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RESEARCH ARTICLE

Impact on Extreme Rainfall and Flood Events during Boreal Summer Intraseasonal Oscillation (BSISO) in Aceh Province

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Abstract

The Boreal Summer Intraseasonal Oscillation (BSISO) is an intraseasonal climate variability in addition to the Madden-Julian Oscillation (MJO) that affects weather and climate in the Indo-Pacific region, including the Province of Aceh. The impact of BSISO on extreme rainfall and flooding in Aceh needs to be investigated to enhance preparedness, mitigation, and adaptation strategies against its negative impacts. The datasets use in situ daily rainfall data from 5 BMKG stations in Aceh and the BSISO indices (BSISO1 and BSISO2) during the extended boreal summer (May–October) period 2001–2020, as well as flood event data in Aceh from 2008–2020. The results of this study show that rainfall in Aceh province is influenced by BSISO variability and has the potential to increase extreme rainfall and even cause flooding in some areas in Aceh, depending on the propagation path of BSISO. The frequency of extreme rainfall in Aceh during BSISO is identified using daily rainfall beyond the 95th percentile in each BSISO phase, which increases the probability of extreme rainfall in Aceh by around 20–100% during phases 1–3 in both BSISO1 and BSISO2. During BSISO1, the probability of flooding in phases 1–3 increased by up to 90%, and BSISO2 also increased the probability of flooding in phases 1–4 by up to 72%

Keywords: BSISO; extreme rainfall; flood; power spectral

1. Introduction

Global climate variability plays a significant role in influencing the Earth's climate system, affecting diverse sectors. In Indonesia, climate variability impacts rainfall diversity, particularly through intraseasonal oscillation (ISO) variability, which comprises two primary modes (Kikuchi et al., 2012; Lee et al., 2013). The first mode, known as the Madden-Julian Oscillation (MJO), prevails during the boreal winter months from December to April, with a cycle lasting 40 to 50 days (Muhammad et al., 2021; Permana & Supari, 2021; Purwaningsih et al., 2020). The second mode is Boreal Summer Intraseasonal Oscillation (BSISO), which dominates from May to November during the boreal summer, exhibiting a period of 10-60 days. (Kikuchi, 2021; Muhammad & Lubis, 2022; Strnad et al., 2023; Wang et al., 2018).

The BSISO plays a crucial role in regulating climate variability over the Indo-Pacific warm pool region (Chen & Wang, 2021; Guo et al., 2021). Unlike the MJO, which predominantly exhibits eastward propagation, the BSISO demonstrates a more complex spatiotemporal pattern characterized by northward and northeastward movement originating from the Indian Ocean, as well as eastward propagation along the equator towards the Western North Pacific (WNP) and eastward propagation along the equator (Chen & Wang, 2021; Lee et al., 2013; Wang et al., 2018). The BSISO can be categorized into two types of intraseasonal oscillation modes: BSISO1, which propagates throughout 30 to 60 days, and BSISO2, which has a shorter propagation time of 10 to 20 days. Each of these modes is further divided into eight distinct phases (Kikuchi, 2021; Lee et al., 2013; Wang et al., 2018).

The propagation of the BSISO has a significant impact on weather and climate phenomena over the region it traverses. This includes the occurrence of tropical cyclones, disruptions to the onset of monsoon, and other extreme climatic events (Kikuchi, 2021). Research indicates that the BSISO activity has led to an increase in extreme rainfall in China by 35-45% during phases 4–8 and 2-4 of the BSISO (Hsu et al., 2016; Ren et al., 2018). A study by Olaguera et al., (2022) found an 80% likelihood of experiencing extreme rainfall in the Philippines during phases 4 to 8 of the BSISO. In Sumatra Island, Indonesia, the probability of extreme rainfall has also risen, contributing to flooding events. Especially, during phases 1-3 of the BSISO, the likelihood of extreme rainfall has increased by approximately 20-120% (Faqih & Nurussyifa, 2017; Muhammad & Lubis, 2022; Sagita et al., 2021).

To comprehend the specific effects of the BSISO, it is essential to analyze the rising intensity and frequency of extreme weather events linked to climate variability, particularly concerning extreme rainfall and flooding in Aceh Province. A thorough understanding of BSISO modulation is vital for improving preparedness, mitigation, and adaptation strategies to counter its adverse impacts.

2. Data and Methods

This research utilized daily rainfall data collected from five stations operated by the Meteorological, Climatological, and Geophysical Agency (BMKG) in Aceh. These stations include the Cot Ba'u Maimun Saleh Meteorological Station in Sabang City, the Malikussaleh Meteorological Station in Aceh Utara, the Sultan Iskandar Muda Meteorological Station in Aceh Besar, the Tjut Nyak Dhien Meteorological Station in Nagan Raya, and the Aceh Climatological Station in Aceh Besar (Figure 1). The BSISO indices (BSISO1 and BSISO2) were sourced from the APEC Climate Center (APCC) website (https://apcc21.org/ser/moni.do?lang=e) covering a 20-year data period from 2001 to 2020). Additionally, flood data for Aceh Province was obtained from the National Disaster Management Agency (BNPB) website: (https://gis.bnpb.go.id/) for the 13 years from 2008 to 2020.

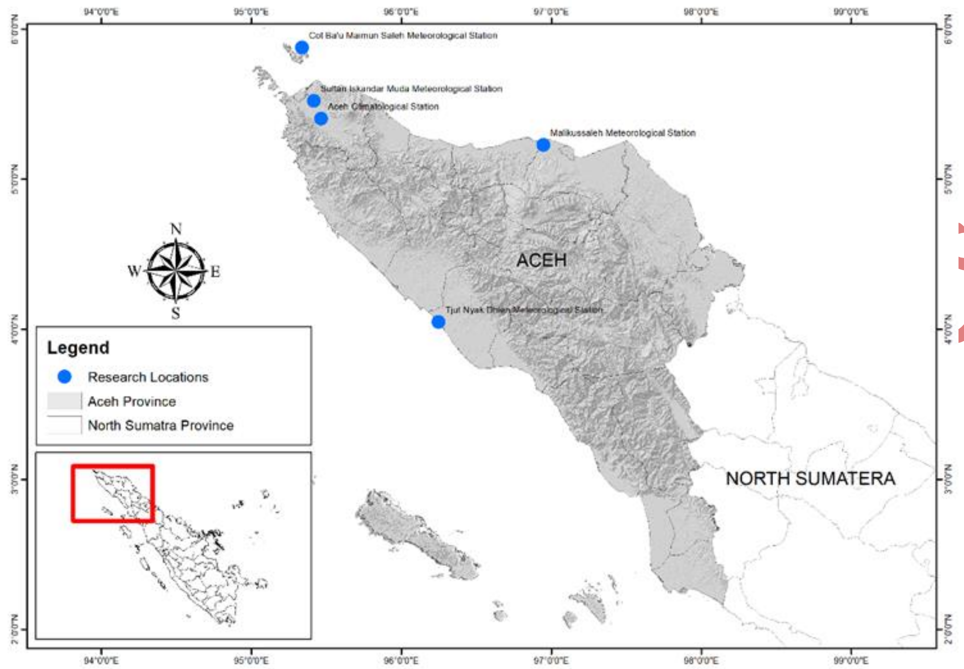


Fig 1. The location of the Meteorological, Climatological, and Geophysical Agency (BMKG) Stations in Aceh

The influence of strong BSISO1 and BSISO2 during phases 1–8 with an amplitude greater than 1 on extreme rainfall in Aceh Province was assessed through probability analysis. An extreme rainfall event was defined as a cumulative daily rainfall exceeding the 95th percentile of daily rainfall (Ren et al., 2018; Zhang et al., 2011). To calculate the probability of changes in extreme rainfall, the probability density function was employed, as follows using the probability density function (PDF), as follows (Ren et al., 2018):

$$\Delta P_{BSISO} = \frac{P_{BSISO}(x \geq x_c) - P_{all}(x \geq x_c)}{P_{all}(x \geq x_c)} x\, 100\% \text{........................ (1)}$$

Where ΔP_{BSISO} represents the probability of change in extreme rainfall when BSISO occurs during summer, P_{BSISO} denotes the probability of rainfall events in each BSISO1 (or BSISO2) phase exceeding the 95th percentile threshold. Then, P_{all} is the probability of all rainfall exceeding the threshold during the season. The thresholds used by BMKG stations in Aceh Province to identify extreme rainfall are detailed in Table 1.

Table 1. The 95th percentile threshold for each BMKG Aceh Station

BMKG Stations	Threshold (mm)
Cot Ba'u Maimun Saleh Meteorological Station	30.09
Malikussaleh Meteorological Station	16.19
Sultan Iskandar Muda Meteorological Station	27
Tjut Nyak Dhien Meteorological Station	55.3
Aceh Climatological Station	27

Extreme rainfall events occurring during the active period of the BSISO can lead to hydro-meteorological disasters, including flooding. By utilizing flood events data in Aceh from the BNPB website for the 13 years from 2008 to 2020, the probability of flood occurrences during the May–October period was analyzed using a modified version of Equation 1, as follows:

$$\Delta P = \frac{\Delta P_{BSISO}(f) - \Delta P_{all}(f)}{\Delta P_{all}(f)} x100\% \text{ ....(2)}$$

Where ΔP is the probability of change in flood events, $\Delta P_{BSISO}(f)$ is the probability of flood events during each active phase of BSISO, and $\Delta P_{all}(f)$ is the probability of flood events during the boreal summer.

3. Results and Discussion

Oscillation Cycle of BSISO and Rainfall in Aceh

According to the updated Indonesian Season Zone for the 1991–2020 period (BMKG, 2022), Aceh Province experiences an equatorial rainfall type characterized by two peaks in rainy seasons. This rainfall pattern is primarily influenced by annual oscillations, such as the monsoon, and semi-annual oscillations, such as the Inter-Tropical Convergence Zone (ITCZ) (Aldrian & Dwi Susanto, 2003). Additionally, It is affected by tropical intraseasonal oscillations, notably the Boreal Summer Intraseasonal Oscillation (BSISO), which is predominant during the extended boreal summer months of May to October (Kikuchi et al., 2012; Lee et al., 2013). The BSISO is derived from the principal components (PCs) of daily anomalies in outgoing longwave radiation (OLR) and zonal wind at 850 hPA (U850) over the region spanning10°S to 40°N and 40° to 160°E. It consists of two modes: BSISO1 (PC1 and PC2), which has a propagation period of 30–60 days, and BSISO2 (PC3 and PC4), which has a shorter cycle of 10–20 days. The BSISO influences rainfall variability in the region it traverses when the BSISO amplitude $(PC_{1,3}^2 + PC_{2,4}^2)^{1/2}$ exceeds 1 (Lee et al., 2013).

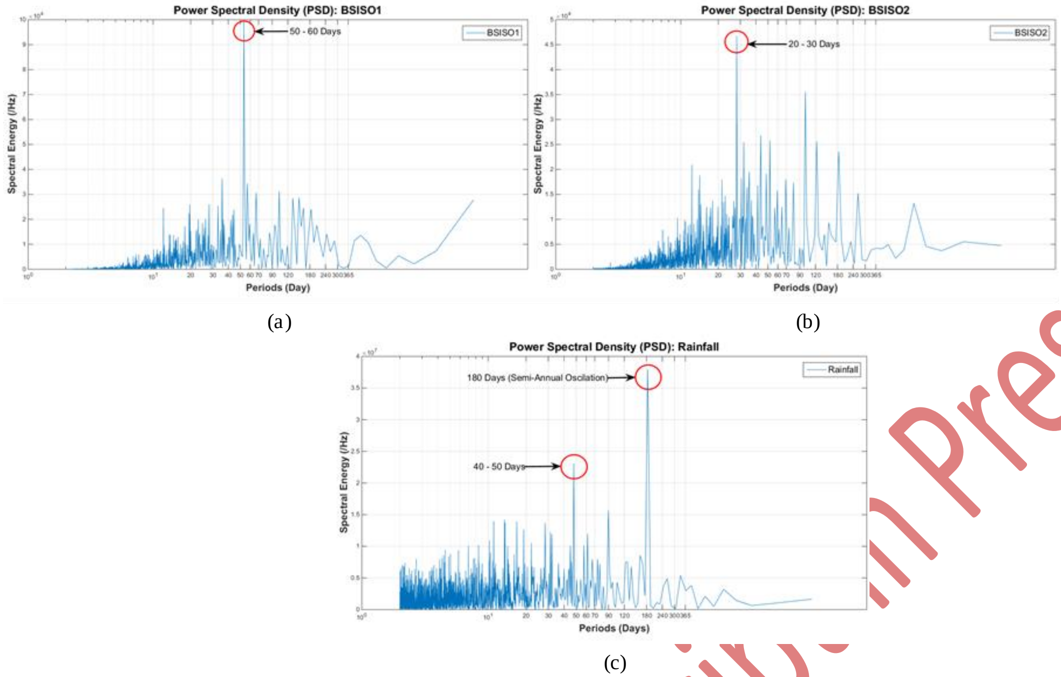


Fig 2. Power Spectral Density (PSD) graphs of (a) BSISO1, (b) BSISO2, and (c) Rainfall in Aceh Province during May-October for the period 2001 to 2020

To examine the impact of the BSISO on rainfall in Aceh Province during the boreal summer months, we can utilize power spectral density (PSD) analysis. This method helps identify the primary oscillations present in time series data (Hermawan, 2010). The relationship between BSISO and rainfall variability in Aceh can be discerned through the dominant spectral features observed in the PSD charts of rainfall, which align with findings from the PSD analyses of the BSISO indices (BSISO1 and BSISO2) (Faqih & Nurussyifa, 2017).

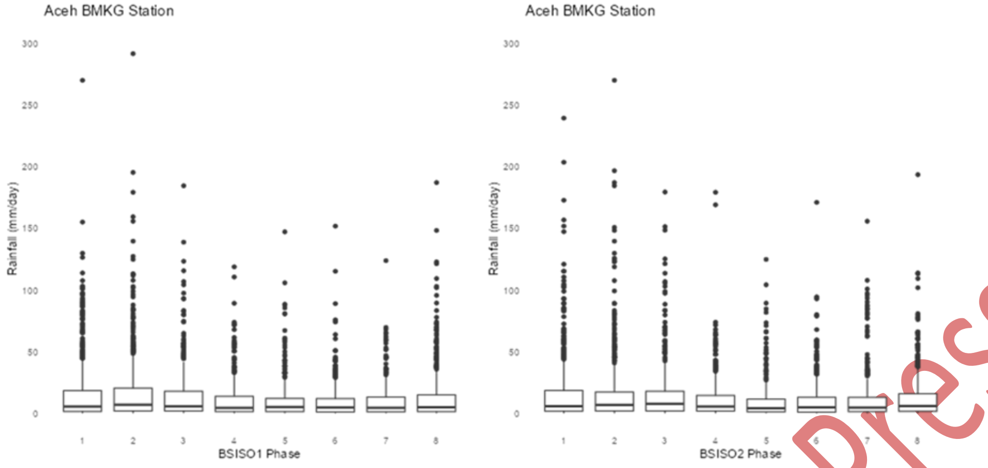
For BSISO1, the power spectrum derived from daily index data over 20 years (2001 to 2020) from May to October reveals peak spectral energy within the 50-60-day range (Figure 2a). In contrast, the PSD for the BSISO2 index during the same timeframe indicates spectral energy concentrated in the 20-30-day range (Figure 2b). his observation is supported by Lee et al., (2013), who noted that BSISO1 exhibits variability with a periodicity of 30 to 60 days, while BSISO2 shows variability within the 10–20-day range.

The PSD analysis for rainfall, utilizing daily precipitation data from Aceh Province during the same period as the BSISO indices, reveals two significant peaks in spectral energy: one in the range of 40–50 days and another at 180 days (Figure 2c). These peaks suggest the presence of two distinct oscillation patterns. The first, a semi-annual oscillation (SAO), peaks at 180 days or 6 months, likely influenced by the Intertropical Convergence Zone (ITCZ) phenomenon (Aldrian & Dwi Susanto, 2003; Hermawan, 2010). The second, an intraseasonal oscillation (ISO), peaks at 40–50 days, which is likely connected to the variability of BSISO (Faqih & Nurussyifa, 2017; Lee et al., 2013), mirroring the oscillation cycle of BSISO1. Additionally, while less pronounced, BSISO2 also contributes to the increase in spectral energy of rainfall within the 10–20-day range.

Impact on Extreme Rainfall during BSISO

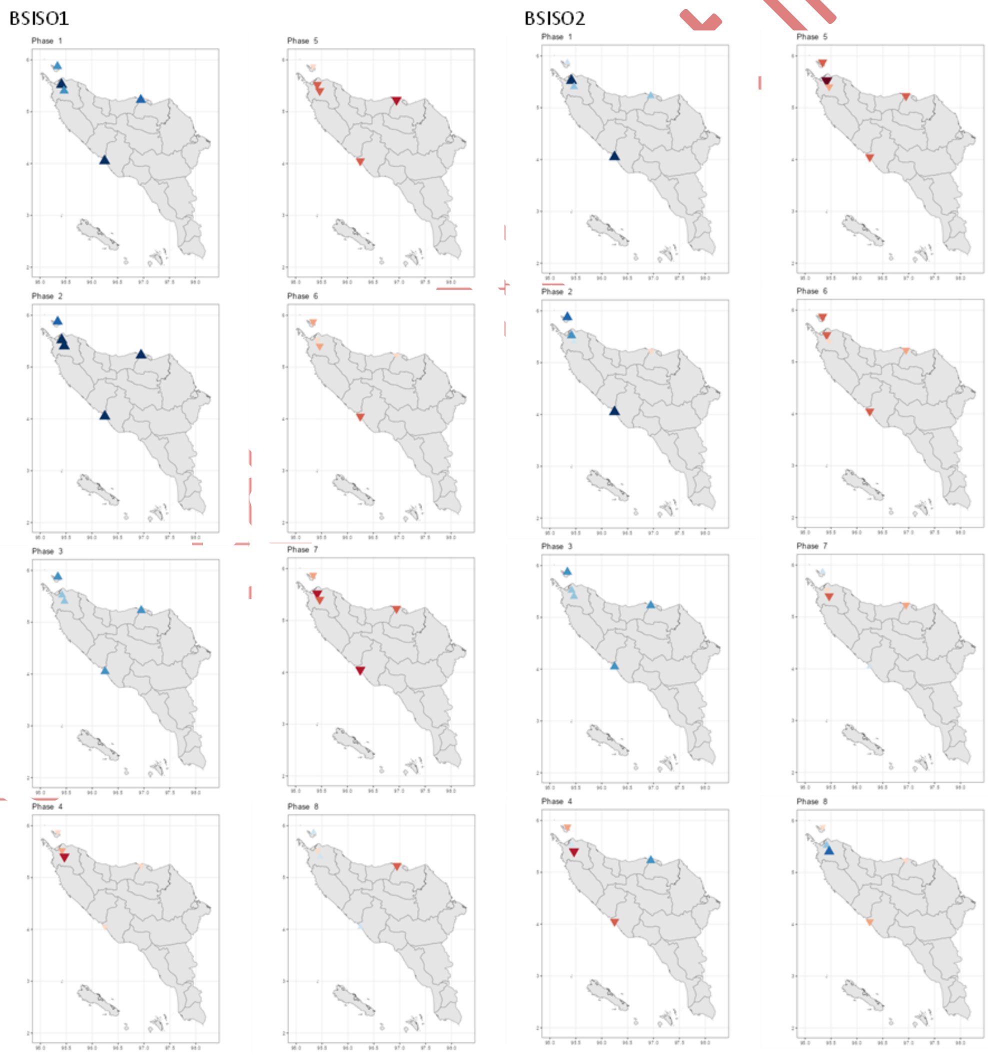
The oscillations of BSISO1 and BSISO2 travel from the Indian Ocean to the northwest Pacific Ocean, each consisting of eight distinct phases. These oscillations are linked to convection, with each phase reflecting the movement path of this convection. In phase 1, the initial convection of BSISO1 moves over the Indian Ocean, subsequently expanding over Sumatra Island and reaching western Borneo Island by phase 3. By phase 4, the convection currents shift away from Sumatra towards central and eastern Indonesia, eventually spreading over the Philippine Islands. During phases 5 through 8, the convection flows continue to move east and northward towards the Northwest Pacific. In contrast, BSISO2 begins its propagation over the Indian Ocean and the Philippine Sea in phase 1. In phases 2 and 3, the convection intensifies and extends across much of the Indonesian maritime continent, reaching the northern Philippines. Throughout phases 4 to 8, the convection advances northeast from Indonesia towards the northern Philippines and the Northwest Pacific (Lee et al., 2013; Muhammad & Lubis, 2022).

Figure 3 illustrates rainfall amounts recorded at BMKG stations in Aceh during the active phases of BSISO1 and BSISO2. Daily extreme rainfall is defined as values exceeding the 95th percentile of daily rainfall (Table 1) (Ren et al., 2018; Zhang et al., 2011). The probability composites for extreme rainfall changes at each BMKG station in Aceh (Figure 4) indicate that the most significant extreme rainfall events occur during BSISO1 phases 1 to 3, with the likelihood of extreme rainfall increasing by 20% to 100% across Aceh Province. Similar findings by Muhammad & Lubis, (2022) report an increase in extreme rainfall of approximately 20% to 120% during these phases across Sumatra. This phenomenon is attributed to BSISO1 being relatively close to Aceh in the Indian Ocean during these phases, with the most intense rainfall occurring in phase 2. Conversely, in phases 4 to 8, the probability of extreme rainfall decreases by 20% to over 80% in Aceh as BSISO1 moves away towards the Northwest Pacific. Faqih & Nurussyifa (2017) also noted that the trajectory of BSISO propagation significantly affects the frequency of extreme rainfall in the regions it traverses..



(a) (b)

Fig 3. Boxplots of rainfall at BMKG Aceh Station in each active phase (a) BSISO1 and (b) BSISO2



(a) (b)

Fig 4.. Probability of changes in extreme rainfall exceeding the 95th percentile in (a) BSISO1, and (b) BSISO2 during May to October for the period 2001-2020

BSISO2 also contributes to an increase in extreme rainfall during phases 1 and 2. Over the Indian Ocean and the Philippine Sea, there is a heightened probability of extreme rainfall changes, ranging from 20% to over 100%, with the most significant changes occurring in phase 1. Muhammad et al., (2023) further emphasize that during phases 1 and 2, the probability of extreme rainfall changes increases significantly, reaching up to 40%.

In phase 3, BSISO2 moves over India and the South China Sea, continuing to influence the likelihood of extreme rainfall in Aceh, with probabilities rising to 20–80%. However, by phase 4, this probability drops significantly, with reductions of up to 80%. Some stations, however, still report an increase in the probability of extreme rainfall changes, reaching up to 40%. This suggests that phase 4 serves as a transitional period. During phases 5 to 8, the probability of changes in extreme rainfall declines by 20% to over 80%, as BSISO2 shifts away from Aceh toward the Northwest Pacific. Notably, some stations in phase 8 exhibit an increased probability of extreme rainfall changes. However, these changes may not be directly linked to increased extreme rainfall in Aceh, as the primary focus of this phase is situated in the Northwest Pacific. A similar observation was noted by Faqih & Nurussyifa (2017) and Sagita et al. (2021). Consequently, it is essential to consider the influence of other climatic phenomena

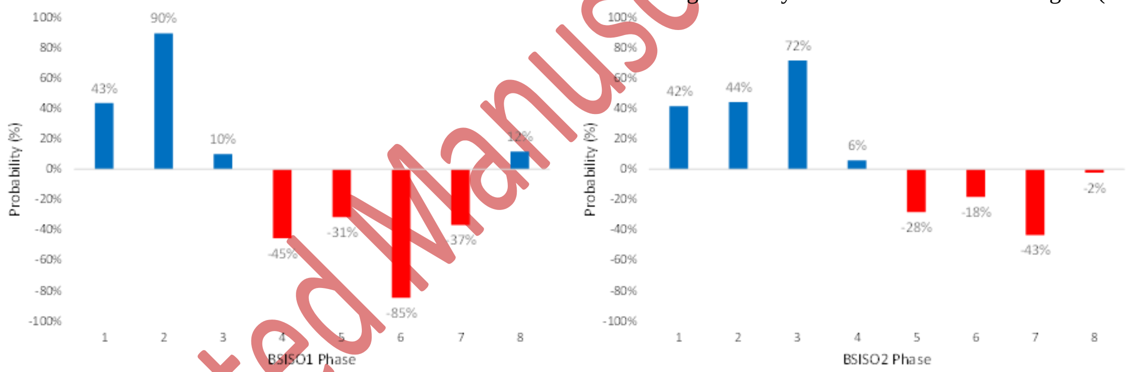
Impact on Flood Events during BSISO

An increase in extreme rainfall can result in hydro-meteorological disasters, such as floods. To assess the impact of BSISO1 (and BSISO2) on flood events during the May–October period from 2008 to 2020 in Aceh Province, an analysis was conducted (Figure 5). Flood data were sourced from the National Disaster Management Agency (BNPB) website at https://gis.bnpb.go.id/.

During the active phase of BSISO1, the probability of flooding is approximately 43% in phase 1. This probability rises significantly to 90% in phase 2, but then drops to 10% in phase 3. In contrast, during phases 4 to 7 of BSISO1, the likelihood of flood events decreases, reaching a low of 85% in phase 6. Phase 8, however, shows a slight increase in flood probability, around 12%. This increase may not be directly linked to flooding impacts, as the focus of this phase is in the Northwest Pacific, indicating that other climatic factors should also be taken into account.

During the active phase of BSISO2 (Figure 4b), there is a change in the probability of flooding, which is 42% during Phase 1 and continues to increase to 72% during Phase 3. Then, during phase 4, the probability of flooding changes to 6%. When it reaches phases 5–8, the change in the probability of flooding decreases to 43%, which occurs during phase 7.

One of the vulnerable regions in Aceh to flooding is Aceh Besar District. We have selected the amplitudes of BSISO1 and BSISO2 during floods occurred in Aceh Besar in the period May to October 2008 to 2020, then compared with daily rainfall from the Sultan Iskandar Muda Meteorological Station that also located in Aceh Besar. The results during Phases 1–3 of BSISO1/BSISO2 were correlated with flood events, but only BSISO1 significantly increased rainfall in the region (Table 2).



(a) (b)

Fig 5.. Probability of changes in flooding events (a) BSISO1, and (b) BSISO2 during May to October for the period 2008-2020

Table 2. The flood events occur in Aceh Besar district compared to rainfall and BSISO

Flood Events (dd/mm/yyyy)	Rainfall (mm)	Location	Amplitude of BSISO1	BSISO1 Phases	Amplitude of BSISO2	BSISO2 Phases
7/6/2010	2.1	Aceh Besar	0.78	1	2.096	3
2/10/2010	6.4	Aceh Besar	0.688	2	1.555	2
7/10/2014	6	Aceh Besar	0.877	6	1.698	1
24/8/2016	30	Aceh Besar	1.707	8	2.075	2
6/10/2018	62.1	Aceh Besar (Kuta Malaka)	2.456	2	0.462	8
7/5/2020	107.8	Aceh Besar (Darul Imarah, Peukan Bada, Lhoong)	1.144	1	1.08	3

8/5/2020	147.5	Aceh Besar (Ingin Jaya, Darul Imarah, Peukan Bada, Lhoong)	1.102	1	1.107	2

4. Conclusion

Rainfall in Aceh Province during the boreal summer (May–October) is affected by the variability of BSISO1 and BSISO2, which can significantly increase the likelihood of extreme rainfall and potentially lead to flooding in certain areas, depending on the propagation path of the BSISO. Generally, BSISO1 and BSISO2 contribute to a heightened probability of extreme rainfall changes during phases 1 to 3, reaching up to 100%. These phases are linked to a high likelihood of flood events in Aceh. Between May and October from 2008 to 2020, the highest probability of flooding is observed in phase 2 (90%) and phase 3 (72%).

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