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Analysis Of The Distribution Of Volcanic Ash From The Eruption Of Mount Merapi In 2010 Using Three-Dimensional Gaussian Plume Modeling And Hysplit (Hybrid Single-Particle Lagrangian Integrated Trajectory)

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Abstract: The powerful 2010 eruption of Mount Merapi produced a widespread volcanic ash cloud with significant impacts, making a clear understanding of its dispersion pattern essential for disaster mitigation efforts. This study attempts to remodel this ash dispersion using two different approaches: the 3D Gaussian Plume and HYSPLIT models. The research aimed to analyze how eruption parameters and weather conditions influenced the ash's direction and spread, and to qualitatively compare the model outputs with MODIS Terra satellite imagery. To achieve this, the study processed volcanological data, such as column height and eruption volume, alongside meteorological data from ERA5 reanalysis for three key eruption phases: October 26, October 30, and November 5, 2010. The results show that the 3D Gaussian Plume model tended to produce an idealized dispersion pattern, spreading symmetrically from the peak with concentrations of 1.494E-03 kg/m³ (Oct 26), 4.395E-05 kg/m³ (Oct 30), and 0.0336 kg/m³ (Nov 5). In contrast, the HYSPLIT model provided more realistic results, depicting an elongated ash plume that followed the prevailing wind direction, with maximum mass load reaching 8.2 mg/m² (Oct 26), 0.1 mg/m² (Oct 30), and 110 mg/m² (Nov 5). The analysis confirms that the interplay between the eruption's characteristics (especially column height and emission rate) and meteorological conditions (wind speed) was the primary factor determining the ash's trajectory and reach. While both models accurately pinpointed the eruption's source, further validation was challenging as persistent cloud cover on the satellite images obscured the view of the ash plume.

Keywords : volcanic ash, Merapi Eruption 2010, Gaussian Plume, HYSPLIT, Dispersion Modeling.

INTRODUCTION

Mount Merapi is one of the most active volcanoes in Indonesia. One of the most significant eruptions in modern history occurred in 2010. This eruption, classified as Volcanic Explosivity Index (VEI) 4, was characterized by a series of explosive eruptions that produced ash columns up to 17 km in the atmosphere and massive pyroclastic flows [1]. This eruption has a broad impact, including environmental damage, health problems, and paralysis of air transportation that is risky to flight safety [2].

An in-depth understanding of the pattern of volcanic ash spread is a crucial aspect in disaster risk mitigation. However, accurately estimating distribution patterns is a complex challenge. The main factors that affect this uncertainty are the dynamic atmospheric conditions and topography around Mount Merapi which varies and can affect the movement of volcanic ash after an eruption [3].

A variety of numerical models have been developed to predict ash dispersion, more complex models often require high computing capacity as well as access to detailed and accurate data, which is not always available, especially in emergency situations or areas with limited infrastructure. In this study, two approaches were used: the 3D Gaussian Plume model and the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model. The Gaussian Plume model offers a relatively simple but effective approach to estimating the distribution of pollutants based on the advection-diffusion principle [4]. Meanwhile, HYSPLIT is a more advanced Lagrangian model, capable of simulating the transport and deposition of particles using dynamic three-dimensional meteorological data [5]. Both models were then validated with MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data that provided esential satellite data on volcanic ash, including column-integrated ash concentrations and cloud peak heights [6].

This study aims to apply the Gaussian Plume 3D and HYSPLIT models to simulate the ash distribution pattern from the 2010 eruption of Mount Merapi, and analyze the influence of meteorological factors and eruption characteristics on the distribution pattern

THEORETICAL BASIS

Volcanism and Volcanic Ash

Volcanism is a phenomenon related to volcanic activity, including the release of magma from the earth to the surface. This process occurs due to the movement of tectonic plates that trigger an increase in pressure and temperature, so that magma is pushed up. In general, volcanism is divided into two types, namely effusive and explosive. Effusive volcanism is characterized by the gradual release of lava, while explosive volcanism is characterized by eruptions that produce pyroclastic materials such as volcanic ash [1].

Volcanic ash is fine-grained pyroclastic material (< 2 mm in diameter) that is ejected into the atmosphere during an explosive eruption. This material is made up of fragments of rock, minerals, and volcanic glass. The behavior of ash in the atmosphere is regulated by two main processes, namely advection and diffusion. Advection is the process of transporting mass of ash by an average wind field, which determines the direction and speed of the main movement of the plume. Diffusion is the process of scattering ash due to random turbulent movements in the atmosphere, which causes the plume to expand both horizontally and vertically [5]. Volcanic ash carries health risks, volcanic ash also has an impact on the environment, infrastructure, and transportation [7].

Eruption of Mount Merapi in 2010

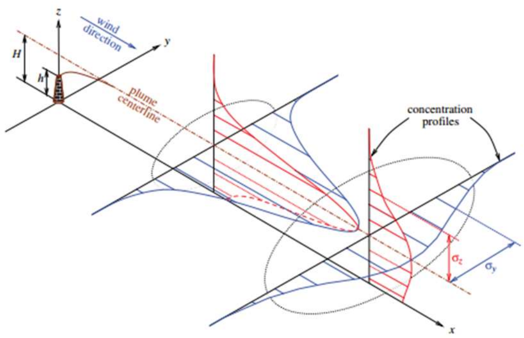
The eruption of Mount Merapi in 2010 took place in several phases, starting on October 26 and reaching its peak in early November. The first phase on October 26 was marked by an explosive eruption that destroyed an old lava dome and produced a 12 km high ash column. Subsequent phases involved rapid growth of new lava domes, dome collapse, and ever larger pyroclastic flows. The peak of the eruption occurred between 4 and 5 November, with continuous eruptions producing ash columns up to the stratosphere (17 km) and pyroclastic flows that traveled more than 15 km from the summit [1].

The total volume of material released during the eruption of Mount Merapi in 2010 is estimated to reach 140 million m³. The eruption of Merapi in 2010 resulted in the loss of more than 380 people. Nearly 400,000 people were displaced [8]. The eruption of Merapi in 2010 also had an impact on an extensive area, including settlements covering an area of 133.31 ha, rice fields covering an area of 92.32 ha, dry fields covering an area of 235.60 ha, plantations covering an area of 570.98 ha, and vacant land covering an area of 380.86 ha [9].

Model Dispersi Gaussian Plume

The Gaussian Plume model is one of the most commonly used analytical dispersion models. The model solves the advection-diffusion equation with several simplification assumptions, such as stationary and homogeneous meteorological conditions, flat ground surfaces, and perfect reflection of pollutants on the surface. This model assumes that the concentration of pollutants in each section of the plume perpendicular to the direction of the wind has a normal (Gaussian) distribution [4].

The basic principle of the dispersion of pollutants in the Gaussian Plume model, which is the basis for its mathematical formulation, is visually illustrated in Figure 2.1.



Picture 1. Gaussian Plume atmospheric dispersion model

The basic equation for a 3D Gaussian Plume model of a continuous source is:

$$C(x, y, z) = \frac{Q}{2\pi u \;\; {}_{y}(x)\sigma_z(x)} . \exp\left(-\frac{y^2}{2\sigma_y^2(x)}\right) . \left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2(x)}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right)\right] \quad (1)$$

In the statistical approach, empirical functions are used in the form of:

$$\sigma_y(x) = a_y . x^{b_y} , \sigma_z(x) = a_z . x^{b_z} \quad (2)$$

The a and b value are obtained from the atmospheric stability table, $C(x, y, z)$ is the concentration of volcanic ash at a given point (g/m^3), Q is the rate of volcanic ash emission (g/s), u is the average wind speed (m/s), σ_y and σ_z is the coefficient of vertical and horizontal dispersion (m), H is the height of the emission source (m)(Stockie, 2011).

Important Parameters in Modeling

The rate of volcanic ash emission (Q) refers to the amount of ash material released into the atmosphere over a given period of time, which is generally expressed in kilograms per second (kg/s). The magnitude of the emission rate is influenced by the intensity of the eruption, the composition of magma, the pressure of gases in the mountain body, and the atmospheric conditions when the eruption occurs. In addition to the emission rate, the height of the eruption column (H) is an important parameter in the volcanic ash dispersion process. The height of the eruption column determines the layer of the atmosphere where the ash is distributed, which in turn influences its dispersal pattern. The relationship between the emission rate and the height of the eruption column follows equation (3):

$$Q = kH^{\beta} \quad (3)$$

k is a pre-exponential factor and β is an exponent [10].

The dispersion coefficient describes the scattering of the clump in both horizontal (σ_y) and vertical (σ_z) directions. In unstable atmospheric conditions, either σ_y or σ_z tends to have higher values, so ash can spread more widely and reach higher altitudes. However, in more stable atmospheric conditions, ash dispersion tends to be more localized, and distribution patterns are more concentrated around eruption sources [4].

Wind speed (u) is a key factor in the advection mechanism. This parameter determines how quickly and how far volcanic ash can spread from the eruption point. The higher the wind speed, the greater the potential for ash to be pushed away from the eruption source in a short period of time. In addition to speed, the direction of the wind also plays a role in determining the pattern of the distribution of volcanic ash in the atmosphere. In the Gaussian Plume model, the wind is considered constant, in the direction

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of the x-axis, and its value is inversely proportional to the concentration, i.e. the quicker the wind, the quicker the ash spreads but with a lower concentration at a given point [4].

Model HYSPLIT

HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) is a more advanced dispersion model that combines Lagrangian and Eulerian approaches. For dispersion simulation, the model uses a Lagrangian approach in which the movement of many virtual particles is tracked through a 3D meteorological field that changes over time. The new position of each particle is calculated as the sum of the transport by the average wind field and random turbulent components [6]. The equation of particle motion can be simplified as:

$$\frac{dx}{dt} = v(x,t) + w(x,t) \quad (4)$$

x is the particle position (m), v is the wind speed (m/s) that drives advective transport, and w is the vertical component (m/s) that includes the effects of atmospheric turbulence as well as the precipitation velocity of particles.

To describe the particle size, a log-normal distribution is used which is expressed as:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} \quad (5)$$

f(x) is a function of the size distribution, μ is the logarithmic mean of particle size, and σ is the standard deviation of the logarithmic [5].

RESEARCH METHODS

Place and Time

This research focuses on the area located at the coordinates of 07°22'33" - 07°52'30" South Latitude and 110°15'00" - 110°37'30" East Longitude, with Mount Merapi as the main study center. The scope of the study area in this study is limited by geographical coordinates: North (N): -6.5° LS, South (S): -8.5° LS, West (W): 109.5° E, East (E): 111.5° E.

Research Data

The data used in this study includes volcanic data, meteorological data, and also satellite data. Data on the eruption activity of Mount Merapi in 2010 was obtained from BPPTKG [11], including the date of the eruption, the volume of the erupted ash, the duration of the eruption, and the height of the ash column. This data was used to calculate the rate of ash emission (Q) using an empirical relationship [13]; [12].

Meteorological data in this study was obtained from the ERA5 hourly reanalysis product released by the European Centre for Medium-Range Weather Forecasts (ECMWF) through the Copernicus Climate Data Store (CDS) portal. The following are the characteristics of the downloaded research meteorological data presented in table 3.2.

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Table 3. 1 Research meteorological data

Component	Value
Variabel	*u, v* (wind components), *T*
Pressure Level	300 hPa, 500 hPa, 700 hPa
Date	26 October, 30 October & 5 November 2010
Time	Adjusting the eruption
Region (lat/lon)	N: -6.5, S: -8.5, W: 109.5, E: 111.5
Format	NetCDF (.nc)

The wind components u and v are used to calculate the total wind speed (V) and wind direction (θ) based on equations (3.1) and (3.2).

$$V = \sqrt{u^2 + u^2} \quad (6)$$

$$\theta = \left(\tan^{-1}\left(\frac{u}{v}\right) + 180\right) \bmod 360 \quad (7)$$

[14].

The value σ_y and σ_z is determined based on the empirical approach of the Pasquill-Gifford Stability Class. Based on the meteorological conditions during the eruption, stability class D (neutral) was selected, so that the value σ_y and σ_z calculation was calculated using equation (8).

$$\sigma_y(x) = a_y . x^{b_y} , \sigma_z(x) = a_z . x^{b_z} \quad (8)$$

suitable for both horizontal and vertical directions. The values of a and b are taken from the reference [4].

Research Procedure

This research will be conducted in several structured stages with the aim of analyzing the pattern of volcanic ash dispersion generated by the eruption of Mount Merapi in 2010, using three main methods, Gaussian Plume 3D, HYSPLIT, and validation with MODIS satellite data.

3D Gaussian Plume Modeling Procedure

The simulation was carried out based on parameters: ash emission rate (Q), wind speed (u), column height (H), and horizontal and vertical dispersion coefficients (σ_y and σ_z). Volcanic data is converted into input parameters. The estimated ash emission rate value (Q) is calculated based on the height of the eruption column (H)

$$Q_{totoal}(kg/s) = 10^{(0{,}245 \times H)+1{,}25} \quad (9)$$

Assuming, 50% of the total eruption mass (Qtotal) is assumed to be a fine ash fraction (Qabu), this determination is based on research Mastin et al., (2009) [13].

The Q, u, and H parameters are included as inputs from the volcanology and ERA5 data, whereas σ_y and σ_z are calculated based on the distance from the source point and the atmospheric stability category. Compile Python code and compute it for various points in three-dimensional space (x, y, z). The simulation results are visualized in the form of ash distribution at any given time and pressure.

HYSPLIT Modeling Procedure

The HYSPLIT simulation was carried out by entering parameter inputs which included the eruption time, emission rate, effective altitude, then configuration and execution of the HYSPLIT model. Then analyze and interpret the results. In this study,

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two dispersion models were used with different approaches and types of output. The Gaussian Plume model, which produces volumetric concentrations in kg/m³ represents the mass of volcanic ash particles per unit volume of air at a specific point in three-dimensional space (x, y, z coordinates). On the other hand, the main output of the HYSPLIT model is a mass loading with g/m² which represents the total mass of volcanic ash suspended vertically in a single column of air from the surface to a certain height. Therefore, the comparison between the results of the Gaussian Plume and HYSPLIT models in this study was not done numerically (comparing the value of kg/m³ with g/m²), but qualitatively. The comparison focused on the suitability of the spatial distribution pattern, the direction of movement of the main ash, as well as the location of the emission centers generated by the two models.

The research flow diagram is shown in Figure 2 as follows.

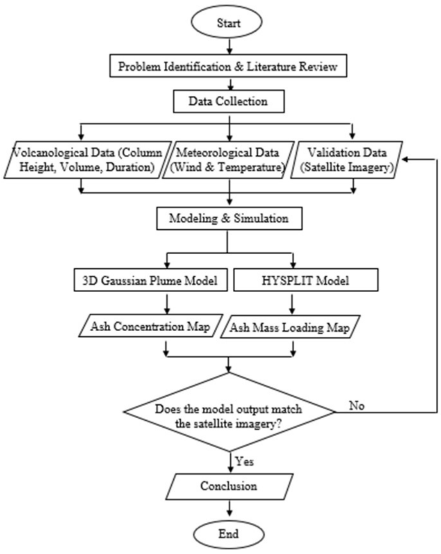

Figure 2. Research flowchart

RESULTS AND DISCUSSION

Characteristics of Modeling Inputs

Modeling was carried out for three significant eruptions of Mount Merapi, namely on October 26, October 30, and November 5, 2010. The following is a table of modeling input characteristics:

Table 4. 1 Modeling input characteristics

Date of eruption (2010)	Column height (km)	Volume of erosion (km3)	Duration of eruption (hours)	Ash emission rate (kg/s)
Oct 26	12	0,006	1,87	7744,09
Oct 30	3,57	0,005	0,57	66,62
5 Nov	17	0,011	1,73	130000

Comparison of Model Distribution Patterns and Satellite Observations

The 2010 Merapi volcanic ash distribution was analyzed by comparing simulations from 3D Gaussian Plume and HYSPLIT models with MODIS satellite imagery for qualitative validation.

Eruption October 26, 2010

To validate the simulation results, a qualitative comparison was made between the model distribution pattern and satellite imagery data, as shown in the Figure below.

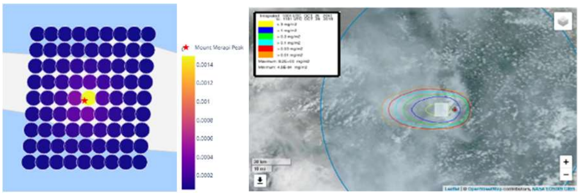

Figure 3. Comparison of distribution patterns October 26, 2010 UTC (a) Gaussian Plume model (b) HYSPLIT and satellite observations

Gaussian Plume 3D modeling projects the highest concentration of ash released around the summit of Mount Merapi, which is marked by a red star, reaching a maximum value of 1,494 E-03 kg/m³. This distribution pattern shows a symmetrical and radial decrease in concentration away from the source, which reflects the assumption of an ideal Gaussian distribution. HYSPLIT modeling overlaid on the MODIS Terra satellite imagery (Figure b), integrated from 10:01 to 11:01 UTC, shows a strong fit with the Gaussian Plume model in determining the location of the source. The HYSPLIT model also predicts the highest ash mass load in the Merapi proximal area, with a maximum value of 8.2 mg/m2. More detailed qualitative validation of the shape and area of the ash column from satellite imagery faces considerable challenges. MODIS imagery from this period shows substantial cloud cover around the Merapi region, which inhibits the ability of optical sensors to clearly visualize the structure and full extent of the volcanic ash column.

Eruption 30 October 2010 (29 October UTC)

The comparison between the simulated ash distribution pattern with satellite observation data for October 30, 2010 is presented in Figure 4.9.

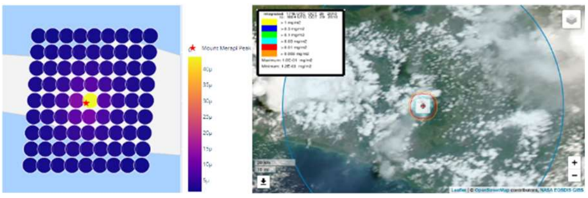

Figure 4. Comparison of distribution patterns October 29, 2010 UTC (a) Gaussian Plume model (b) HYSPLIT and satellite observations

Based on the 3D Gaussian Plume modeling, the ash scatter shows the highest concentration centered around the summit of Mount Merapi, indicated by the red star symbol. The peak point of concentration reaches 4.395E-05 kg/m³. This distribution is radially reduced and symmetrically away from the source, according to the ideal Gaussian distribution. The maximum concentration on this date was lower compared to October 26, signaling a smaller volume of eruptions or a quieter phase. Complementing the analysis, HYSPLIT modeling overlaid on the MODIS Terra satellite image with a time range of 17:16 to 18:04 UTC, also showed the dispersion of concentrated ash near the summit of Merapi. The maximum mass load calculated by HYSPLIT was recorded as 0.1 mg/m2. Although the units and scale of values differ, both the Gaussian Plume and HYSPLIT models place the highest emission centers and ash concentrations at the same eruption point. The MODIS Terra imagery shown geospatial compatibility with both models, with the maximum ash concentration prediction area at a centralized location above Mount Merapi. However, as on October 26, more detailed qualitative validation of the shape and range of the ash plume is having difficulties. During this period, MODIS imagery was obstructed by significant cloud cover around Merapi, limiting optical sensors in depicting the distribution of volcanic ash clearly

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Eruption 5 November 2010 (4 November UTC)

The comparison between the simulated ash distribution pattern with satellite observation data for November 5, 2010 is presented in Figure 4.10.

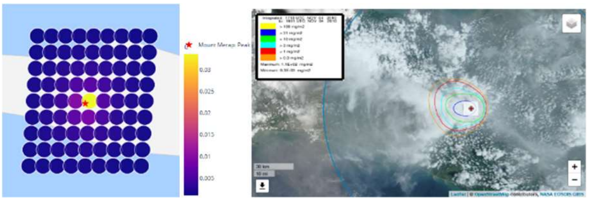

Figure 5. Comparison of distribution patterns November 4, 2010 UTC (a) Gaussian Plume model (b) HYSPLIT and satellite observations

The map of the ash distribution from the 3D Gaussian Plume modeling shown in Figure 4a shows the highest concentration centered around the summit of Mount Merapi, which is shown by the red star on the map. At that central point, the maximum concentration value was recorded at around 0.033628655 kg/m³, assuming a unit that was in line with previous measurements that revealed the massive magnitude of the largest eruption. The distribution pattern then decreases radially and symmetrically away from the source. The results of the HYSPLIT modeling overlay with the MODIS Terra satellite imagery in Figure b, and integrated between 17:13 and 18:01 UTC. The HYSPLIT model shows a maximum mass load of up to 110 mg/m2. The MODIS Terra image shows the same geographic pattern as both models, showing the point with the highest ash concentration right at the top of Mount Merapi. However, qualitative validation to map the shape and size of ash clumps remains hampered. The MODIS image is monitored with a thick cloud cover around Merapi, so that optical sensors cannot capture the visualization of the distribution of volcanic ash.

CONCLUSION

The Gaussian Plume 3D model provides a symmetrical and radial ash distribution with peak concentrations near the source (1.494E-03 kg/m³ on 26 October, 4.395E-05 kg/m³ on 29 October, and 0.0336 kg/m³ on 4 November). Meanwhile, NOAA's HYSPLIT, with its ability to integrate dynamic 3D meteorological data, represents a more realistic and longitudinal distribution pattern according to the direction of the dominant wind, with a maximum mass load of 8.2 mg/m2 on October 26, 0.1 mg/m2 on October 29, and 1.1E+02 mg/m2 on November 4. The ash distribution pattern is strongly influenced by the interaction between eruption characteristics (column height, ash volume, emission rate) and meteorological conditions (wind speed and temperature).

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