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# Drone and Flare Technology for Efficient and Sustainable Weather Modification Operations in Indonesia

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**Abstract**: This review examines drone and flare technologies as an alternative to manned aircraft for weather modification operations in Indonesia. Until now, weather modification operations have generally used aircraft as the primary means of cloud seeding. However, this method has limitations, including high operational costs, limited flight hours, low visual precision, and high human risk. These conditions have prompted the need for more efficient and flexible alternative technologies. This study aims to examine the potential of using drones equipped with flares as an effective solution to support modern weather modification operations. The study employs a qualitative methodology that combines a systematic literature review, technical specification analysis of certified UAV platforms, and comparative cost and operational assessments against conventional manned aircraft. The analysis identifies six certified UAV platforms currently being tested for weather modification in Indonesia — including the PUNA Wulung fixed-wing UAV and its multirotor variants — and evaluates their advantages in lower operational costs (estimated at 5× cheaper per day than manned aircraft), greater operational flexibility, and improved seeding precision. In addition, the use of drones can minimize risks to flight crew safety. However, they have limitations in payload capacity that need to be addressed. Thus, it can be concluded that drone technology has the potential to be an effective and sustainable alternative solution in weather modification operations in Indonesia. The implementation of this technology not only increases efficiency but also strengthens capacity.

**Keywords**: UAV, PUNA, flare, cloud seeding, weather modification, Indonesia



## 1. Introduction

Global climate change has triggered an increase in the frequency and intensity of extreme events such as floods and droughts [1]. Weather modification technology offers a potential solution to climate problems that cause droughts and floods in Indonesia by manipulating the rain formation process in the atmosphere [2]. Currently, modification mostly uses aircraft with manual seeding systems and flares, which are relatively expensive compared to other platforms [3]. In addition, the use of aircraft in cloud seeding with flares is considered ineffective and emphasizes the operational safety aspects of aircraft in weather modification operations [3]. Thus, drones offer an alternative solution in operations with effectiveness and efficiency [4], [5], but require technical innovation and regulatory support. From an engineering standpoint, the key challenges concern UAV system design, specifically maximum takeoff weight (MTOW), endurance, payload integration, and airworthiness certification, which this study addresses through comparative technical analysis.

The most important aspects in weather modification operations using drones are that the drones must have sufficient range or coverage, endurance, and maximum takeoff weight (MTOW) capacity to carry cloud seeding flares. Flare contains a mixture of seeding materials and chemicals consisting of potassium perchlorate ($KClO_4$), magnesium (Mg), lithium carbonate ($Li_2CO_3$), calcium chloride ($CaCl_2$), and other materials [6]. These flares are programmed to ignite along a predetermined flight path, ensuring that the target area is seeded evenly and efficiently [7].

Although drone technology offers great potential for weather modification operations, there are several challenges that need to be overcome. Regulations and permits for the use of drones in weather modification operations are difficult to obtain because they require certification and airworthiness from the authorities. A legal framework is needed to ensure safe and responsible operations, especially if the seeding material carried is flares, which are categorized as low explosive materials [3]. In addition, the limitations of drone capabilities, particularly their range, operational endurance, and payload capacity, as well as cost analysis, are a concern because they can limit the range and effectiveness of cloud seeding operations.

This review systematically examines the technical feasibility of UAV-flare integration as an alternative to manned aircraft in weather modification operations, with analysis focused on maximum takeoff weight (MTOW), payload capacity, flight coverage, endurance, and airworthiness certification requirements in Indonesia.

# 2. Methods

This study employs a qualitative research methodology based on systematic literature review and documentary analysis. No new primary field experiments were conducted. All data used in the analysis were obtained from secondary sources, including published academic literature, Indonesian government regulations, and institutional technical reports from national agencies involved in weather modification operations.

## 2.1. Data Sources

Data collection focused on four categories of sources:

(a) *Regulatory documents* — Indonesian regulations governing the operation of unmanned aerial vehicles and weather modification activities, specifically: Minister of Defence Regulation No. 26 of 2016 [8], Minister of Transportation Regulation PM 37 of 2020 [9], CASR Part 119 (PM 33/2022) [10], PM 34 of 2021 on remotely piloted aircraft systems [11], and BMKG Regulation No. 2 of 2025 on weather modification operations [12].

(b) *UAV certification records* — Airworthiness certification data for UAV platforms issued by the Indonesian Defence Airworthiness Authority (IDAA) and the Directorate of Airworthiness and Aircraft Operations (DKUPPU). Specifications were obtained from publicly available institutional documents and published technical reports from BRIN (formerly BPPT) and PT. Dirgantara Indonesia.

(c) *Flare certification records* — Technical specifications and certification data for weather modification flares approved by BMKG, sourced from BMKG institutional publications and peer-reviewed studies on flare composition and safety testing.

(d) *Operational trial reports* — Published reports and journal articles describing the outcomes of UAV-based weather modification trials conducted by BRIN, BMKG, the Indonesian Military Academy, and PT. Atmosphere Engineering Indonesia (RAI), including field trial data for the PUNA Wulung, Hexacopter TMC, and other platforms listed in Section 3.1.6.

### 2.2. Analysis Framework

The comparative analysis between manned aircraft and UAV platforms was structured around five technical parameters selected based on their direct relevance to cloud seeding mission requirements:

1. *Maximum Take-Off Weight (MTOW)*, used as a proxy for overall platform capacity and structural capability to carry flare payloads under operational conditions.
2. *Flare payload capacity*, the maximum additional payload available after accounting for avionics, fuel/battery, and structural weight, which determines how many flares can be carried per sortie.
3. *Operational endurance*, maximum continuous flight time, which determines the coverage duration and area that can be serviced in a single sortie without landing for refuelling or battery replacement.
4. *Flight coverage radius*, the maximum operational range from the ground control station, which determines whether a UAV can reach and sustain operations at the target cloud location.
5. *Airworthiness certification status*, the type of certification held (military via IDAA or civil via DKUPPU), which determines the legal conditions under which each platform may be deployed for weather modification operations.

Cost comparison between manned aircraft and UAV platforms was based on published and publicly available operational rate estimates from Indonesian weather modification agencies. Figures are presented as estimated ranges (IDR/day) rather than precise values, given the variability of costs by location, aircraft type, and contract terms. The suitability of each identified UAV platform for weather modification operations was assessed by cross-referencing its technical specifications against the minimum requirements established by BMKG for TMC operations, as stipulated in BMKG Regulation No. 2 of 2025 [12].

## 3. Results and Discussion

### 3.1. Results

#### 3.1.1. Regulations for the Operation of Unmanned Aircraft in Indonesian Territory

The operation of unmanned aircraft systems for national defense and security or military purposes refers to Minister of Defense Regulation No. 26 of 2016 concerning Unmanned Aircraft Systems for National Defense and Security [8]. In this regulation, military unmanned aircraft are categorized based on weight, operating altitude, operating radius, and operating time. The regulation also covers technical and procedural aspects of military unmanned aircraft operation. Meanwhile, the operation of aircraft in civil airspace refers to Regulation of the Minister of Transportation of the Republic of Indonesia No. 37 of 2020 concerning the Operation of Unmanned Aircraft in Serviced Airspace in Indonesia [9], and PM 33/2022: Civil Aviation Safety Regulation (CASR) Part 119 concerning Aircraft Operation Certification for Air Transport Activities [10].

#### 3.1.2. Regulations for the use of flares in Weather Modification Technology

The use of flares in weather modification technology (*Teknologi Modifikasi Cuaca* or TMC) in Indonesia is regulated by regulations established by the Meteorology, Climatology, and Geophysics Agency (BMKG) through BMKG Regulation Number 2 of 2025, which stipulates that TMC can be carried out by the BMKG or other parties that have a permit, such as research institutions, universities, Indonesian legal entities, and Indonesian citizens [12]. Parties conducting TMC must have a registration certificate issued by the BMKG. In addition, the implementation of TMC must be carried out with good coordination between the implementer and the user to achieve the desired objectives.

#### 3.1.3. Comparison of Aircraft and Drone Use for Weather Modification in Indonesia

The use of weather modification platforms in Indonesia is dominated by aircraft. The process begins with meteorologists identifying target clouds and determining the appropriate flight direction and altitude based on atmospheric conditions. Once identified, the aircraft is loaded with seeding materials such as silver iodide or salt flares, which are prepared according to the desired seeding effect. The pilot then directs the aircraft toward the target cloud and releases or ignites the seeding materials using specialized equipment to ensure even distribution. These particles act as condensation nuclei, encouraging the formation of water droplets that eventually merge and fall like rain. The effectiveness of cloud seeding depends on various factors, including cloud type, humidity, temperature, and wind conditions, and when conducted under favorable circumstances, it can significantly increase rainfall and support water resource management, agriculture, and drought mitigation efforts.

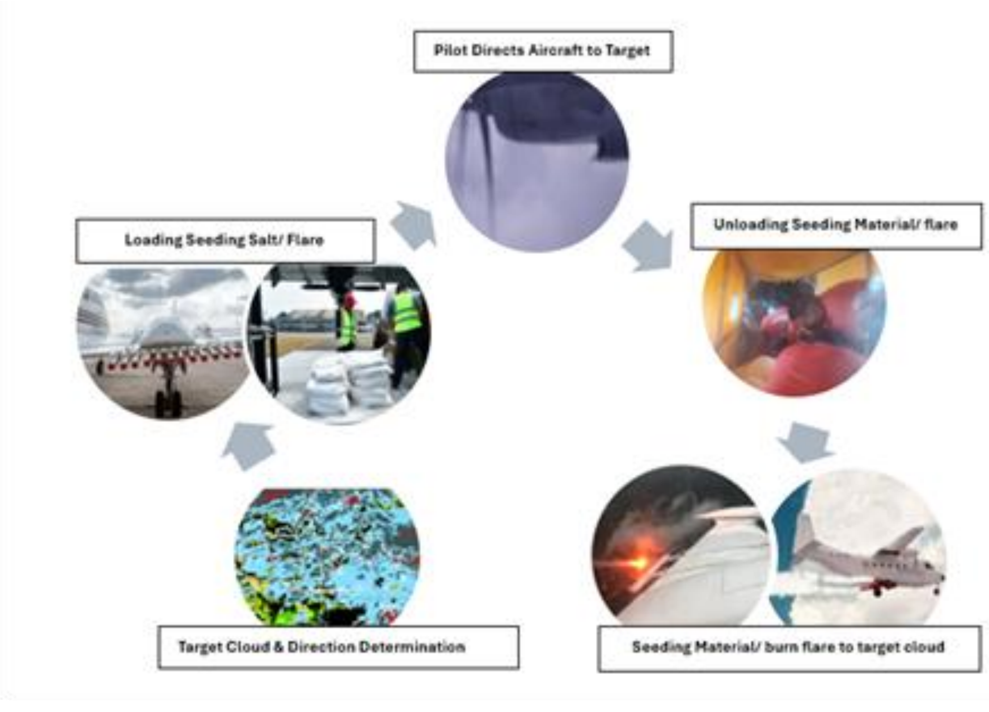
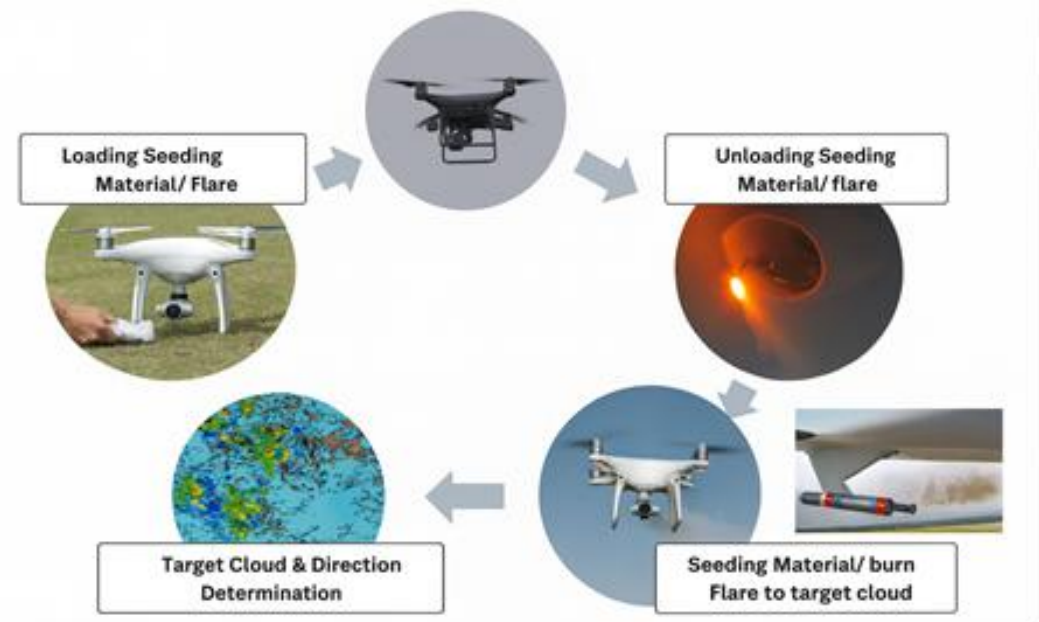



**Figure 1.** Cloud seeding process using aircraft.

Compared to cloud seeding processes, drone-based cloud seeding is an advanced weather modification technique that utilizes unmanned aerial vehicles (UAV) to disperse seeding agents into selected clouds to increase rainfall. The process begins with meteorologists analyzing weather conditions to identify suitable target clouds and determine the flight path, altitude, and optimal time for seeding. Once the targets are identified, the drones are prepared and loaded with seeding materials or flares, such as silver iodide or salt particles, which are measured based on the properties of the clouds. The drones are then directed autonomously or remotely to the target clouds, following pre-programmed coordinates and meteorological guidance. Upon reaching the target area, the drone releases or burns the seeding material using a special dispenser or flare mechanism to ensure even particle distribution. These particles act as condensation nuclei that attract water vapor, forming droplets that coalesce and eventually fall as rain. Compared with aircraft-based operations, drone-based cloud seeding offers advantages such as lower operational costs, greater precision, reduced risk to human pilots, and the ability to operate in challenging weather conditions.

**Figure 2.** Cloud seeding process using drone or UAV.




When compared, the use of aircraft in weather modification operations is significantly more expensive than using drones. Table 1 is a comparison of the use of aircraft and drones in weather modification operations in Indonesia.

#### 3.1.4. List of Unmanned Aircraft that have Obtained Airworthiness Certification from IDAA and DKUPPU

In Indonesia, there are several unmanned aircraft that have obtained civil and military airworthiness certificates issued by Directorate of Airworthiness & Aircraft Operations (DKUPPU) and Indonesian Defence Airworthiness Authority (IDAA), as shown in the Table 2.

**Table 1.** Comparison of aircraft and drone use for weather modification.

| Note | Seeding Vehicle | |
|---|---|---|
| | Aircraft | Fixed-wing/Evtol Drones |
| Operating Hours | Sunrise and before sunset | 24-hour operation/ depending on permits |
| Estimated operating rental costs | >IDR 150,000,000/day depending on the location of the operation | IDR15,000,000-50,000,000/day depending on location and drone type |
| Safety for Human | High risk to human pilots; limited ability to operate in challenging weather conditions | Lower risk to human pilots, and the ability to operate in challenging weather conditions |
| Precision | Low precision; depends on visual identification and manual navigation | Higher precision with system control and target cloud |
| Seeding Material | Powder or flares | Powder or flares |
| Seeding material costs | Depends on the mission target | Depends on the mission target |
| Payload Capacity | High (hundreds of kg; multiple flare racks) | Limited (varies by platform; typically <20 kg for multirotor, up to ~50 kg for large fixed-wing) |
| Operational Altitude | High altitude capability (typically 10,000–20,000 ft, adaptable to cloud base height) | Lower ceiling depending on platform type; regulatory altitude restrictions apply under PM 37/2020 |

**Table 2.** Specifications of drones that have passed military or civil airworthiness certification tests in Indonesia.

| Drone/UAV Name | Type of Certification | MTOW, Endurance & Coverage |
|---|---|---|
| PUNA Wulung | Military | 120 kg, ±6 hours & 120 km |
| PUNA Alap-Alap PA-06D | Military | 31 kg, 5-6 hours & 100 km |
| OS-Wifanusa SL-D70 | Military | N/A*, 6-8 hours & 100 km |
| OS-Wifanusa SL-D28 | Military | N/A*, 6-8 hours & 100 km |
| CH-4 Rainbow | Military | 345 kg, ±30 hours & 3,500-5,000 km |
| EHang 216 | Civil | 220 kg, ±25 minutes & 35 km |

*MTOW data not publicly disclosed in available documentation.

#### 3.1.5. List of Weather Modification Flares That Have Passed Testing in Indonesia

The use of flares in Weather Modification Technology (TMC) in Indonesia is regulated by the Meteorology, Climatology, and Geophysics Agency (BMKG) through BMKG Regulation No. 2 of 2025. Table 3 shows some flares that have been certified and used in weather modification operations.

**Table 3.** List of weather modification flares that have passed certification tests.

| Flare | Manufacturer | Composition | Year |
|---|---|---|---|
| CoSAT 1000 | PT. Pindad / BPPT (BRIN) | NaCl, $KClO_4$, Sirlak, $BaClO_3$ | Certification 2020 |


**Figure 3.** Structure of CoSAT 1000 [13].

### 3.1.6. Unmanned Aerial Vehicles That Have Been Tested with Flares for Weather Modification

The use of drones with flares in Weather Modification Technology (TMC) indonesia has been tested. Table 4 shows some of the drones that have been tested to carry out weather modification operations with flares.

**Table 4.** List of drones that have been tested for weather modification.

| Drone/UAV Name | Type/Model | Institution/Operator |
|---|---|---|
| PUNA Wulung | Fixed-wing | BPPT (BRIN) and PT.DI |
| Hexacopter TMC | Multirotor (hexacopter) | Indonesian Military Academy, BRIN, PT RAI |
| Rotary/Extended GBG Drone | Rotary/Multirotor | PLN Nusantara Power, BRIN, BMKG |
| RAI Seeding Drone | Multirotor Modification | PT Atmosphere Engineering Indonesia (RAI) |
| EVtol Drone | Evtol | Indonesian Military Academy |
| Alap Alap & LSU Drones | Fixed-Wing and VTOL | BRIN |

**Figure 4.** PUNA Wulung with flare.

### 3.2. Discussion

The comparative analysis in Table 1 reveals that UAV-based weather modification offers a significant cost advantage over manned aircraft operations, with estimated daily costs approximately five times lower. As shown in Table 1, the use of drones is considered more efficient than conventional aircraft, with estimated daily costs that are almost five times lower, greater mission flexibility, high precision and low risk for humans. However, the obstacles faced are payload limitations, the optimal altitude range for cloud seeding, and operational safety certification that still needs to be strengthened.

In addition to technical aspects, in Table 2 and Table 4, several types of drones have been certified and are used in Indonesia to support weather modification operations. Each drone has different characteristics according to mission requirements, such as MTOW, flare payload capacity, endurance, flight range, and maneuverability. Fixed-wing drones such as PUNA Wulung can cover a wider area but require a larger runway and logistical support. Conversely, multirotor drones such as Rotary and Hexacopter are superior in maneuverability and can take off easily in limited terrain but have shorter endurance. Based on Table 3 there is CoSAT 1000 of Indonesia flare that have certification.

A critical gap identified in this analysis is the mismatch between current flare payloads and UAV payload capacities. The CoSAT 1000 flare (Table 3) requires only a modest payload, but cloud seeding operations typically require multiple flares per sortie to cover a target area adequately. For large fixed-wing UAVs such as the PUNA Wulung (MTOW: 120 kg), this is manageable, but for multirotor platforms such as the Hexacopter TMC (Table 4), payload constraints limit the number of flares per mission and therefore the effective seeding coverage per flight. Future engineering development should prioritize MTOW expansion in multirotor UAV platforms or modular multi-flare dispenser systems that maximize seeding efficiency within existing payload limits. The integration of real-time BMKG meteorological data feeds into UAV autonomous flight control systems would further improve targeting precision and reduce wasted sorties due to cloud movement.

Overall, the discussion results indicate that drone technology can be an effective solution for weather modification operations in Indonesia. The combination of cost efficiency, maneuverability, and operational flexibility makes drones a modern solution that can complement, and in certain conditions even replace, the role of conventional aircraft. However, regulatory development, payload technology improvements, and integration with weather forecasting systems are still needed to maximize their effectiveness.

## 4. Conclusions

This study concludes that drone technology has great potential as an effective solution for weather modification operations in Indonesia. UAVs offer cost efficiency, operational flexibility, maneuverability in confined or inaccessible areas, higher seeding precision, and reduced risk to human pilots compared to manned aircraft. The types of drones that have been tested, both fixed-wing and other types, have their own advantages and limitations in terms of endurance, payload, and infrastructure requirements. However, limitations in MTOW, flare carrying capacity, flight altitude, range, endurance, and certification and regulatory aspects remain challenges that need to be overcome. Therefore, this study recommends the need to strengthen UAV regulations and certification, develop payload technology to carry flares more optimally, and integrate with the BMKG weather prediction system to improve operational accuracy. In addition, cross-institutional collaboration between government institutions (BRIN, BMKG, the Indonesian Air Force, universities, and the UAV industry) needs to be enhanced to encourage innovation in the use of weather modification in various fields, including disaster mitigation, food security, and others in Indonesia.

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**Data Availability Statement:** The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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