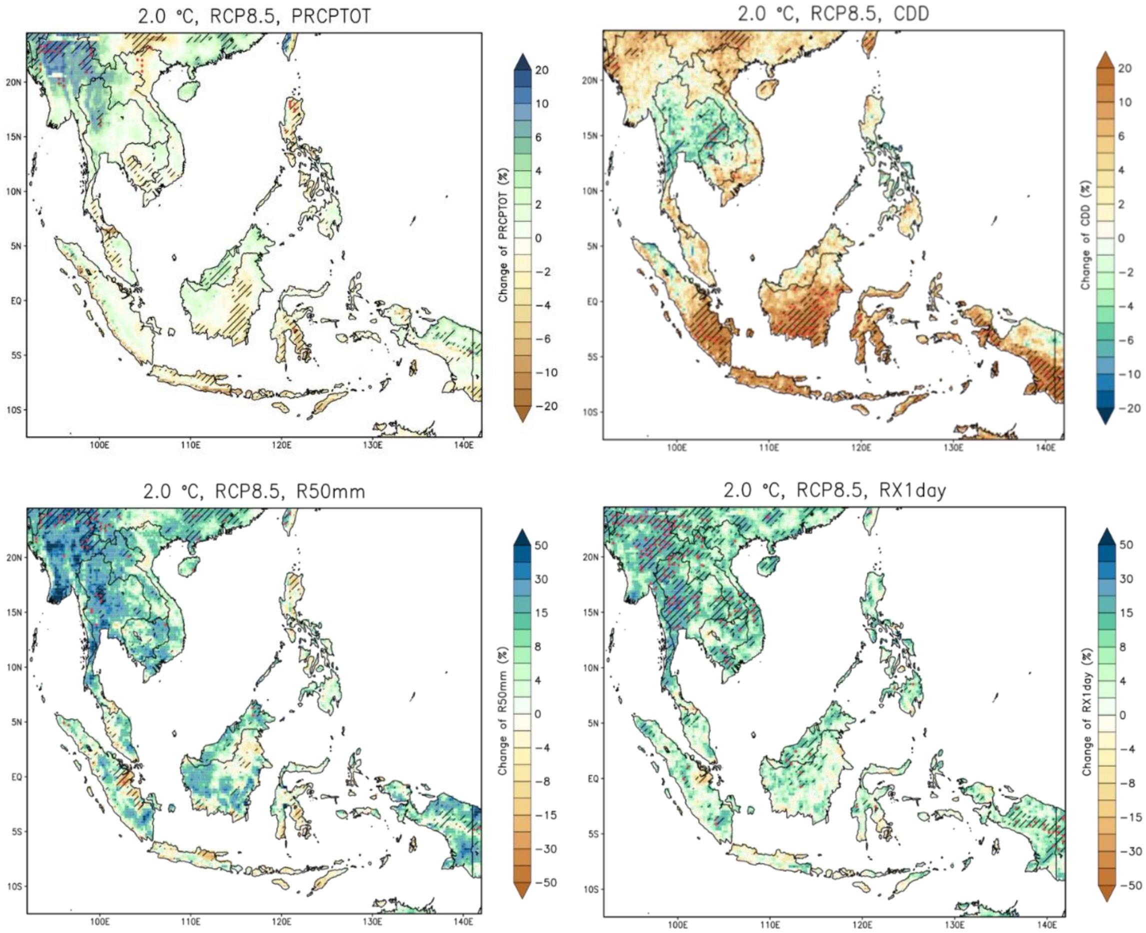

Figure 6. The projected annual precipitation total PRCPTOT (upper left), Annual maximum number of consecutive days when daily precipitation < 1 mm, CDD (upper right), annual count of days when daily precipitation ≥ 50 mm, R50 (lower left) and RX1day (right) changes relative to the historical period (1986–2005) when global warming reaches 2°C (relative to pre-industrial level). Hatched areas show significant changes at the 95% level, while red dots show the robustness of the changes. (Figures 3 to 6 of Tangan *et al.* (2018)).

The implications of such a strong drying trend were severe, threatening water security, agricultural productivity (particularly for rain-fed crops), and increasing the background risk of uncontrollable wildfires, similar to or worse than those observed in 2015. This projected increase in drought duration is consistent with the AR6 assessment for Southeast Asia, which finds that the frequency and intensity of agricultural and ecological droughts are likely to increase (Seneviratne *et al.,* 2021; IPCC, 2021). In AR6, heavy rainfall is unequivocally projected to intensify under global warming conditions (IPCC, 2023), primarily due to thermodynamic effects. The annual maximum daily precipitation (RX1day), an extreme precipitation index, is projected to intensify in Indonesia, as shown in Figure 4.

Recent future climate projections for Indonesia showed a significant shift towards greater weather extremes, particularly concerning precipitation, though the specific impacts varied regionally. For Indonesia's new capital, CORDEX-SEA models projected a future with more intense rainfall events by the late 21st century, with the maximum 5-day precipitation (RX5days) increasing by 5.88% and the number of very heavy precipitation days (R50mm) rising by 29.30% (Marzuki *et* *al.,* 2025). This intensification of rainfall was echoed in broader projections for Java, where wet seasons were expected to become wetter even as annual rainfall declines (Hendrawan *et al.,* 2025). However, these periods of heavy rain were juxtaposed with severe drying. The new capital was projected to see a 41.12% increase in consecutive dry days, signalling longer droughts (Marzuki *et al.,* 2025). This drying trend was the dominant projection for West Java's Majalaya Basin, where CMIP6 models consistently forecast significant reductions in mean monthly rainfall across all future scenarios and seasons, indicating an increased risk of drought (Sa'adi *et al.,* 2025; Figure 7). Collectively, these studies painted a complex picture where many regions in Indonesia were prepared for the dual threats of more extreme floods during concentrated wet periods and longer, more severe droughts.

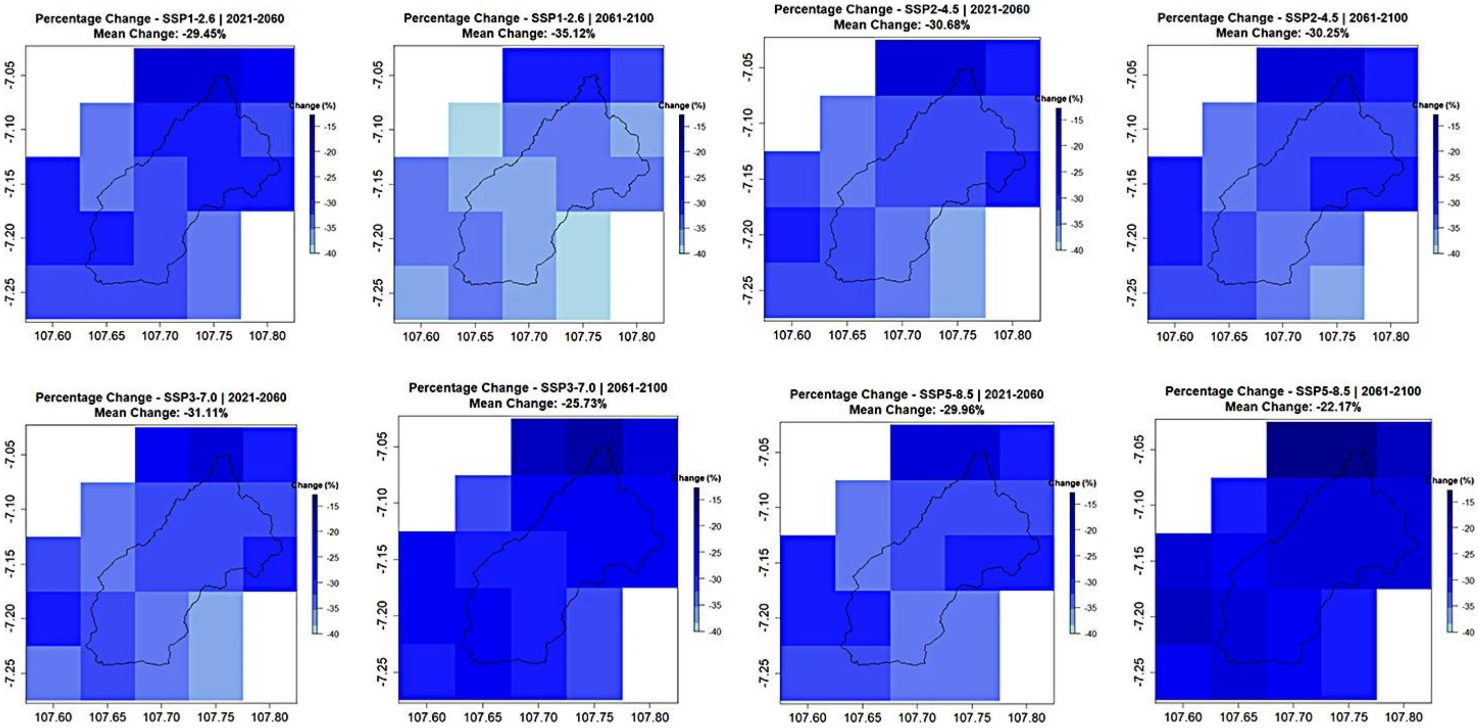

Figure 7. Projected Distribution of Future Mean Annual Rainfall (Percentage Change) of the West Monsoon for the Periods 2021–2060 and 2061–2100 in the Majalaya Basin Under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, Respectively. (Figure 11 of Sa'adi *et al.,* 2025).

Alongside volatile rainfall, Indonesia faced a future of significantly higher temperatures, compounding the climate risks. Projections for Java, the nation's most populous island, showed a substantial increase in maximum daily temperatures between 1.7 °C and 3.1 °C by the end of the century (2060-2099) under RCP4.5 and RCP8.5 scenarios (Hendrawan *et al.,* 2025). Under the high-emissions RCP8.5 scenario, an estimated 63% of the island's vast population was exposed to a temperature increase of at least 3 °C, severely elevating heat-related health risks and stress on energy infrastructure (Hendrawan *et al.,* 2025). This escalating heat would exacerbate the drying trends identified in other studies. The projected increase in consecutive dry days (Marzuki *et al.,* 2025) combined with higher temperatures intensified soil moisture evaporation, increased agricultural water demand, and heightened wildfire risk. Furthermore, the combination of hardened, dry land from prolonged droughts and the subsequent onset of more intense, concentrated rainfall events was inclined to increase surface runoff, elevating the risk of flash floods and landslides in vulnerable areas. This convergence of extreme heat and erratic rainfall patterns posed a formidable challenge to Indonesia's environmental stability, water security, and public health. The projected increase in drought duration was consistent with the AR6 assessment for Southeast Asia, which stated that the frequency and intensity of agricultural and ecological droughts would increase (Seneviratne *et al.,* 2021; IPCC, 2021).

5.3. Future Changes in Diurnal Cycles of Precipitation

Future changes in the diurnal cycle of precipitation in Indonesia were investigated with a non-hydrostatic regional climate model with a 5-km horizontal resolution (Nosaka *et al.,* 2024). The precipitation intensity peak was projected to be delayed to midnight due to strengthening monsoonal northerly winds and weakening of the land breeze. Carbon sinks into a massive source of emissions. This event was a powerful illustration of a compound event, where a climate extreme interacted with local land use to create a cascading disaster.

5.4. The Future of the Indonesian Throughflow

AR6 projected a decline in ITF on a centennial timescale under increased radiative forcing (Figure 8). Recent analyses using the full suite of CMIP6 models have provided a more constrained view of this projection, which was due to a weakening of the northward flow of deep waters entering the Pacific Basin at ~40°S and an associated reduction in the net basin-wide upwelling north of the southern tip of Australia (Sen Gupta *et al.,* 2024). The multi-model mean continued to show a weakening of ITF transport by 10-20% by 2100 under high-emission scenarios.

The projected weakening was physically connected to the projected slowdown of the Pacific Walker Circulation, which reduced the sea-level pressure gradient driving the flow into the Indonesian seas. A weaker ITF would have significant consequences, altering the heat and nutrient distribution between the Pacific and Indian Oceans. A recent study showed that the weakening of the ITF due to global warming was remotely influenced not only by changes in Pacific Ocean winds but also by the weakening of the north–south Atlantic thermohaline circulation (Peng *et al.,* 2023). A more complex mechanism in which changes in North Atlantic Ocean temperature and salinity propagated as waves into the Indian and Pacific Oceans reduced the ITF flow. These results in Section 6 underscored that future changes would not be uniform and local-scale climate information was critical for effective resource management.

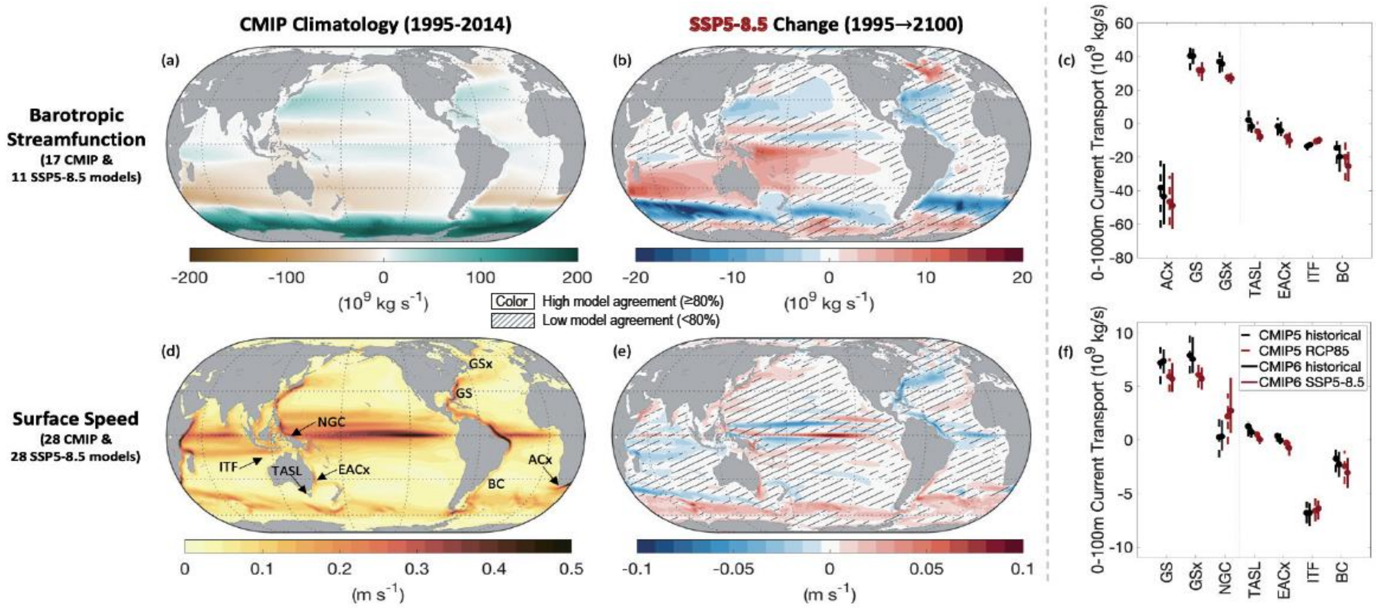

Figure 8. Simulated Barotropic Streamfunction, Surface Speed and Major Current Transport in Coupled Model Intercomparison Project Phase 5 and 6 (CMIP5 and CMIP6). (a) Mean Barotropic Streamfunction (Unit: 10^9 kg s–1; 1995–2014) and Projected Barotropic Streamfunction Change (10^9 kg s–1; 2018–2100 vs 1995–2014) Under (b) SSP5-8.5. (d) Mean Surface (0–100 m) Speed (m s–1) and Projected Surface Speed Change (m s–1, 2081–2100) Versus 1995–2014 Under (e) SSP5-8.5. (c, f) Median and Likely Range of 1995–2014 and 2081–2100 Transport of Three Currents with the Largest Transport Change and Four with the Largest Fractional Change (Sen Gupta *et al.,* 2016). (c) Deep Currents: Agulhas Extension (ACx), Gulf Stream (GS), Gulf Stream Extension (GSx), Tasman Leakage (TASL), East Australia Current Extension (EACx), Indonesian Throughflow (ITF), and Brazil Current (BC). (f) Shallow Currents: as for Deep but with the New Guinea Current (NGC), and Without ACx. No Overlay Shows Regions with High Model Agreement, Where ≥80% of Models Agree on the Sign of Change. Diagonal Lines Show Regions with Low Model Agreement, Where <80% of Models Agree on the Sign of Change. (Figure 8.11 of IPCC AR6 WG I).

6. Climate Changes Reported by BMKG

BMKG published the latest information about climate change in Indonesia. These were governmental publications but not peer-reviewed, in contrast to scientific articles, although the contents could be based on peer-reviewed articles. In this section, climate change reports from BMKG were summarized.

Observational analyses showed a clear warming trend across Indonesia over recent decades. For example, national data showed an average annual air temperature increase of around 0.03°C per year during the 1981–2020 period, corresponding to a warming of roughly 0.9°C over 30 years. This warming was corroborated by the finding that 2024 was recognized by BMKG as the warmest year on record in Indonesia, suggesting regional climate change was proceeding at a pace relevant for hydrological and atmospheric systems (BMKG, 2024a). In the context of future climate conditions, BMKG's Climate Outlook 2025 reported that large-scale drivers of variability (e.g., ENSO and IOD) were projected to remain in a neutral or weak state for much of 2025. However, BMKG nonetheless anticipated that the mean surface air temperature in key months (May–July) could rise by about +0.3 °C to +0.6 °C above the climatological normal, and certain regions, such as southern Sumatra, Java, NTB/NTT, should be monitored for higher-than-normal heat stress (BMKG, 2024b).

BMKG's national climate monitoring outlined observed shifts in rainfall seasonality and extreme rainfall frequencies in Indonesia. For example, the BMKG bulletin 'Catatan Iklim dan Kualitas Udara Indonesia 2024' reported that the mean annual air-temperature anomaly for the Indonesian land area relative to the 1991–2020 normal was +0.8 °C in 2024, and over the 1981–2024 period, the cumulative warming was approximately +0.9 °C, with the two most recent decades being the warmest on record. Alongside warming, BMKG further asserted that in 2024, many regions of Indonesia experienced an earlier onset of the wet season (e.g., Sumatra and Kalimantan entered the rainy season in August–September) and a delayed onset in others (e.g., Sulawesi and parts of Kalimantan) compared to normal (BMKG, 2024c). These observed changes in seasonal timing and warming trends carried key implications for hydrological regimes, including altered soil moisture recharge, shifting flood/drought windows, and changes in extreme rainfall reliability — all of which demanded attention when coupling climate projections to catchment-scale hydrological modelling.

Concerning linkages between climate change and hydrometeorological hazards, BMKG emphasized that climate change was not only a long-term warming trend but also a driver of more frequent and more intense hydrometeorological extremes. For example, heavier rainfall bursts, extended dry spells, and increased wildfire and haze risk in Indonesia's peatland and forested areas. In the recent outreach and monitoring products, BMKG outlined the strong interconnection between climate change, air-quality degradation (e.g., PM 2.5, black carbon), and land/hydrology-driven hazard potential (BMKG, 2024d). For hydrologists and atmospheric scientists modelling Indonesian regional systems, the BMKG results underscored an accelerating baseline climate shift, shifting seasonality, and increased hazard potential.

7. Discussion and Future Directions: Elucidating Uncertainties in the Physical Climate System

This article presents critical insights into the physical science basis of climate change in Indonesia, drawing upon the IPCC AR6 and recent advances. Adopting physically based analyses of historical climate variations and future projections was essential for conducting reliable and robust assessments of socioeconomic impacts such as litigation (Sulistiawati, 2024) and adaptation to multi-hazard climate-related risks (Gaborit, 2022), sustainable mangrove restoration (Sasmito *et al.,* 2023), and rice production (Ansari *et al.,* 2023). Moreover, the development and implementation of best practices for adapting to future climatic changes were critical. Mitigation efforts likewise remained indispensable for ensuring a sustainable future for human society. It was crucial that policymakers acquired a comprehensive understanding of the relevant scientific literature and applied that knowledge effectively to promote societal well-being. Equally important was the cultivation of a shared understanding among all individuals engaged in addressing climate change.

The understanding must be reinforced by establishing effective communication channels that enable participants to exchange ideas and collaboratively address key challenges. It had become increasingly evident that all actors engaged in climate-related issues—including those responsible for producing information, mediating the dissemination, and making policy decisions—must engage in reciprocal information exchange. To realize the objective, it was essential to create consistent and equitable opportunities for dialogue among a diverse range of stakeholders. Consequently, strengthening the science communication competencies of information producers and intermediaries was essential to ensure that climate knowledge was effectively transmitted and applied.

The translation of physical science into actionable policy was particularly critical for Indonesia's energy and mitigation challenges. Indonesia ranks as the world's ninth-largest greenhouse gas (GHG) emitter, with its energy supply heavily dependent on coal-fired power generation. As of 2023, the share of renewable energy in its portfolio remained at only 13.1%, and CO2 emissions from the energy sector continued to rise, driven by rapid economic growth. As the world's fourth-most populous nation, Indonesia's energy transition would have a profound impact on the global community's collective efforts to achieve the objectives of the Paris Agreement (Dwei *et al.,* 2010). Addressing this challenge necessitated the establishment of an innovative socio-technical system capable of stably supplying variable renewable energy (VRE) to society. As discussed in this review, global warming and the increasing risk of natural disasters were closely intertwined, underscoring the need to implement adaptation measures alongside mitigation strategies. An integrated solution was the establishment of a "SolarEV City" (Kobashi *et al.,* 2021). This represented a new paradigm for a decentralized energy system, centered on solar photovoltaics and electric vehicles, which simultaneously advanced decarbonization (mitigation) and enhanced disaster resilience (adaptation).

Indonesia had significant potential to implement the system. However, significant uncertainties persist within this complex system, necessitating further research to address these challenges and to facilitate the development of more effective adaptation and mitigation strategies. This section outlines the key future directions and specific proposals for climate change publications in Indonesia. Articles aimed at understanding the fundamental physical processes governing Indonesia's climate, particularly those outlined as uncertain in IPCC AR6, were essential to deepen the scientific understanding of climate change.

Mechanisms and Future Projections of the Pacific Walker Circulation's Shift to a La Niña-like State: The observed persistent shift of the Pacific Walker Circulation towards a La Niña-like state in recent decades impacted climate patterns across the Indo-Pacific region, including Indonesia. Detailed analysis was required to clarify the precise mechanisms driving this shift, the contribution of anthropogenic influences, and future projections. An integrated method combining high-resolution models, paleoclimatic data, and modern observations would be particularly valuable.

Mechanisms of Multi-decadal Variability in ITF and its Regional Climate Impacts: The ITF was a globally significant ocean current system, and the multi-decadal variability significantly influenced regional ocean ecosystems and climate. Further analysis was required to precisely unravel the mechanisms driving ITF variability, particularly the roles of atmospheric-oceanic interactions and remote forcing, and how these impacted Indonesia's precipitation and temperature distribution. Reducing Uncertainties in the Modelling of Physical Processes: Modelling these physical processes included uncertainties. Further examination was needed to reduce these uncertainties and enabled more reliable future projections through enhanced observational data (particularly in the ocean and upper atmosphere), improved data assimilation techniques, and the development of more advanced climate models.

Socioeconomic scenarios in the future climate projections: Socioeconomic scenarios mostly affected future climate projections. Shared Socioeconomic Pathways or SSPs have been used for future climate projections in CMIP6 and IPCC AR6 WG I. Furthermore, SSPs were elements from the new narratives about future societal development (the SSPs) with the previous iteration of scenarios, the Representative Concentration Pathways (RPCs), which described trajectories of change in atmospheric GHG and aerosol concentrations. In CMIP7 and IPCC AR7 WGI, low emission scenarios included overshoot where atmospheric CO2 was decreasing but with positive values due to anthropogenic emissions before the middle of this century and was removed from the atmosphere with new technologies for negative emissions after the middle of this century. The former required a decarbonized society and renewable energy systems, and the latter needed direct atmospheric carbon capture (DACC) and artificial photosynthesis. The scenarios remained highly uncertain, and many of them should be considered in future climate projections.

8. Conclusion

In conclusion, this study synthesized key results from the IPCC AR6 and integrated insights from subsequent critical analyses, offering a comprehensive overview of the physical science basis of climate change in the Indonesian archipelago. As a nation uniquely vulnerable to these global shifts, Indonesia's climate was undergoing profound anthropogenic alteration driven by a complex interplay of atmospheric and oceanic processes. The analysis showed significant changes, including an increase in tropospheric ozone, a persistent shift towards a La Niña-like state in the Pacific Walker Circulation, accelerated warming of tropical oceans, and increased multi-decadal variability in the Indonesian Throughflow. Concurrently, the regional water cycle was intensifying, marked by an increase in the severity of rainfall extremes, against the backdrop of powerful climate variability modes such as ENSO and IOD, which have contributed to severe events, including the 2015-2016 drought and fire crisis.

Future projections assessed with high confidence indicated a warmer, substantially drier future, particularly during the summer months. The projected decrease in mean rainfall and increase in drought risk posed fundamental threats to Indonesia's water and food security, invaluable ecosystems, and economic development. Crucially, the new analysis added crucial granularity to these results. It confirmed the role of specific emission sources, improved the understanding of recent extreme events, and provided higher-resolution projections that outlined important sub-regional differences in future climate. The continued warming of the surrounding seas and the associated rise in marine heatwaves represented a clear and present danger to marine ecosystems. The projected future of a drier dry season and a more intense wet season, coupled with a long-term weakening of the critical Indonesian Throughflow, signaled a fundamental shift in the region's climate.

Navigating the profound challenges ahead required that Indonesia be guided by the latest available and actionable science. To this end, future publications must adopt a more integrated, hazards-focused approach. Efforts should expand to investigate rainfall-induced landslides and flash floods across all vulnerable, high-gradient terrains while dedicating comprehensive analysis to under-studied threats, such as the slow-onset impacts of drought on agriculture and society. Crucially, all works must account for the exacerbating influence of global climate drivers such as ENSO and the IOD reviewed in this article. Enhancing national resilience required implementing a holistic framework that integrates downscaled climate models, rigorous impact assessments, effective early warning systems, and adaptive land-use planning to translate scientific knowledge into policy and community-level interventions.

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Author Contributions

Conceptualization: Nakaegawa, T., & Kobashi, T; **investigation**: Nakaegawa, T., & Kobashi, T; **writing—original draft preparation**: Nakagawa, T.; **writing—review and editing**: Nakagawa, T., & Kobashi, T; **visualization**: Nakagawa, T. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Not applicable.

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Glossary

El Niño–Southern Oscillation (ENSO): the leading source of year-to-year climate variability in the tropical Pacific Ocean. It has two main opposite phases: El Niño and La Niña. ENSO acts as a climate “switch” for Indonesia, alternating between drought (El Niño) and flood (La Niña) risks, with major consequences for water resources, agriculture, health, and disaster management.

El Niño: see ENSO above

Indian Ocean Dipole (IOD): a climate pattern defined by differences in sea surface temperatures between the western and eastern Indian Ocean. The IOD strongly controls whether Indonesia faces droughts or floods, making it a key driver of year-to-year climate variability.

Indonesia Throughflow (ITF): a flow that transports water from the Pacific Ocean to the Indian Ocean, a key component of the ocean circulation surrounding Indonesia. When it weakens, the exchange of heat between the Indian and Pacific Oceans changes, directly affecting dry season rainfall in Indonesia.

La Niña: see ENSO above

Walker Circulation: Walker circulation functions as a key component of the tropical climate system, regulating whether Indonesia experiences wet or dry conditions. When it strengthens, it causes increased rainfall; when it weakens, it leads to drought. Long-term change in Walker circulation is an important factor influencing water resources, agriculture, and disaster risk in Indonesia.

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