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ANALYSIS OF SIGNIFICANT WEATHER PHENOMENA TRIGGERING DIVERSIONS AT SOEKARNO-HATTA INTERNATIONAL AIRPORT USING MULTI-DATA OBSERVATIONS (CASE STUDY OF JANUARY 28, 2025)

Muhizzadin Abdul Adzan[1], Pertiwi Risky Setyowati[*], Yosafat Donni Haryanto
[1]Meteorology Study Program, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, Tangerang, Indonesia

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ABSTRACT

Significant weather is one of the crucial factors that can affect flight safety and cause flight diversions. However, analyses of atmospheric dynamics causing diversions often use limited observational data, and observational data have their own limitations. Therefore, this study aims to analyze the atmospheric dynamics that caused diversion incidents (23 flights) at Soekarno-Hatta International Airport on January 28, 2025, using multi-observation data, including radiosondes, Automatic Weather Stations (AWS), the Himawari-9 satellites (CCO method), and weather radar. The results of the study show that ordinary cells triggered by atmospheric instability and low convective inhibition (CIN) create extreme rainfall, causing diversion. Total rainfall reached 255.4 mm/day, with the highest intensity at 13:00 and 14:00 UTC at 86.4 mm/hour and 93.8 mm/hour, respectively, and was classified as extreme rainfall. In addition, the maximum radar reflectivity reached 50.5 dBZ. The use of multi-source observation data is expected to provide a comprehensive understanding of the triggers of significant weather events, as well as a scientific basis for determining thresholds to improve the accuracy of aviation weather forecasting and risk mitigation strategies.

A. INTRODUCTION

Meteorological conditions are crucial parameters for flight safety, especially during takeoff and landing, which can contribute to aircraft accidents (Jarošová & Janošková, 2023). In tropical regions, significant weather phenomena can occur due to mesoscale convective systems that can form cumulonimbus (Cb) clouds. Cb clouds have the potential to cause serious hazards such as extreme weather, extreme turbulence, icing, wind shear, and microbursts due to heavy rain below the required meteorological safety threshold (Janwar & Munandar, 2015; Sasmito et al., 2020). Additionally, high rainfall intensity can reduce horizontal visibility and contribute to flooding in airport areas, which can affect air traffic (Kim et al., 2023; Kwasiborska et al., 2023).

One of the aviation traffic disruptions that can occur due to significant weather conditions is the

[*]Correspondence address: pertiwirisky118@gmail.com

phenomenon of aircraft diversion. Diversion is a disaster mitigation measure that can be implemented to reduce the impacts and risks caused by significant weather conditions forming in the vicinity of the destination airport (Kwasiborska et al., 2023). A diversion is carried out by redirecting aircraft landings to a safer alternative airport to ensure flight safety and reduce the risk of accidents (Špák & Olexa, 2020).

Extensive research has linked weather to flight disruptions, including route diversions. Budnukaeku (2022) reported that 94% of respondents considered bad weather (heavy rain, thunderstorms) to be the main factor causing operational disruptions, but the study stopped at attribution and did not investigate the specific atmospheric conditions or mechanisms involved. Goodman and Small Griswold (2019) analyzed the influence of meteorology on flight delays and cancellations at US airports using METAR data, which are surface observations from instruments and observers. Each weather observation instrument has its own limitations. Upper air observations using radiosondes have spatial limitations (only at certain locations) and temporal limitations (generally flown twice a day) (Pauley & Ingleby, 2022).

Surface observations have spatial limitations because they only represent points and do not provide information on vertical atmospheric conditions (Pauley & Ingleby, 2022). Satellite imagery observations have limitations in capturing vertical resolution because they are often more optimal at cloud tops (Kidd et al., 2021). In addition, radar data observations have limitations, such as the depiction of cloud top structures, and are affected by distance and the effective intervention of other objects (Lin et al., 2023).

Therefore, based on previous research and the limitations of using several observation instruments, this study aims to gain a more comprehensive understanding of atmospheric dynamics, including significant weather conditions that cause operational disruptions in aviation, particularly route diversions, by utilizing multi-data observations. The incident studied was the diversion of 23 flights at Soekarno-Hatta International Airport on January 28, 2025, from 6:30 PM to 9:00 PM local time (UTC+7). As one of the largest airports in Indonesia and Southeast Asia and a key gateway to Indonesia, operational disruptions at Soekarno-Hatta International Airport, particularly diversions, can result in economic losses and other domino effects.

The use of multi-source data, including surface observations, vertical atmospheric observations, satellite imagery, and radar, is expected to provide a solid physical understanding of the triggers of diversion at Soekarno-Hatta International Airport and serve as a scientific basis for improving future weather risk mitigation strategies.

B. METHOD

The research location for the diversion incident was at Soekarno Hatta International Airport, located in Tangerang, Banten, which was significantly affected by extreme weather that caused flight diversions and contributed to flooding in the area. The focus of the incident was on January 28 and 29, 2025, local time (UTC+7). Astronomically, Soekarno Hatta International Airport is located at 6° 7' 12.4“ S and 106° 39' 24.2” E.

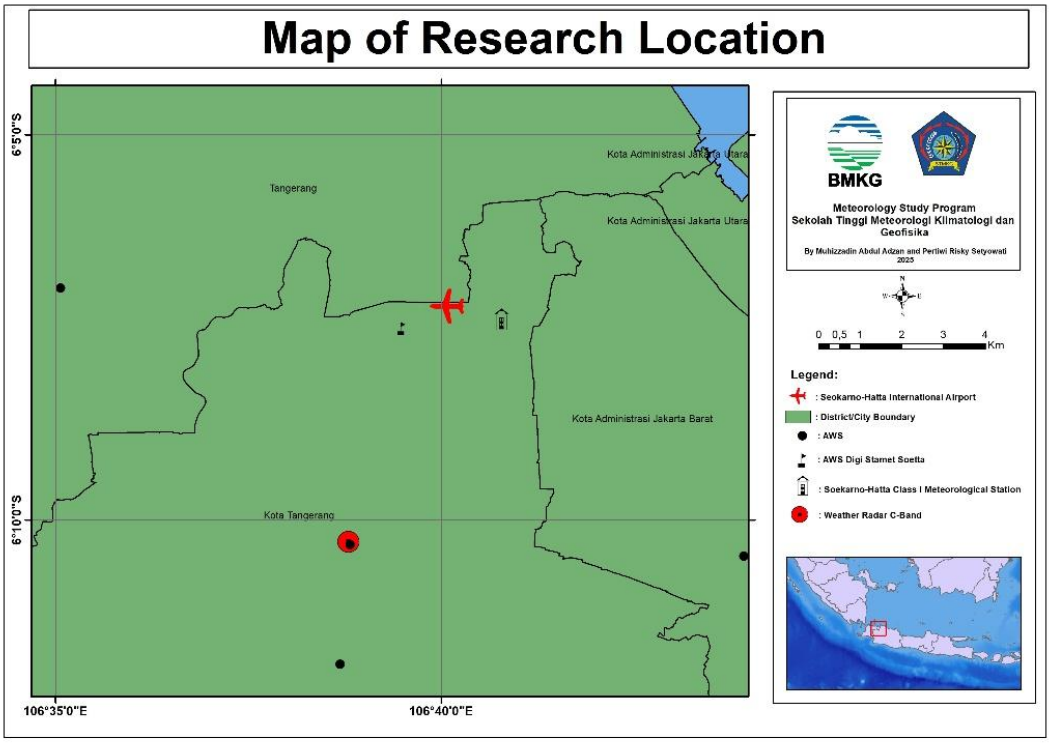


Figure 1. Map of the location of the Soekarno-Hatta International Airport research site

(Source: Processed by the author, 2025)

Four types of data were used in this study: upper-air observation data (radiosonde), Automatic Weather Station (AWS) data, Himawari-9 satellite imagery data, and weather radar data. The first data is the radiosonde upper air plotting graph, which displays atmospheric stability, wind direction and speed, and maintenance obtained through upper air observations conducted by the Soekarno-Hatta Class I Meteorological Station. The second data is the AWS Digital Soekarno-Hatta Class I Meteorological Station data to produce a time series graph of total rainfall obtained through the BMKG AWScenter. The third data used is Himawari-9 satellite imagery in bands 8 (WV 6.2 μm), 13 (IR1 10.4 μm), and 15 (IR2 12.4 μm), obtained through Satellite Image Management in netCDF format (*.nc). Additionally, the fourth data set is single-polar C-band weather radar data from the Class I Soekarno-Hatta Meteorological Station.

In analyzing atmospheric dynamics, radiosonde data processed using the Rawinsonde Observation program (RAOB) is used to interpret upper-air observations into upper-air plotting graphs. Furthermore, the interpretation of the stability index obtained from the radiosonde upper-air plot graph will be interpreted based on Table 1 to determine the atmospheric stability category influencing the diversion event. Additionally, AWS Digi Stamet Soetta data in Excel format is processed using the Python programming language to generate daily (mm/day) and hourly (mm/hour) time series graphs to assess rainfall intensity.

Table 1. Atmospheric stability index category

Stability Index	Category		
	Weak	**Moderate**	**Strong**
CAPE (J/kg)	< 1000	1000– 2500	>2500
CIN (J/kg)	< 50	51 – 199	≥ 200
KI	< 29	29 – 37	> 37
SI	> 4	4 to -4	< -4
LI	> -2	-2 to -6	< -6
SWEAT	< 135	135– 239	>239

(Source: Fibriantika & Mayangwulan, 2020; Kusumawardani & Azani, 2022; Syaifullah, 2017)

Furthermore, Himawari-9 with multi-band consisting of band 8 (WV 6.2 μm), 13 (IR1 10.4 μm), and 15 (IR2 12.4 μm) is used to identify the distribution of cumulonimbus (Cb) clouds (Adzan et al., 2025; Hastuti & Mulsandi, 2017; Syaifullah & Nuryanto, 2016). In addition, weather radar data were used to identify the maximum reflectivity value using the CMAX product. The distribution of cumulonimbus clouds (Cb) affecting diversion events at Soekarno-Hatta Airport was identified using the Cloud Convective Overlays (CCO) method, which was visualized using Python. The algorithms used in the CCO method were Split Windows (1) and Dual Channel Difference (2) based on Equations 1 and 2.

$$IR - IR2 \leq 2 \quad \ldots\ldots\ldots\ldots\ldots(1)$$

$$IR - WV \leq 3 \quad \ldots\ldots\ldots\ldots\ldots(2)$$

Information:

IR: band 8 (6.2 μm)

IR2: band 13 (10.4 μm)

IR3: band 15 (12.4 μm)

(Source: Hastuti & Mulsandi, 2017; Syaifullah & Nuryanto, 2016)

The use of radiosonde data provides vertical profiles and vertical cloud structures that are important for weather dynamics analysis and early detection of extreme weather (Yuan et al., 2022). The use of rainfall data with AWS has the best accuracy in representing the actual rainfall intensity in a region, and is important for model validation and radar/satellite data calibration (Sokol et al., 2021). The use of CCO method data is very effective for detecting convective clouds that cause heavy rain and identifying dangerous cloud types such as cumulonimbus (Hastuti & Mulsandi, 2017; Syaifullah & Nuryanto, 2016).In addition, the use of weather radar data with CMAX products has advantages in describing vertical relativity across the entire atmospheric column, as well as lower error values and higher correlations with surface observation data (AWS and ARG) (Tondang et al., 2023). The stages of this study are described in the flowchart (Figure 2).

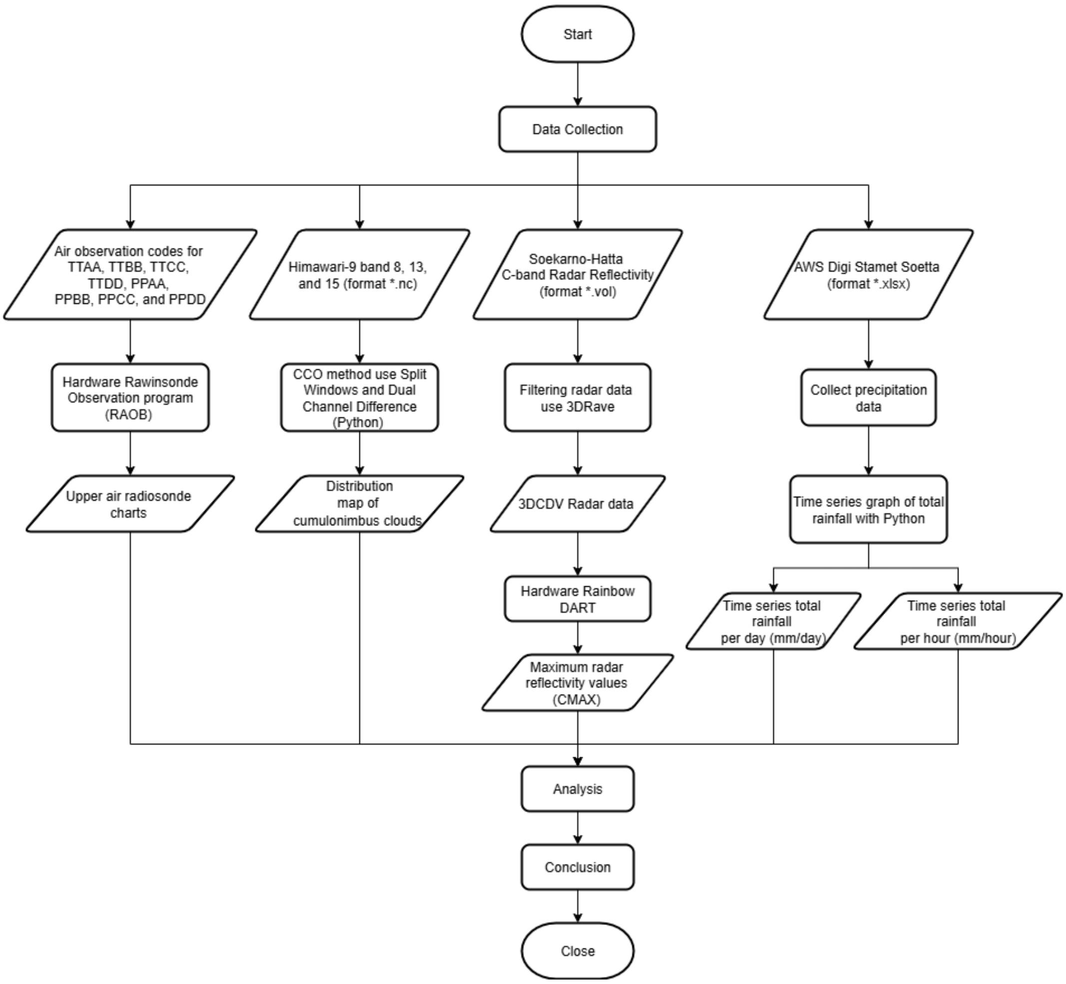


Figure 2. Research flowchart related to diversion at Soekarno-Hatta International Airport
(Source: Processed by author, 2025)

C. RESULT AND DISCUSSION

C.1. RESULT

Upper-Air Analysis With Radiosonde

Upper air observations are a crucial tool for identifying stability indices and vertical atmospheric conditions, which are essential for understanding meteorological phenomena and atmospheric dynamics (Fibriantika & Mayangwulan, 2020; Kusumawardani & Azani, 2022). Figure 3 shows the results of upper air observations using a radiosonde on January 28, 12:00 UTC at Soekarno-Hatta International Airport. Based on the radiosonde data, there is an ordinary cell system of cumulonimbus clouds accompanied by rain and lightning. The base height of the convective cloud is approximately 734 MSL based on the convective condensation level (CCL) value of the radiosonde. Additionally, the level of free convection (LFC) is approximately 947 MSL, and the lifted condensation level (LCL) is approximately 168 MSL.

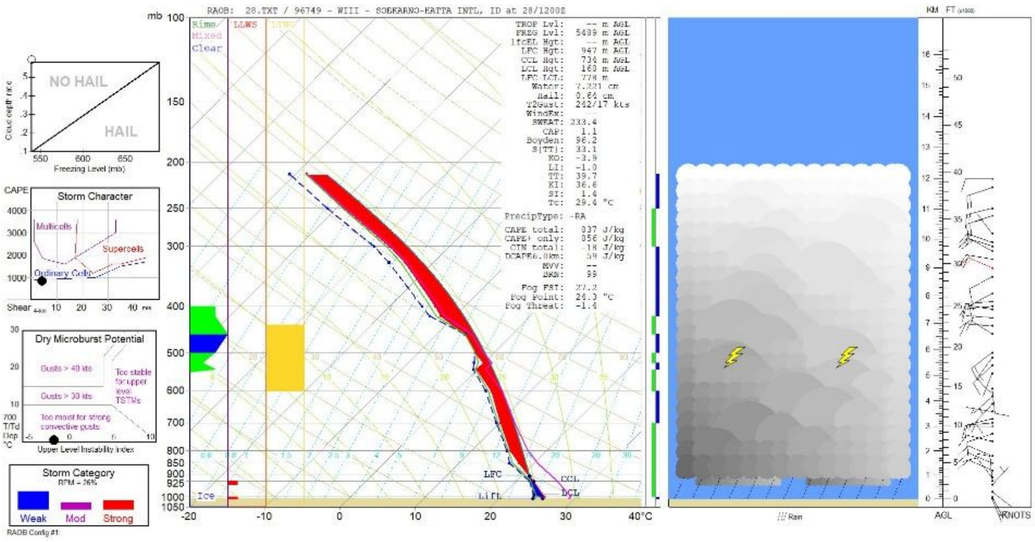
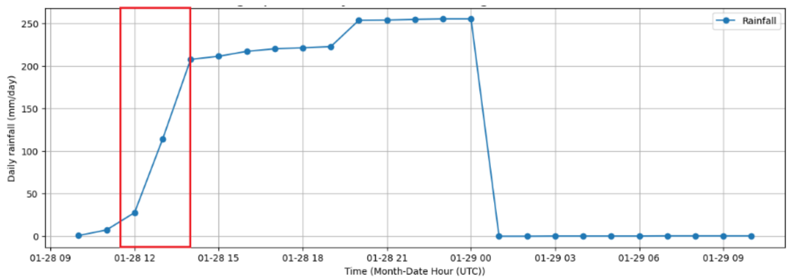


Figure 3. Upper air radiosonde charts at Soekarno-Hatta Class I Meteorological Station on January 28 at 12:00 UTC and during the diversion period (11:30 to 14:00 UTC) identified atmospheric instability and convective cloud formation.
(Source: Soekarno-Hatta Class I Meteorological Station, 2025)

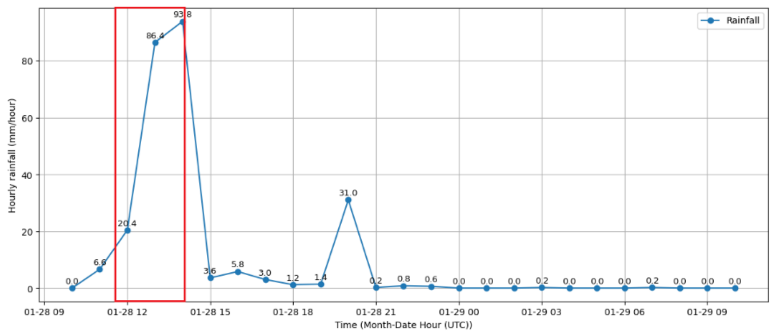
Based on radiosonde data and atmospheric stability index values in Table 1, the Convective Available Potential Energy (CAPE) value is classified as weak (856 J/kg), and the value of convective inhibition (CIN) is classified as weak (-18 J/kg). In addition, several other atmospheric stability indices were also measured, including the K Index (KI) of 36.6 (moderate to strong category), the Showalter Index (SI) of 1.4 (moderate category), the Lift Index (LI) of around -1 (weak category), and the Severe Weather Threat Index (SWEAT) of 233.4 (moderate category approaching strong).

Rainfall Graph Analysis

In addition to radiosonde data, AWS Digi Stamet Soetta data were also used to identify the intensity of rainfall at Soekarno-Hatta International Airport. Figure 4 is a time series graph of total rainfall per day (mm/day) and rainfall per hour (mm/hour) during the flight diversion event at Soekarno-Hatta International Airport on January 28, 2025 (UTC). Based on Figure 4(a), the rainfall intensity over a single day on January 28 reached 255.4 mm/day.



(a)



(b)

Figure 4. Time series graphs of total rainfall (a) daily (mm/day) with daily intensity reaching 255.4 mm/day and (b) hourly (mm/hour) with the extreme intensity at 13:00 and 14:00 UTC based on AWS Digi Stamet Soetta data with red boxes indicating diversion times (11:30 to 14:00 UTC).
(Source: Processed by the author, 2025)

Based on Figure 4(b), which represents hourly rainfall intensity. Based on the graph, rainfall intensity above 20 mm/hour occurred at 12:00, 13:00, 14:00, and 20:00 UTC. In addition, the highest rainfall intensity was recorded at 13:00 and 14:00 UTC with rainfall intensities of 86.4 mm/hour and 93.8 mm/hour, respectively.

Analysis of Cumulonimbus Cloud Distribution

The distribution of cumulonimbus (Cb) clouds in the Soekarno-Hatta International Airport area was identified using Himawari-9 satellite imagery with the Cloud Convective Overlays (CCO) method. Figure 5 shows the distribution of cumulonimbus clouds observed between

11:00 and 00:00 UTC in the Greater Jakarta area and its surroundings. Based on the image, at 11 UTC, no Cb clouds had formed in the area. At 12:00 UTC, Cb clouds began to form around Soekarno-Hatta International Airport, identified by the red area on the map. The intensity and distribution of Cb clouds continued to expand over time, eventually covering the Jabodetabek area and its surroundings. At 00 UTC, the spread of Cb clouds began to decrease.

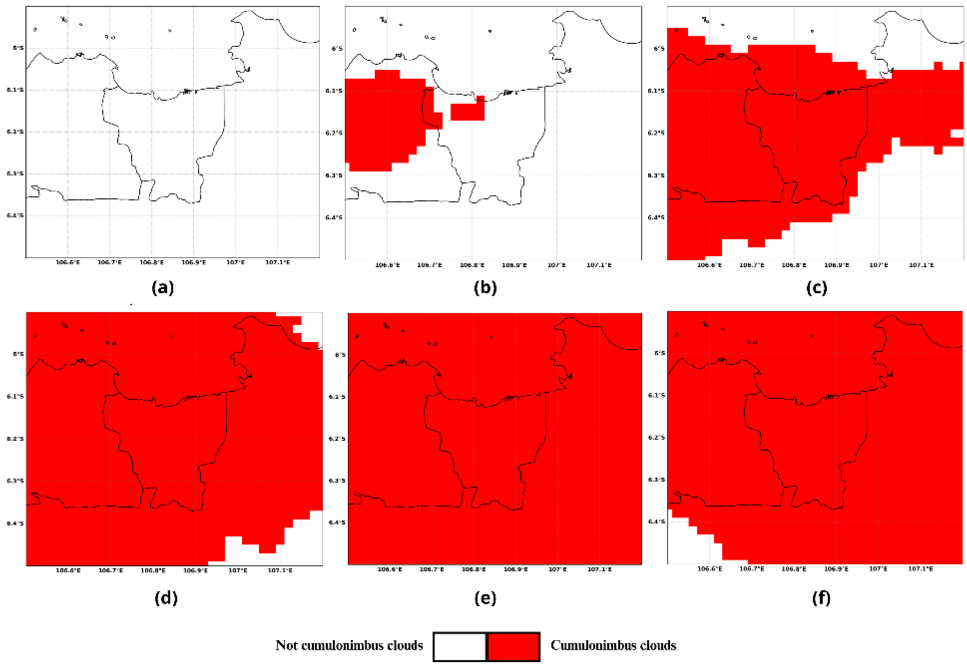


Figure 5. Distribution map of cumulonimbus clouds from (a) 11:00 UTC, (b) 12:00 UTC, (c) 13:00 UTC, (d) 14:00 UTC, (e) 20:00 UTC, and (f) 00 UTC showing the spread of Cb clouds, especially during the period of extreme rainfall intensity (13:00 and 14:00 UTC).
(Source: Processed by the author, 2025)

Weather radar analysis

In addition to using radiosonde data, AWS, and satellite imagery, the identification of weather systems is carried out by identifying maximum reflectivity using the CMAX product. Figure 6 shows the maximum reflectivity from the CMAX product at the hours with hourly rainfall intensity (mm/hour) classified as very heavy, namely at 12:00, 13:00, 14:00, and 20:00 UTC. Based on Figure 5, at 11:54 UTC, the reflectivity value reached 50.5 dBZ with rainfall intensity at 12:00 UTC. At 12:02, the reflectivity value was 48.5 dBZ with rainfall intensity at 13:00 UTC. At 13:14 UTC, the reflectivity value reached 41 dBZ with a widespread distribution and rainfall intensity at 14:00 UTC. Additionally, at 19:14 UTC, the reflectivity value reached 43.5 dBZ with rainfall intensity at 20:00 UTC.

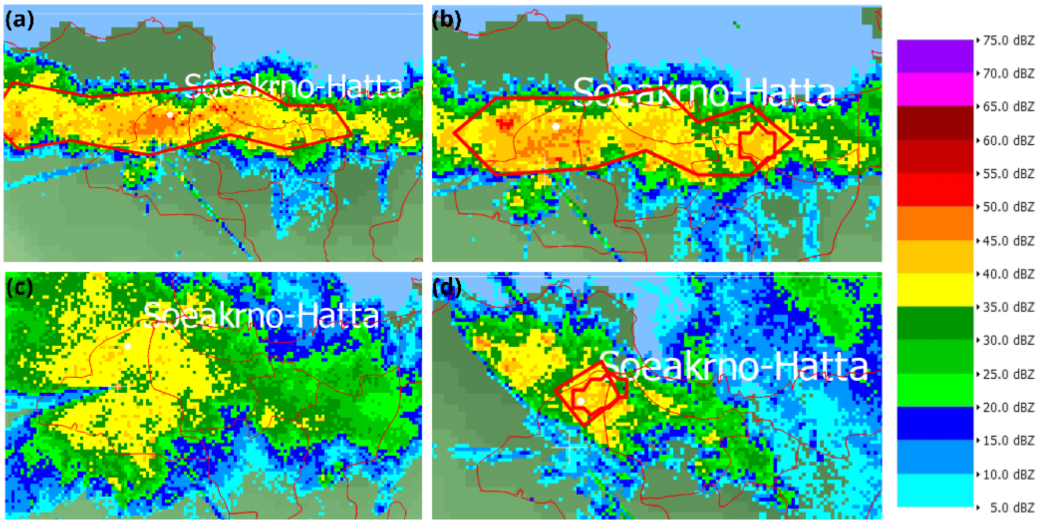


Figure 6. Maximum radar reflectivity values (CMAX) at (a) 11:54 UTC, (b) 12:02 UTC, (c) 13:14 UTC, and (d) 19:14 UTC contributed to the hourly rainfall intensity (mm/hour) at 12:00 (20.4 mm/hour), 13:00 (86.4 mm/hour), 14:00 (93.8 mm/hour), and 20:00 (31 mm/hour) UTC.
(Source: Processed by the author, 2025)

C.2. DISCUSSION

Atmospheric dynamics triggering significant weather

Analysis of radiosonde observations on January 28 at 12:00 UTC showed unstable atmospheric conditions, triggering the formation of an ordinary cell system at Soekarno-Hatta International Airport. During this phenomenon, atmospheric stability values such as CAPE were in the low category, which could create unstable atmospheric dynamics and extreme weather in several areas of the airport. This was due to the average CAPE value in Indonesia being 720 Joules, which is lower than at higher latitudes (Syaifullah, 2017). In addition, several extreme weather events in Indonesia show that convective cloud formation and extreme weather can occur when CAPE values are low (< 1000 J/kg), especially when there is abundant air humidity and other supporting stability indices (Taszarek et al., 2021; Vidia et al., 2024; Yudistira et al., 2019).

Significant weather formation is reinforced by low CIN values. Low CIN facilitates the lifting and convective development of air particles because energy resistance to vertical growth is minimized, thereby supporting the formation of convective clouds such as Cb (Bercos-Hickey et al., 2021). Furthermore, other stability indices such as KI and SWEAT indicate the potential for extreme weather due to convective activity, wind, temperature, and humidity, with KI and SWEAT values indicating a moderate category (Kusumawardani & Azani, 2022). The Showalter Index (SI) shows atmospheric instability in the middle layer in the moderate category, so that air parcels can continue to rise to the middle layer and support growth to the middle and upper layers (Agroho et al., 2021). The collaboration of several stability indices and convective inhibition (CIN) supports the development of an ordinary cell system at Soekarno-Hatta International Airport.

Distribution of convective cloud systems with CCO and CMAX producing very heavy rainfall intensity

Atmospheric instability triggered the ordinary cell system of Cb clouds. The distribution of Cb clouds can be identified based on the CCO method, with Cb cloud initiation occurring at 12:00 UTC in several areas, including above the airport. Cb clouds are a type of convective cloud that can produce moderate to very heavy rainfall lasting up to several hours. Based on the distribution during the diversion event (11:30 to 14:00 UTC), Cb clouds covered the airport area, resulting in heavy and continuous rainfall, even reaching extreme levels at 13:00 and 14:00 UTC. This very high rainfall intensity was one of the factors that contributed to flooding in the airport area and affected air traffic, such as affecting the lift and drag forces on aircraft movement (HR Mr & Thakur Dr, 2020; Makuyana et al., 2023).

The impact of Cb clouds on lighting traffic and causing flooding also occurred at an international airport in the United Arab Emirates due to Cb clouds stretching up to an altitude of 16 km with abundant water droplet content and producing very heavy rainfall (around 250 mm/day) (Shah et al., 2024).

Based on CMAX, the maximum reflectivity value (41 to 50.5 dBZ) correlates with rainfall intensity reaching the very heavy to extreme category in several hours of observation. The temporal correlation related to reflectivity values reaching > 40 dBZ reaffirms the presence of a Cb cloud system with large and abundant water droplet content, contributing to the creation of Intense Convective Clouds and producing intense precipitation during those hours (Kumar et al., 2024).

Furthermore, based on Muzayanah et al. (2016) regarding extreme rainfall that occurred in several areas of West Sumatra, with intensities of 384.1 mm/day and 379 mm/day, reflectivity above 40 dBZ continuously contributed to an increase in rainfall intensity, and contributed to causing flooding disasters.

Prospects and challenges

Based on several indicators obtained from research using multi-data observations during significant weather events at Soekarno-Hatta International Airport (causes of diversion and extreme rainfall), it is hoped that the understanding of the indicators that cause extreme weather, especially in airport areas, can be expanded. In addition, a deeper understanding is needed, especially in studying cases of significant weather that have occurred, to create thresholds related to several indicators that are precursors or signs of significant weather.

Determining thresholds using long-term case studies (long-term datasets) can increase the accuracy of models in predicting and providing early warnings of weather conditions that have the potential to cause significant weather, especially in airport areas. Furthermore, it is also necessary to integrate a prediction system using machine learning, integrated with these thresholds, in order to further strengthen the accuracy of weather predictions.

D. CONCLUSION

Atmospheric dynamics and weather conditions are among the external factors that significantly affect aviation safety and traffic, particularly severe weather that can necessitate diversions. On January 28, 2025, a diversion occurred at Soekarno-Hatta International Airport, triggered by convective activity. This was supported by stability indices such as KI, SI, and SWEAT, which fell within the moderate to strong category, as well as a low CIN stability index, which indicated free convection within the air parcel. This was also in line with the increasingly widespread distribution of convective clouds based on CCO diagnosis, as well as maximum radar reflectivity reaching approximately 50.5 dBZ (11:54 UTC), 48.5 dBZ (12:02 UTC), 41.0 dBZ (13:14 UTC), and 43.5 dBZ (19:14 UTC). This contributed to rainfall intensity classified as 255.4 mm/day.

The use of multi-data combining stability indices from radiosondes, AWS rainfall data, Cb identification based on CCO, and C-band radar reflectivity is the first integrated analysis at Soekarno-Hatta International Airport on the phenomenon of diversion. This research is expected to serve as a basis for determining thresholds for predictive data to identify the possibility of significant weather that could disrupt air traffic. In addition, it is hoped that long-term data analysis related to extreme weather can be collected and that nowcasting and short-term prediction of satellite, radiosonde, and radar data can be improved using machine learning integration, such as spatiotemporal and classification.

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