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Analysis of Vertical Atmospheric Structure on the Formation of Convective Clouds and Heavy Rainfall in Padang Pariaman

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ABSTRACT

Padang Pariaman is one of the regions in West Sumatera that is highly vulnerable to hydrometeorogical disasters, particularly flooding caused by heavy rainfall. This study aims to analyze the influence of vertical atmospheric structure on the formation of convective clouds and heavy rainfall in the area. The data used include radiosonde observations and synoptic data from the Minangkabau Meteorological Station, as well as five atmospheric stability indices: Showalter Index (SI), K-Index (KI), Lifted Index (LI), Convective Available Potential Energy (CAPE), and Precipitable Water (PW). The study was conducted over one year, divided into four seasonal periods (DJF, MAM, JJA, SON). Multiple linear regression and correlation analysis were applied to evaluate the relationship between atmospheric indices and the occurrence of convective clouds and heavy rainfall. The results show that atmospheric instability generally increases during the DJF and MAM periods, as indicated by negative values of SI and LI, along with high values of CAPE and PW. These conditions support the development of Cumulonimbus clouds, which have the potential to produce heavy rainfall. Correlation analysis revealed a strong relationship between several stability indices – particularly CAPE and PW – and rainfall intensity. These findings suggest that analyzing vertical atmospheric structure using radiosonde data and RAOB indices can serve as an important early indicator in forecasting extreme weather events in Padang Pariaman.

KEYWORDS : Vertical atmospheric structure, convective clouds, heavy rainfall, RAOB indices

INTRODUCTION

Indonesia is an archipelagic country located in the tropical zone and traversed by the equator, making it one of the regions with a year-round surplus of solar energy. This condition causes the Indonesian atmosphere to be highly dynamic and complex, characterized by intense land and ocean heating that triggers continuous cloud formation—particularly convective clouds that serve as the primary drivers of rainfall in this region [1], [2]. The near-constant solar heating throughout the day leads to the formation of a wide range of weather systems, many of which are extreme in nature. A notable characteristic of tropical regions like Indonesia is the high intensity and frequency of rainfall, which often occurs locally and sporadically [3].

One of the most common forms of extreme weather is heavy rainfall occurring over a short duration, which frequently triggers hydrometeorological disasters such as floods and landslides. Padang

Pariaman, a regency in West Sumatra Province, is highly vulnerable to such events. Its proximity to the coast and predominantly undulating topography—comprising hills and valleys—makes the region particularly sensitive to extreme rainfall. Flash floods that occurred in September 2023 and October 2024 caused significant damage to residential areas and public infrastructure, forcing thousands of residents to evacuate [4],[5]. These incidents underscore the need for a better understanding of the atmospheric factors responsible for heavy rainfall, especially the vertical structure of the atmosphere.

In general, the vertical atmospheric structure consists of profiles of temperature, pressure, humidity, and wind speed extending from the Earth's surface to the upper layers of the atmosphere. These profiles greatly influence atmospheric stability and cloud development processes. Atmospheric instability, which can be identified by significant vertical temperature differences between layers, encourages upward air motion (convection) that can eventually lead to the formation of Cumulonimbus clouds. These clouds are known to produce heavy rainfall and are often accompanied by lightning and strong winds [6],[7].

In weather forecasting, understanding atmospheric stability parameters is crucial. Atmospheric indices such as the Showalter Index (SI), Lifted Index (LI), Convective Available Potential Energy (CAPE), K-Index (KI), and Precipitable Water (PW) are commonly used to assess the potential for strong atmospheric convection. These index values are derived from radiosonde data, typically processed using the Rawinsonde Observation (RAOB) software. Previous studies have shown that these indices are significantly associated with the formation of convective clouds and rainfall intensity, both in Indonesia and in other tropical regions [8], [9], [10].

Although many studies have examined the relationship between atmospheric indices and extreme weather events, specific investigations focusing on the link between vertical atmospheric structure and the development of convective clouds and heavy rainfall in Padang Pariaman remain limited. Therefore, this study aims to fill this gap by analyzing the vertical atmospheric structure using radiosonde data and associating it with convective cloud formation and heavy rainfall events based on synoptic rainfall data[11], [12], [13]. The research covers four main seasonal periods in Indonesia—December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON)—to reflect the typical seasonal variability in tropical regions.

Through a quantitative approach using multiple linear regression and correlation analysis, this study is expected to reveal the contribution of each atmospheric index in identifying the potential for convective cloud development and rainfall intensity. The findings of this research may contribute significantly to the development of early warning systems for disaster preparedness based on atmospheric data, particularly for flood risk mitigation in Padang Pariaman and other tropical areas in Indonesia.

METHODS

This study aims to analyze the influence of vertical atmospheric structure on the formation of convective clouds and heavy rainfall in Padang Pariaman. A quantitative approach was used, utilizing upper-air atmospheric observation data and daily rainfall data analyzed statistically. To clarify the methodological framework, supporting figures are included in this section.

The study was conducted in Padang Pariaman Regency, West Sumatra Province, geographically located between 0°11' – 0°49' South Latitude and 98°36' – 100°28' East Longitude. This region is known as one of the most disaster-prone areas in Sumatra, particularly vulnerable to hydrometeorological hazards such as flooding, often triggered by heavy rainfall.

The study area is clearly illustrated in Figure 1, which displays the administrative map of Padang Pariaman Regency. This map provides spatial context for the study and helps readers better understand the geographical scope of the analysis.

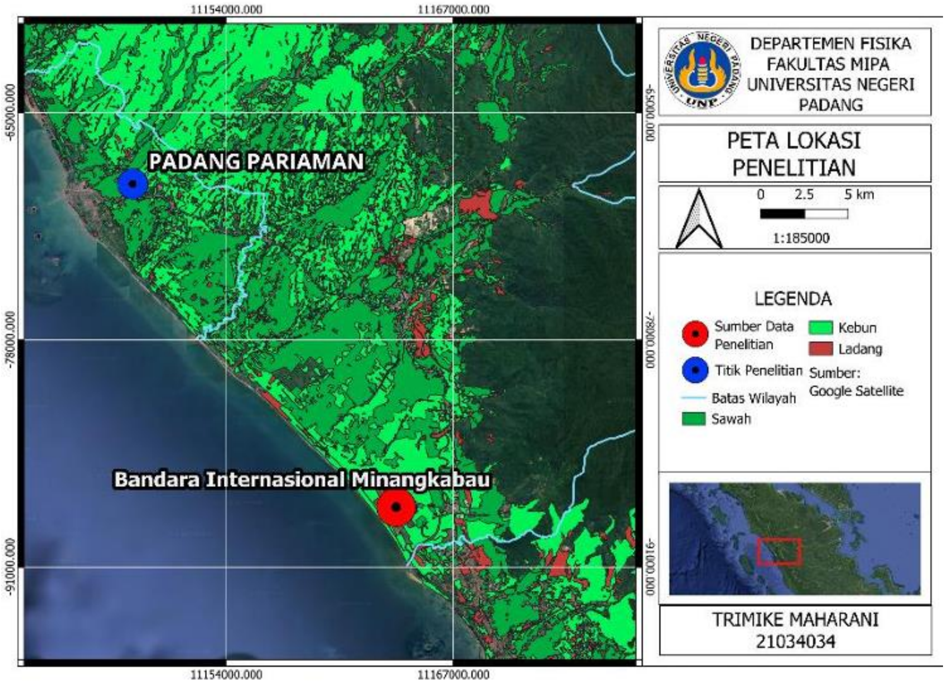

Fig. 1. Map of the study area in Padang Pariaman Regency, West Sumatra.

Rainfall data were obtained from two measurement systems. The first dataset came from the AWS, which records rainfall automatically at 10-minute intervals using a tipping bucket mechanism. The second dataset was derived from manual daily rainfall observations using a standard non-recording rain gauge (OBS), conducted by trained observers. Both datasets were aggregated into monthly totals to ensure comparability under the same temporal resolution.

The research was conducted over a full calendar year (2024), and the analysis was divided into four seasonal periods, in accordance with tropical climatic classifications: DJF (December–January–February), MAM (March–April–May), JJA (June–July–August), SON (September–October–November).

This seasonal classification allows for the examination of atmospheric dynamics throughout the year and facilitates the observation of variations in convective cloud development and heavy rainfall events.

The data used in this study comprised two primary types. The first was radiosonde data, which included vertical atmospheric profiles obtained from the Minangkabau Meteorological Station and supplemented by data from the online source http://weather.uwyo.edu. These data were utilized to calculate various atmospheric stability indices. The second was synoptic data, consisting of daily rainfall records obtained from the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG), specifically from the Padang Pariaman Class II Station. This dataset was used to identify heavy rainfall events associated with convective cloud development[14].

The independent variables in this research were five atmospheric stability indices: the Showalter Index (SI), K Index (KI), Lifted Index (LI), Convective Available Potential Energy (CAPE), and Precipitable Water (PW). Meanwhile, the dependent variable was the occurrence of heavy rainfall (≥ 50 mm per day), which is presumed to be linked to the development of Cumulonimbus (Cb) clouds[15], [16].

The relationship between vertical atmospheric structure, convective cloud formation, and heavy rainfall is conceptually illustrated in Figure 2. This diagram outlines the logical relationship between the independent and dependent variables, and explains how each atmospheric index is hypothesized to influence rainfall through convective processes.

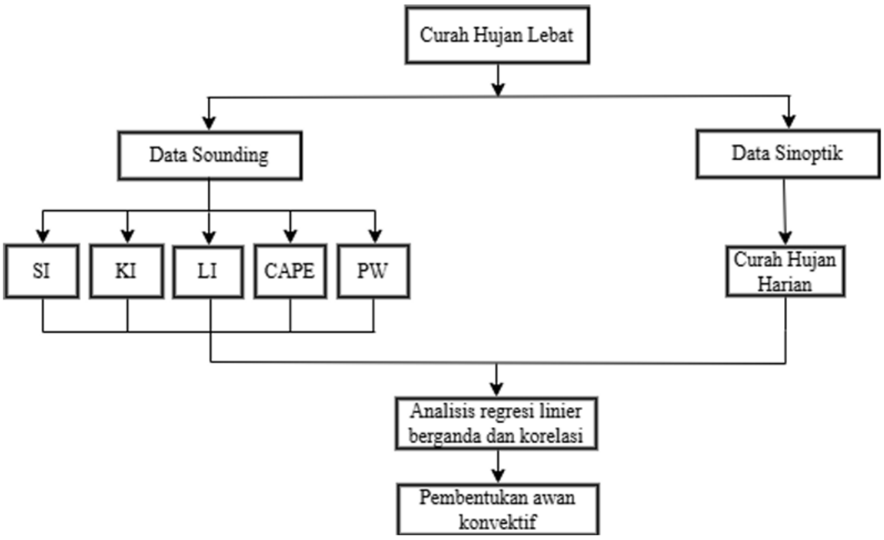

Fig. 2. Conceptual framework of the relationship between vertical atmospheric structure, convective cloud formation, and heavy rainfall.

The data collection process involved two main procedures. Radiosonde data were obtained twice daily at 00 UTC and 12 UTC using weather balloons, which measured vertical atmospheric parameters such as temperature, pressure, humidity, and wind speed up to an altitude of approximately 30 kilometers. Meanwhile, synoptic data were recorded on a daily basis by Automatic Weather Stations (AWS) and manual rain gauges, capturing key meteorological parameters including rainfall intensity, air temperature, and observed weather phenomena.

The collected data were processed using the RAOB (Rawinsonde Observation Program) software to calculate the atmospheric stability indices and to generate aerological visualizations, such as Skew-T Log-P diagrams. After processing, the data were organized and tabulated according to seasonal periods. For the statistical analysis, multiple linear regression was employed to examine the simultaneous influence of the five atmospheric indices on the development of convective clouds and heavy rainfall. Additionally, Pearson correlation analysis was conducted to evaluate the strength and direction of the relationship between each stability index and the intensity of rainfall[17], [18].

The regression model used in this study is expressed as follows:

$$Y = a + b_1X_1 + b_2X_2 + \cdots + b_nX_n + \epsilon$$

In this regression model, Y represents the intensity of heavy rainfall, while X_1 through X_n denote the atmospheric stability indices used in the analysis—namely the Showalter Index (SI), K Index (KI), Lifted Index (LI), Convective Available Potential Energy (CAPE), and Precipitable Water (PW). The parameter a refers to the intercept, b_n represents the regression coefficients for each corresponding index, and ε denotes the error term in the model.

RESULTS AND DISCUSSION

The results of this study indicate that the vertical structure of the atmosphere in Padang Pariaman varies significantly across different seasons. Based on radiosonde data and the calculation of atmospheric stability indices, it was found that during the rainy seasons (DJF and MAM), the atmosphere tends to be unstable, while during the dry season (JJA) and transitional season (SON), it is relatively more stable. The values of the *Showalter Index* (SI), *Lifted Index* (LI), *K Index* (KI), *Convective Available Potential Energy* (CAPE), *and Precipitable Water* (PW) all show consistent patterns in relation to observed rainfall intensity.

The seasonal average of the SI values is presented in Table 1. During DJF and MAM, SI values range from -0.3 to -1.5 in both the 07.00 and 19.00 local time observations, indicating unstable to highly unstable atmospheric conditions. In contrast, during the dry season (JJA), SI values approach or exceed 0, suggesting a more stable atmosphere. These negative SI values are closely correlated with an increased frequency of heavy rainfall events in Padang Pariaman.

Tabel 1. Daily Average of Showalter Index (SI) in Padang Pariaman at 07.00 and 19.00 WIB in 2024

Season	SI at 07.00 WIB	SI at 19.00 WIB	Stability Category
DJF	-0.3 to -0.9	-0.6 to -1.1	Unstable
MAM	-0.4 to -1.5	-0.9 to -1.5	Highly unstable
JJA	-0.1 to +0.2	+0.1 to +0.3	Neutral – Stable
SON	-0.2 to -0.5	-0.3 to -0.6	Weakly unstable

In addition to SI, the CAPE and PW values also play important roles. According to the thesis narrative, CAPE during DJF can exceed 1500 J/kg, while PW may surpass 50 mm. These conditions further reinforce atmospheric instability and support the formation of Cumulonimbus (Cb) clouds, which are capable of producing heavy rainfall. The classification of atmospheric instability levels based on these indices is outlined in Tables 2 through 5 below:

Tabel 2. Atmospheric Instability Categories Based on Showalter Index (SI)

SI Value	Instability Category
> 0	Stable
0 to -4	Unstable
-4 to -8	Highly unstable
< -8	Extremely unstable

A real-world event that reinforces the relationship between atmospheric indices and heavy rainfall occurred on January 22, 2024, when rainfall reached 97 mm/day. Radiosonde data recorded a CAPE value of 1562 J/kg, PW of 54 mm, and LI of -4°C. This combination clearly indicates a highly unstable atmosphere with strong convective potential, leading to the formation of Cumulonimbus clouds and heavy rainfall—fully aligned with the classification shown in Tables 2 through 5.

Tabel 3. Convectivity Categories Based on K Index (KI)

KI Value	Convectivity Level
< 15	None
15 – 25	Low
26 – 39	Moderate
> 40	High

According to the multiple linear regression analysis also presented in the thesis, CAPE was found to have the highest regression coefficient in relation to rainfall intensity, followed by PW. LI and SI exhibited strong negative correlations, while KI showed a weaker positive correlation[17]. This suggests that higher values of CAPE and PW, along with more negative values of LI and SI, significantly increase the probability of heavy rainfall events.

Tabel 4. Stability Categories Based on Lifted Index (LI)

LI Value	Weather Interpretation
> 10	Stable
2 – 10	No significant weather
0 – 2	Light rain potential
-2 – 0	Potential for heavy rain/thunderstorms

LI Value	Weather Interpretation
-4 – -2	Thunderstorm risk
< -4	Severe storms/tornadoes

Overall, the results of this study demonstrate that the vertical atmospheric structure—analyzed through RAOB indices—provides a strong indication of the potential for convective cloud development and heavy rainfall in Padang Pariaman. These findings are consistent with previous studies by Monica et al. (2016) and Spiridonov et al. (2020), which concluded that CAPE and PW are primary indicators for detecting strong convection in tropical regions[7], [8].

Tabel 5. Lability Categories Based on CAPE

CAPE Value (J/kg)	Degree of Instability
< 0	Stable
0 – 1000	Slightly unstable
1000 – 2500	Moderately unstable
2500 – 3500	Unstable
> 3500	Very unstable

However, this study is not without limitations. Radiosonde data were only available twice a day, which restricts the observation of intraday atmospheric dynamics. In addition, visual validation of Cumulonimbus cloud events through satellite imagery or weather radar has not yet been conducted. Therefore, for the advancement of more accurate early warning systems, it is recommended that future research integrates vertical atmospheric data with remote sensing technologies.

CONCLUSION

This study demonstrates that the vertical structure of the atmosphere has a significant influence on the formation of convective clouds and the occurrence of heavy rainfall in the Padang Pariaman region. Based on the analysis of five atmospheric stability indices *Showalter Index* (SI), *Lifted Index* (LI), *K Index* (KI*), Convective Available Potential Energy* (CAPE), and *Precipitable Water* (PW) it was found that these index values vary seasonally and correlate with rainfall intensity.

The rainy seasons (DJF and MAM) are characterized by higher CAPE and PW values and negative values of LI and SI, indicating unstable atmospheric conditions that are highly conducive to the development of Cumulonimbus clouds. In contrast, during the dry season (JJA), the atmospheric indices show greater stability, and heavy rainfall events occur less frequently.

Regression analysis results show that CAPE and PW are the strongest predictors of heavy rainfall events, while LI and SI exhibit significant negative correlations. These findings support the use of atmospheric stability indices derived from radiosonde data as key parameters in early warning systems for extreme weather events.

However, the limitation of radiosonde data availability only twice daily and the absence of integration with remote sensing data present notable challenges. Therefore, to improve prediction accuracy and mitigate hydrometeorological disaster risks in the future, it is recommended to develop integrated systems that combine vertical atmospheric data with real-time satellite imagery and weather radar observations.

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