SIMULATION OF VOLCANIC ASH DISPERSION FROM MOUNT RUANG USING THE PUFF MODEL (APRIL 29-30, 2024)

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ABSTRACT

This study aims to simulate and predict volcanic ash dispersion from the 29 April 2024 eruption of Mount Ruang by coupling the PUFF model with RGB analysis of Himawari-8 imagery. Driven by meteorological fields from the NOAA Global Forecast System, PUFF provides 24-hour forecasts of ash transport and integrates Lagrangian and Eulerian representations of particle motion. For validation, Himawari-8 satellite imagery was processed using the RGB method with IR1, IR2, and IR4 channels to visually detect the spatial distribution of ash clouds. This method enables effective differentiation between volcanic ash and meteorological clouds, improving detection accuracy. Model forecasts closely match the timing and distribution patterns observed in satellite imagery, indicating strong agreement between numerical simulation and remote sensing. The results show that the PUFF model delivers reliable short-term guidance on ash dispersion. The integration of numerical modeling and remote sensing analysis confirms the effectiveness of the PUFF model in supporting early-warning capability and offers practical insights for aviation safety and volcanic hazard risk mitigation.

Keyword: *PUFF model, volcanic ash, Mount Ruang, RGB imagery, ash dispersion*

1. Introduction

Indonesia, located on the Pacific Ring of Fire, is home to more than 500 volcanoes. Of these, 129 volcanoes are classified as active, accounting for approximately 30% of the world's active volcanoes. Frequent volcanic eruptions pose significant hazards, particularly the dispersion of volcanic ash, which threatens nearby populations and infrastructure, as well as disrupts regional and international aviation operations [1].

Volcanic ash clouds can damage aircraft engines, reduce visibility, and cause complete engine failure, making them a critical concern for aviation safety. In this context, accurate and timely forecasts of ash dispersion are essential to support early warning systems and assist aviation authorities in rerouting flights, issuing NOTAMs, and minimizing risk. While awareness of these hazards is well-established, operational forecasting models that can deliver precise, short-term predictions remain underutilized, particularly in Indonesia.

The eruption of Mount Ruang in North Sulawesi on April 29, 2024, at 18:15 UTC, was reported by the Indonesian Center for Volcanology and Geological Hazard Mitigation (PVMBG) through a VONA (Volcano Observatory Notice for Aviation) bulletin issued on April 30, 2024, at 00:35 UTC [2]. The event caused significant disruption to airspace operations, including the temporary closure of seven airports from April 30 to May 1, 2024 [3]. This incident highlights the critical need for effective predictive tools capable of simulating the trajectory and dispersion of volcanic ash in real time.

Several models have been developed to forecast volcanic ash dispersion, including HYSPLIT, FALL3D, and PUFF. HYSPLIT, developed by NOAA, uses a hybrid Lagrangian-Eulerian approach to simulate the atmospheric transport and dispersion of ash [4]. FALL3D is a fully Eulerian model capable of simulating ash and gas dispersal over complex terrain and a range of weather conditions [5]. The PUFF model (UAF/AVO) is a Lagrangian particle model that simulates the transport and dispersion of volcanic ash by tracking representative particles advected by analyzed or forecast winds. Turbulent diffusion is represented through a stochastic random-walk process, and gravitational settling is included using Stokes' law, making the model computationally efficient and suitable for near real-time operations [6][7].

The PUFF model has been operationally implemented by the Alaska Volcano Observatory and the Anchorage VAAC for decades, with extensive validation against satellite and in situ observations for eruptions in Alaska and Japan [6][8][9]. This proven reliability has encouraged its application to numerous volcanic events in Indonesia, including the eruptions of of Mount Merapi in 2010 [10], Mount Rinjani in 2016 [11], Mount Agung in 2017 [12], and Anak Krakatau in 2018

[13]. These studies demonstrate the PUFF model's capability to reproduce ash dispersion patterns with considerable accuracy, underscoring its potential for regional forecasting.

In parallel, satellite-based observation techniques have become increasingly important in monitoring volcanic ash. Himawari-8 imagery, particularly through RGB composite methods, has been widely adopted to detect and track volcanic plumes. This approach has been successfully applied in events such as the eruptions of Anak Krakatau (2018) [14], Mount Agung (2017) [15][16], Mount Sinabung (2018-2019) [17][18], Mount Raung, Rinjani, and Bromo (2015-2017) [19], and Mount Gamalama (2017) [20]. For example, during the Mount Agung eruption, RGB composite imagery combined with HYSPLIT and streamline analysis revealed ash drifting toward I Gusti Ngurah Rai Airport, leading to a temporary closure between November 27 and 30, 2017 [16]. This incident highlighted the importance of integrating satellite-based detection and wind modeling for aviation safety.

However, RGB-based detection techniques exhibit reduced reliability under dense cloud conditions, as reported during the Mount Marapi eruption (2023) [21] and in the case of Mount Sinabung [18]. Subsequent overlays using streamline analysis and RGB imagery revealed that the ash plume from Mount Marapi drifted southwestward. Similarly, Siboro and Firmansyah [22] enhanced ash detection in the Sinabung eruption (2020) by using the Three-Band Volcanic Ash Product (TVAP), confirming east-southeast dispersion despite atmospheric interference. These findings indicate that integrating multispectral satellite data with numerical dispersion models can substantially improve monitoring accuracy in complex environments.

Despite the model's advantages, its application to Indonesian volcanic events, especially those occurring in remote regions such as North Sulawesi, has been relatively limited. Furthermore, the integration of the PUFF model outputs with satellite-based observation techniques, such as RGB composite analysis from Himawari-8 imagery, remains underexplored. Leveraging both modeling and remote sensing could significantly enhance the accuracy and reliability of volcanic ash dispersion forecasts. Accordingly, this study aims to simulate and predict the dispersion of volcanic ash from the 2024 eruption of Mount Ruang using the PUFF model, with validation through RGB analysis of Himawari-8 satellite imagery. The objective is to evaluate the PUFF model's effectiveness for short-term volcanic ash forecasting and assess its potential contribution to real-time aviation hazard mitigation in Indonesia.

2. Data and Methods

Meteorological driver (GFS). The PUFF model's skill depends entirely on the accuracy of the driving wind field, regardless of the NWP provider [23]. In this study, meteorological input from the NOAA's Global Forecast System (GFS) served as the driver because it is global, operational, updated four times daily (00/06/12/18 UTC), openly accessible via NOMADS, and well established for upper-air winds at aviation flight levels [23][24][25]. The GFS dataset at 1.0° horizontal spacing provides four-dimensional fields (u, v, temperature, and pressure/height). Files were retrieved through NOMADS, inputs were then spatially and vertically interpolated with custom scripts before integration into the PUFF grid [23].

Domain and volcano location. The modeled area spans 115°-135° E, 7° S-12°30′ N. Mount Ruang is at 2°19'18.30" N and 125°24'30.42" E in Sitaro Regency, North Sulawesi.

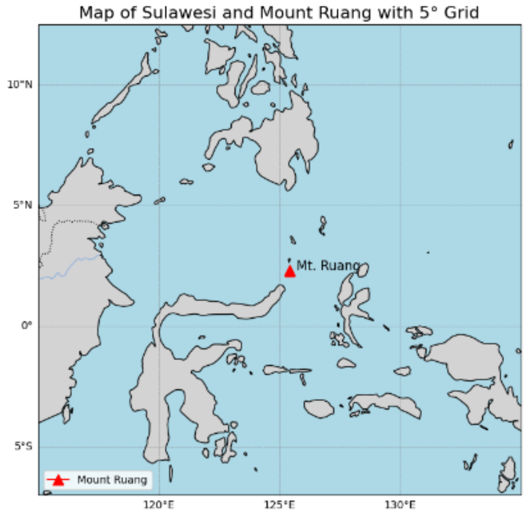

Figure 1. Location of Mount Ruang, North Sulawesi

Plume height (eruption height). Before running the PUFF model, the plume height was obtained from Darwin VAAC and PVMBG VONA flight-level reports for the event period [2]. This aligns with standard PUFF practice of initializing with VAAC/VONA and adjust them using direct observations when available. Independent case studies confirm that such observations can materially improve plume-top estimates in the PUFF model [7][8].

The PUFF Model Configuration. The PUFF model simulates volcanic ash dispersion by integrating Lagrangian and Eulerian techniques. The Lagrangian component tracks individual ash particles using a particle-following method, while the Eulerian approach estimates the concentration fields of ash across fixed spatial grids [6][26]. Each simulation in this study utilized 5,000 particles distributed according to a 3D Gaussian profile centered at the vent. The governing equation in Lagrangian form can be expressed as:

$$\begin{aligned} r_i(0) &= S, \qquad i = 1 \sim M,\ \ for\ t = 0 \\ r_i(t+\Delta t) &= r_i(t) + V\Delta t + Z\Delta t + G\Delta t, \\ &\qquad\qquad i = 1 \sim M, for\ t > 0 \end{aligned}$$

$r_i(t)$ is the position vector of the *i*-th particle at time *t*.

The movement of volcanic ash particles in the PUFF model is governed by a combination of wind-driven advection, atmospheric diffusion, and gravitational settling. Each particle originates from a defined source location S. The wind velocity vector $V = (u, v, w)$ determines the directional transport of particles throughthe atmosphere. Atmospheric diffusion is represented by a stochastic vector $Z = (u, v, w)$, where each component is generated using Gaussian random numbers with zero mean and standard deviations controlling the rate of horizontal and vertical spreading. Gravitational fallout, which influences the downward motion of ash particles, is represented as $G = (0,0,-w_t)$, computed using an extended form of Stokes' Law. The default parameter values used in the simulations follow the configuration recommended by [27], ensuring consistency with previous volcanic ash dispersion studies.

Vertical and temporal settings. GFS pressure levels were converted to height using the hypsometric relation, and vertical interpolation aligned winds with particle release heights [8]. The interpolation of wind vectors followed the PUFF approach, in which the four-dimensional (longitude, latitude, height, and time) wind field is mapped and interpolated to each particle's position using either a nearest-neighbor or a 4-D cubic-spline scheme depending on local wind variability [6][7]. The nearest-neighbor scheme provides computational efficiency for smoothly varying fields, while the cubic-spline option preserves vertical and temporal gradients in regions of stronger shear, ensuring physically consistent advection trajectories [6]. The simulation begins at 19:00 UTC on 29 April 2024, runs for 24 h, and is offset 45 minutes from onset to synchronize with the latest available driver fields and initial satellite data [8][9].

Validation with Himawari-8 RGB. RGB composites at 00, 06, 12, and 18 UTC on 30 April 2024 were generated in SATAID using the IR1-IR2 (Red), IR4-IR1 (Green), and IR4 (Blue) channel combination. In this composite, volcanic ash appears as pink/magenta clusters [28]. Model Validation using Himawari-8 RGB Imagery. Polygons were drawn only where the Ash-RGB signal was spatially coherent with downwind motion from the vent and consistent with upper-level wind vectors.

The georeferenced Ash-RGB polygons were overlaid on the corresponding PUFF plan-view concentration fields in a GIS environment. Agreement was assessed semi-quantitatively based on pixel overlap between polygons and modeled ash, together with expert visual comparison of shape, areal extent, and downwind orientation at each time step. This protocol provides a transparent, reproducible linkage between the yellow-outlined areas and volcanic ash in the satellite imagery [29].

Flight Level Analysis. Flight Level Analysis Ash dispersion patterns were examined at standard aviation flight levels: FL100 (10,000 ft), FL180 (18,000 ft), FL240 (24,000 ft), and FL450 (45,000 ft) to produce flight-level exposure profiles for route planning. Wind vector patterns and ash plume thickness were examined at each flight level using concentration outputs from from the NWP driver. Model accuracy at flight levels therefore hinges on wind fidelity, which has been emphasized and demonstrated in PUFF validation studies [7][8].

Tools and Resources. The PUFF model simulations were executed on a local high-performance computing workstation using compiled Fortran code with supporting Python-based pre-processing and post-processing scripts. Satellite image processing and geospatial overlays were conducted in SATAID and QGIS. Average simulation runtime was approximately 30 minutes per scenario.

Clarifications and Exclusions. The methodology section focuses exclusively on the simulation design, data input, and validation approach used in this study. Comparative results from other eruptions and case studies have been deferred to the Discussion section for clarity.

3. Result and Discussion

The PUFF Model Simulation and Dispersion Patterns. Figure 2 presents horizontal dispersion maps of the Mount Ruang ash plume at 6, 12, 18, and 24 hours after the eruption on April 29, 2024, at 18:35 UTC. Initially, the ash column extended southwest at high altitudes, around 60,000 feet. By the 12-hour mark, dispersion shifted westward and began entering mainland North Sulawesi. At 18 hours, the ash advanced northwest, covering areas in Gorontalo, and by 24 hours, it reached Sabah, Malaysia. This sequence illustrates the progressive expansion and direction change of the ash plume with time and altitude. The area affected grew from an estimated 25 km² to over 150 km².

When compared with previous the PUFF model simulations, Ruang's ash dispersion pattern shares key characteristics with past eruptions. During the 2017 Mount Agung eruption, the PUFF model simulations (particularly those using radar input) showed ash dispersion reaching altitudes above 30,000 feet and moving southwestward within hours after the eruption. The influence of Tropical Cyclone Cempaka was noted to significantly alter wind directions, shifting ash transport paths from westward to eastward. These changes caused volcanic ash to drift toward and eventually close I Gusti Ngurah Rai Airport in Bali, as supported by aviation NOTAMs and PUFF model results [12]. Meanwhile, the PUFF model simulations of the 2010 Mount Merapi eruption showed more localized ash dispersion due to the relatively lower eruption column, reaching altitudes below 20,000 feet and impacting nearby regions without significant long-range transport [10]. In comparison, the Ruang eruption produced a taller plume exceeding 60,000 feet and followed a dominant northwestward trajectory, influenced by strong upper-level winds. Its vertical stratification and directional stability more closelyresemble the 2018 Anak Krakatau event, where the PUFF model simulations and Himawari-8 observations confirmed stable ash dispersal within hours of the eruption [13]. These comparisons indicate that the Ruang eruption aligns more with high-intensity, high-altitude events and highlights similar risks for aviation and transboundary exposure

Figure 3 provides a 3D view of ash dispersion 6 hours post-eruption, showing the vertical distribution of ash particles by flight level. Ash heights ranged up to 60,000 feet, with denser particles appearing in red tones at higher altitudes. Ash movement at lower levels trended west to southwest, while at higher altitudes it shifted northwest, indicating a vertical stratification in dispersion behavior influenced by prevailing winds..

Figures 4 illustrate vertical cross-sections of ash plume dispersion along longitudinal (left) and latitudinal (right) axes. The ash cloud extends vertically from the surface up to 20,000 meters, with peak density clusters appearing between 10,000 and 20,000 meters. The longitudinal profile shows dispersion primarily between 124°E and 126°E, while the latitudinal section displays spreading between 2°N and 4°N. These layered structures suggest stratified ash transport influenced by altitude-specific wind fields. Although quantitative values such as ash mass loading are not directly available, the visual profiles indicate a complex and evolving plume with moderate density cores. Similarly, Tanaka's research indicates that the movement of the ash column varies significantly between the upper and lower sections of the ash cloud, a phenomenon attributed to substantial differences in wind conditions [7]

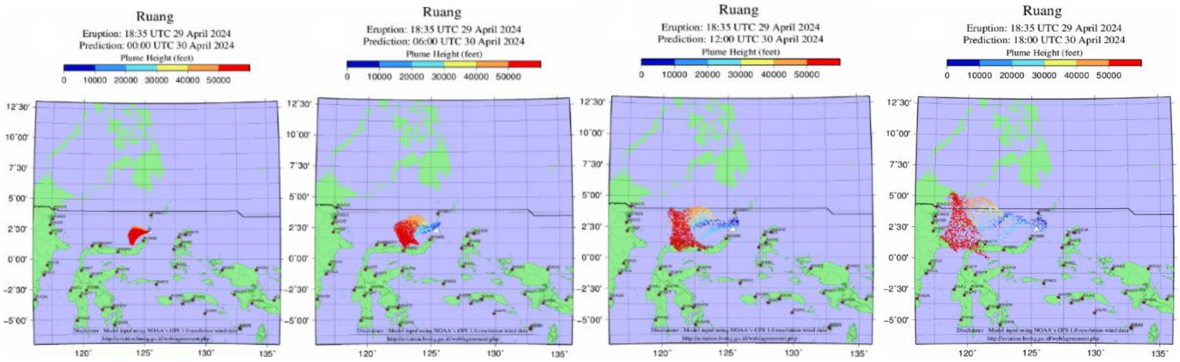

Figure 2. Simulated horizontal dispersion of volcanic ash plumes at 6, 12, 18, and 24 hours after the Mount Ruang eruption on April 29, 2024, 18:35 UTC, using the PUFF model. Colors represent different altitude levels.

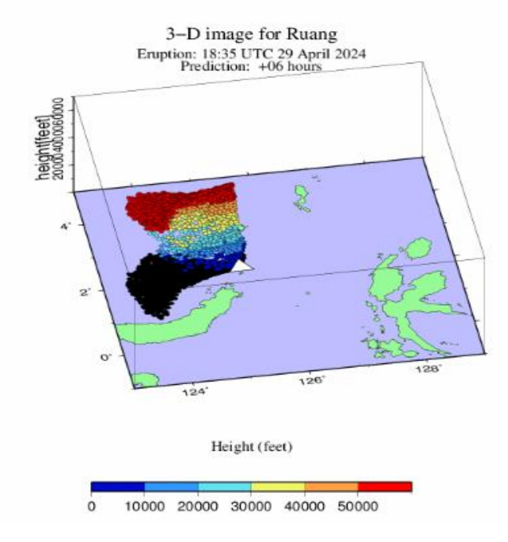

Figure 3. The PUFF model simulates the spread of volcanic ash at 6 hours after the eruption starting from April 29, 2024, at 18:35 UTC in 3-D image.

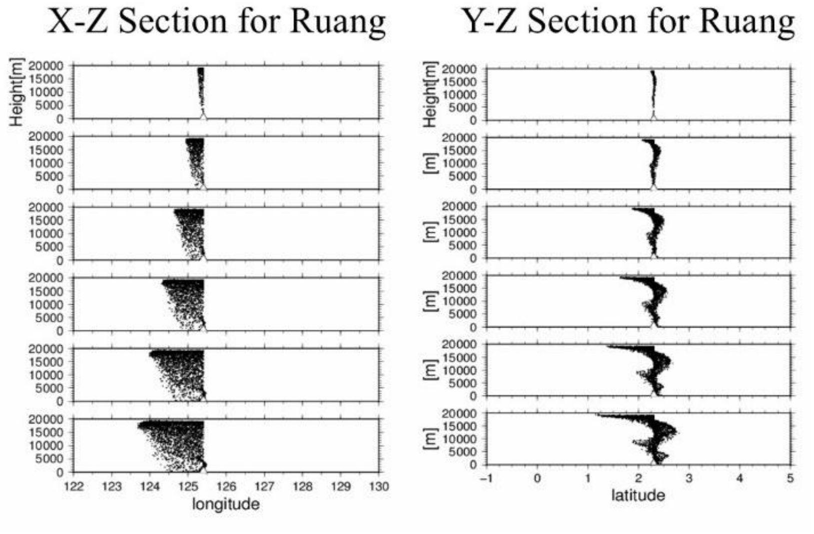

Figure 4. Vertical cross-sections of volcanic ash dispersal from Mount Ruang, generated hourly from April 29, 2024, at 18:35 UTC, showing height variations along longitudinal and latitudinal axes.

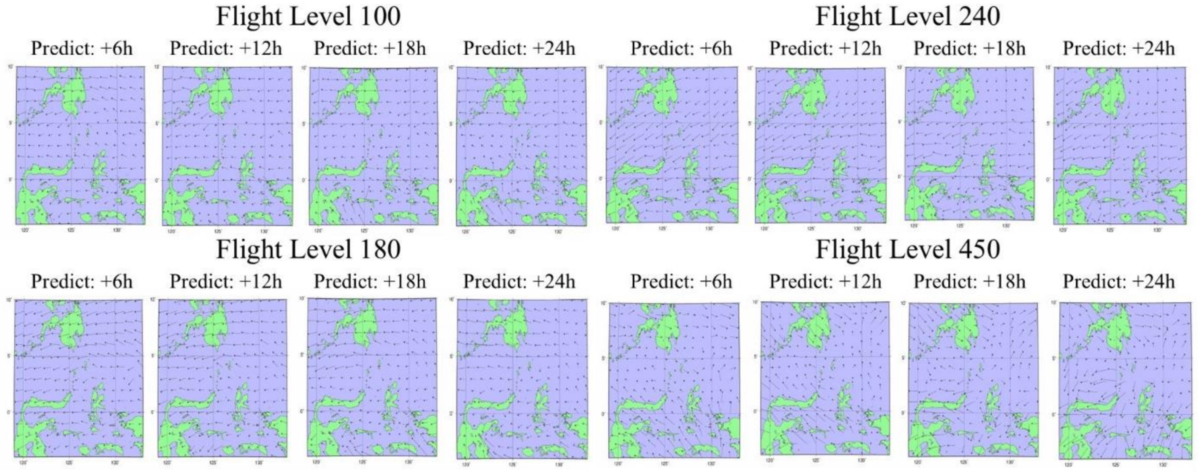

Figure 5. Simulated wind vectors at multiple flight levels (FL100-FL450) at 6, 12, 18, and 24 hours after the April 29, 2024, eruption, starting from April 29, 2024, at 18:00 UTC.

Wind Vector Interpretation. Figures 5 display wind vector simulations across four flight levels (10,000, 18,000, 24,000, and 45,000 feet) at time intervals of 6, 12, 18, and 24 hours. At 10,000 and 18,000 feet, winds flowed predominantly west and northwest, aligning with near-surface ash transport directions identified in the PUFF model output. The 18,000-foot layer showed slightly stronger and more variable wind fields, suggesting enhanced lateral dispersal. At 24,000 feet, wind patterns initially moved northwestward before gradually curving westward. Meanwhile, at 45,000 feet, winds were more variable—initially blowing north-northwest and later shifting southwest. These observations indicate the presence of vertical wind shear, which affects the stratification and long-range direction of ash dispersion.

Overall, the wind structure across layers suggests consistent west to northwest ash transport, influenced by altitude and evolving wind regimes. The layered divergence in direction supports the vertical stratification patterns observed in both the PUFF model simulation and satellite imagery.

Ground-Level Ash Concentration Simulation. Figure 6 illustrates the PUFF model simulation of ground-level volcanic ash concentration at 6, 12, 18, and 23 hours after the Ruang eruption on April 29, 2024, at 18:35 UTC. The spatial extent of the volcanic ash cloud expanded gradually during this period, initially covering approximately 25 km² northeast of the volcano. By 18 hours, the cloud had spread west-northwestward across marine and coastal regions, reaching an estimated 60-100 km². At 23 hours, the dispersion covered approximately 150 km². The contour lines represent ash concentration in logarithmic units (log10(mg/m³)), with initial values exceeding 10^3 mg/m³ and decreasing over time as the plume diluted. This trend indicates a decrease in aviation-related hazard potential and highlights the importance of continuous ground-level monitoring.

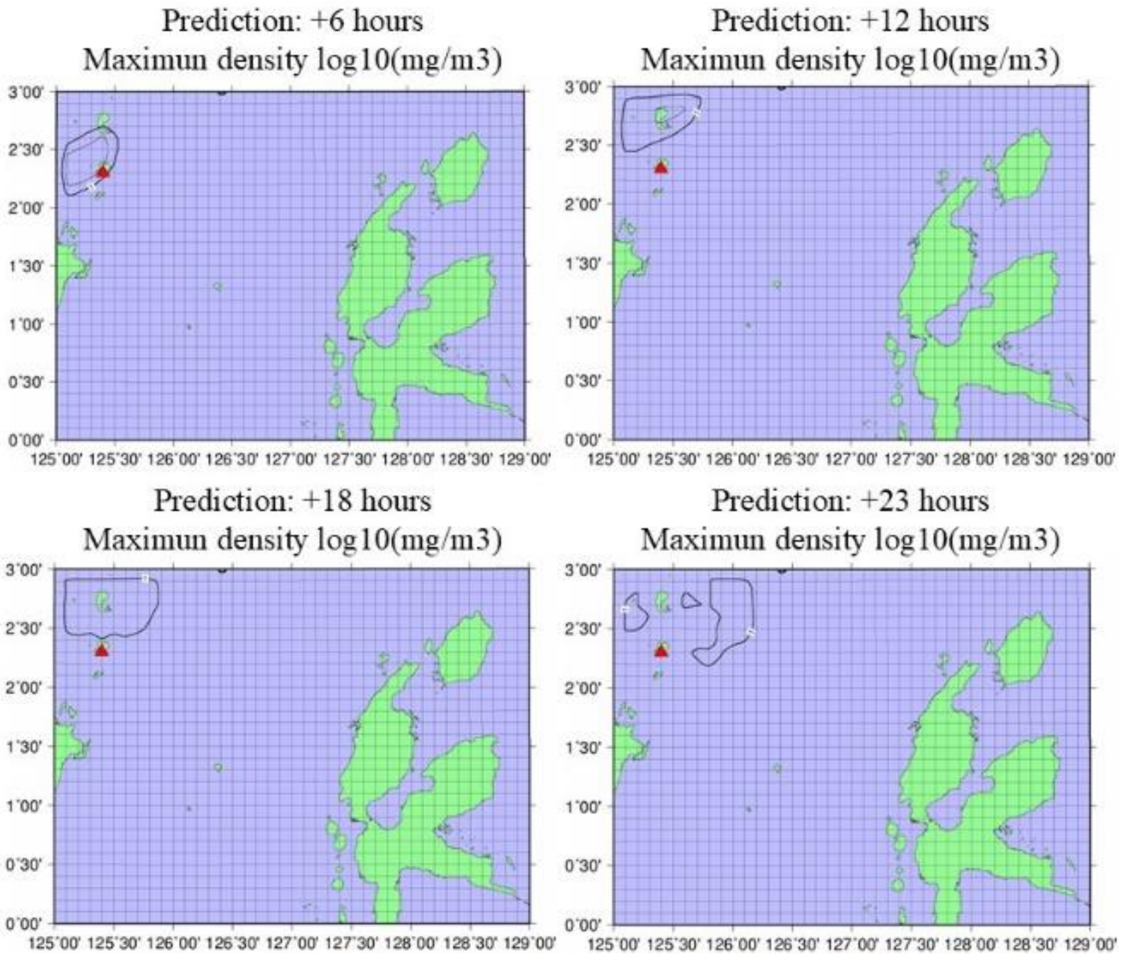

Figure 6. The PUFF model simulation of ground-level volcanic ash concentration at 6, 12, 18, and 23 hours after the Ruang eruption on April 29, 2024, at 18:35 UTC.

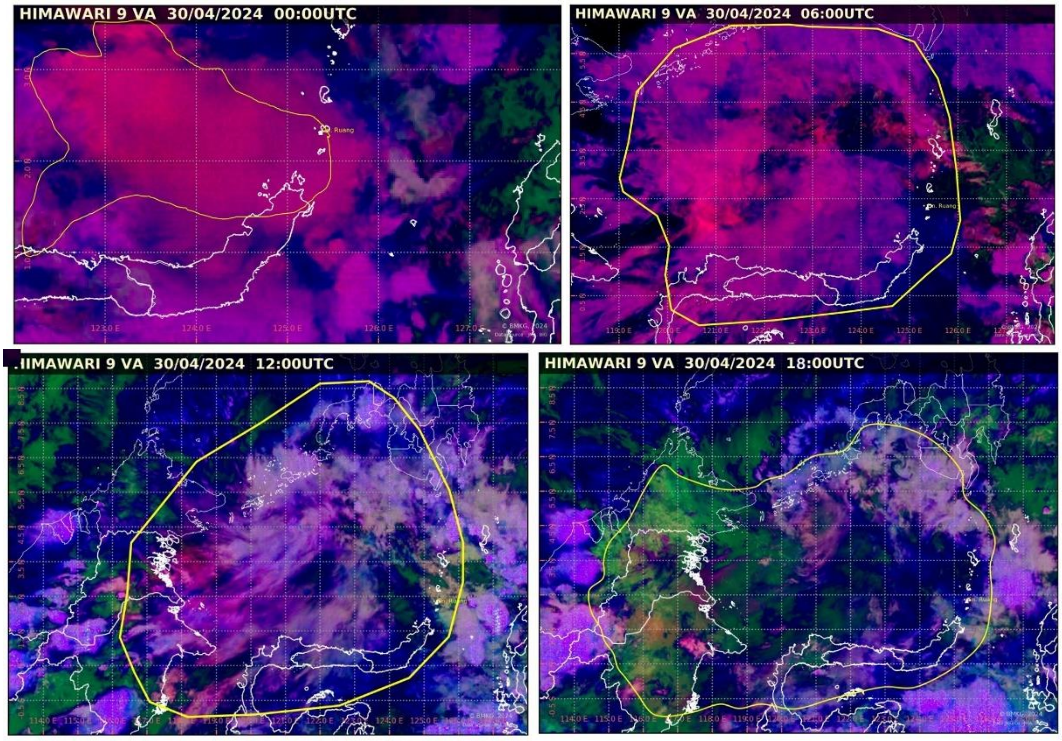

Figure 7. Results of Himawari-8 satellite image display using RGB method for volcanic ash on April 30 at 00:00, 06:00, 12:00, and 18:00 UTC.

Satellite Data Validation. To assess the accuracy of the PUFF model simulation, a qualitative comparison was performed using Himawari-8 satellite imagery. This approach enabled the validation of simulated ash dispersion patterns based on visual consistency in both direction and spatial extent.

Figure 7 shows Himawari-8 Ash-RGB snapshots at 00:00, 06:00, 12:00, and 18:00 UTC on 30 April 2024. The yellow polygons delineate contiguous pink/magenta clusters RGB signature of volcanic ash dominant pixels and cold high clouds. From the Manado region, the ash plume progresses west-northwest and, by 18:00 UTC, extends into Malaysian airspace. The observed motion is spatially coherent with the PUFF plan-view concentration fields at matched times, reinforcing the model's operational applicability for aviation decision-making.
Despite partial obscuration beneath deep cloud, the Ash-RGB frames remain a reliable qualitative reference for high-altitude ash transport. To strengthen future evaluations, quantitative image-model comparisons are recommended (such as intersection-over-union/spatial overlap, centroid distance, correlation, and RMSE on gridded masks).

Implications and Limitations. It is important to acknowledge the PUFF model's inherent simplifications, including assumptions about Gaussian particle dispersion and exclusion of complex terrain effects or eruptive parameter uncertainties. These factors may introduce error margins that need to be quantified in future work.

In addition to aviation safety, which was the primary concern of this study, ground-level impacts such as public health, agricultural disruption, and infrastructure damage were not addressed. Ash transported at lower altitudes (<20,000 feet) could have considerable implications for these sectors. Therefore, future assessments should incorporate ground-based observations and deposition measurements.

A brief comparison with previous the PUFF model-based studies, such as the Mount Agung eruption in 2017 [12] and Anak Krakatau in 2018 [13], reveals that while Mount Ruang's ash displayed similarly extensive horizontal dispersion driven by upper-level winds, its vertical stratification was more complex. Unlike Anak Krakatau, where ash layers remained relatively stable at mid-altitudes within the first 4 hours, Ruang's plume reached over 60,000 feet and exhibited multi-directional spreading. This emphasizes the importance of incorporating multi-altitude wind vector analysis in volcanic ash forecasting, especially for eruptions with high column heights and regional aviation.

The simulated near-surface ash deposition for the 29-30 April 2024 Mount Ruang event is consistent with contemporaneous situational reports indicating rapid-onset ashfall, population displacement, and disruptions to transport infrastructure on 30 April 2024. Humanitarian situational reporting documents immediate evacuations and emergency needs following the eruption [30]. The Global Volcanism Program summary for 24-30 April 2024 further corroborates widespread ash dispersion and records operational impacts such as temporary airport closures and ground-level tephra coverage on nearby islands [31]. National response dashboards likewise log the event and early evacuation responses on 30 April, underscoring the need to link atmospheric dispersion modelling with targeted surface-impact assessments (air-quality monitoring, agricultural damage surveys, and infrastructure inspections) during post-eruption response [32].

4. Conclusion

The simulation of the 2024 Mount Ruang eruption using the PUFF model demonstrated the utility of combining numerical modeling with satellite-based validation to understand ash dispersion dynamics. The results revealed a high-altitude plume exceeding 60,000 feet, with stratified transport patterns influenced by wind vectors at multiple atmospheric layers. The ash traveled northwestward, ultimately affecting airspace extending to Malaysian territory. Qualitative validation using Himawari-8 satellite imagery showed a strong visual alignment with the PUFF outputs, confirming the model's potential for aviation hazard forecasting.

However, this study acknowledges several limitations. The PUFF model depends heavily on GFS meteorological input, which may not capture local wind anomalies or terrain-induced effects. Additionally, the model assumes Gaussian particle dispersion and relies on simplified eruption parameters (e.g., fixed column height, particle size), which introduces uncertainty particularly in ground-level concentration estimates.

From a broader perspective, the Ruang eruption showed dispersion characteristics similar to previous high-altitude eruptions like Mount Agung (2017) and Anak Krakatau (2018), suggesting that intense eruptions with strong vertical plumes require layered wind analysis for accurate prediction. Compared to these cases, Ruang's ash showed greater vertical complexity, underscoring the need for future simulations to account for multi-level wind shear and evolving plume structure.

To improve operational preparedness, future work should integrate higher-resolution wind models, real-time data assimilation, and quantitative validation. Finally, because ash transited international boundaries during this event, we recommend strengthening operational linkages between national agencies (BMKG, PVMBG) and VAAC Darwin building on established ICAO/IAVW procedures and recent Volcex exercises to ensure rapid sharing of model outputs, satellite observations, and aviation advisories across the region.

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