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Estimating the Volcanic Ash Plume Course, $PM_{2.5}$ Emissions, and Environmental Impacts Based on the December 4, 2021, Mount Semeru Eruption

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Abstract
Recently on the December 4, 2021 at 03:00 PM, 3676 m high Mount Semeru located in the East parts of Java Island has erupted. To our best knowledge, an immediate and rapid systematic analysis of the volcanic ash plume courses, $PM_{2.5}$ emissions, and environmental impacts based on Mount Semeru eruption has not been implemented so far. Then, this research aims to provide and fill the research gap on the rapid assessment of recent Mount Semeru eruption. From the result, it is clearly visible that for 12 hours the volcanic ash plume course was eastward. The volcanic ash plume can travel a distance of 0–10 km to the North and South directions, and more than 10 km to the East direction. The size of the volcanic ash plume was large at 02:00 AM on December 5, 2021. The smallest size of a volcanic ash plume was recorded at 09:00 PM on December 4, 2021. Most parts of the ash plume (55.98%) or equals 39.01 km^2 contain fallen volcanic material amounts ranged from 1 kg/m^2 to 10 kg/m^2. The fallen volcanic material amount peaked between 08:00 PM and 11:00 PM. Based on the estimation, the $PM_{2.5}$ content in the atmosphere increased after the eruption. The mean of $PM_{2.5}$ before the eruption was 48.5 ± 19.3(95%CI: 29.2 to 67.8 ug/m^3). While after eruption the mean of $PM_{2.5}$ was 79.4 ± 32.2(95%CI: 47.2 to112 ug/m^3). It indicated that the Mount Semeru eruption has increased the $PM_{2.5}$ equals 63.65%.

Keywords: ash plume, course, eruption, $PM_{2.5}$, Semeru

1. Introduction

1.1 Volcanic ash

Volcanic ash is composed of jagged rock fragments, minerals, and volcanic glass. In contrast to the soft ash produced by wood burning, volcanic ash is hard, abrasive, and does not dissolve in water. Volcanic ash particles are typically 2 millimeters (.08 inch) or smaller in size. Coarse volcanic ash particles have the appearance and feel of grains of sand, whereas very fine particles are powdery. Particles are sometimes referred to as tephra, which refers to all solid material ejected by volcanoes (Cutler et al 2021). Volcanic ash is a byproduct of explosive eruptions. When gases inside a volcano's magma chamber expand, molten rock (magma) is violently pushed up and out of the volcano. The force of these explosions shatters the liquid rock and propels it into the air. Magma cools and solidifies in the air, forming volcanic rock and glass fragments. Eruptions have the potential to shatter the solid rock of the magma chamber and the volcanic mountain itself. These rock fragments can mix with the solidified lava fragments in the air and create an ash cloud.

Volcanic ash in the atmosphere is a dangerous byproduct of volcanic eruptions, especially for ecosystems. This is due to the fact that volcanic ash can severely harm ecosystems and organisms living along its paths. Volcanic ash can be widely dispersed to synoptic and global scales, degrading air quality and posing environmental threats. Small volcanic ash particles can travel long distances in the wind. Ash has been discovered thousands of kilometers away from the site of an eruption. The smaller the particle, the further it will travel in the wind. The 2008 Chaitén eruption in Chile generated an ash cloud that blew 1,000 kilometers (620 miles) across Patagonia to Argentina, reaching both the Atlantic and Pacific coasts (Lara 2009).

Volcanic ash deposits tend to be thicker and have larger particles closer to the eruption site. As distance from the volcano increases, the deposit tends to thin out. The 1994 double eruption of Vulcan and Tavurvur in Papua New Guinea covered the nearby city of Rabaul in a layer of ash 75 centimeters deep, while areas closer to the volcanoes were buried under 150-213 centimeters of ash.

1.2 Volcanic ash plume impact

Volcanic ash plumes can cover large areas of the sky, turning daylight into total darkness and drastically reducing visibility. Volcanic ash and gases can occasionally reach the stratosphere (Kaminski et al 2010), the upper layer of the Earth's atmosphere. This volcanic debris can reflect incoming solar radiation and absorb outgoing land radiation, causing the Earth's temperature to decrease.

Ash also endangers ecosystems, including humans and animals. Carbon dioxide and fluorine, both of which are toxic to humans, can accumulate in volcanic ash. Crop failure (Clive et al 2017), animal death and deformity, and human illness can all result from the ash fall. The abrasive particles in ash can scratch the skin's and eyes' surfaces, causing discomfort and inflammation. Volcanic ash can cause breathing problems and lung damage if inhaled. Suffocation can result from inhaling large amounts of ash and volcanic gases. The most common cause of death from is suffocation (Gundmundsson 2011).

1.2 Mount Semeru eruption history

The monitoring records confirmed volcanic activity at Mount Semeru in 1990, 1992, 1994, 2002, 2004, 2005,

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2007, and 2008. In 2008, several eruptions were recorded, from May 15 to May 22, 2008. Based on observations on May 22, 2008, volcanic ash was observed in the Besuk Kobokan area, reaching a distance of 25 km in the East side of Semeru. Last year, the Semeru eruption started at 01:23 AM on December 1, 2020. Recently, the Semeru eruption started at 03:00 PM on December 4, 2021.

2. Methods

2.1. Study area

The study area was 3676 meter high Mount Semeru (Mt) located in East Java. The geocoordinate of Mt Semeru were 8°6′28.8″S and 112°55′12.0″E. The observation and forecasting was made after the eruptions of Mt Semeru on December 4, 2020 started from 03:00 PM. The forecasting durations were made for 12 hours from 03:00 PM to 03:00 AM.

2.2. Estimating the volcanic ash plume

The volcanic ash plume course estimation was based on a model developed by Mcgrattan (2003) and Magalhes et al (2019) using GIS. The initial step was to determine the location of the volcano. For developing the volcanic ash plume estimation, temporal data was a prerequisite. That data included the month, day, year, and time (am/pm) of the volcano eruption. These data were important since the estimation model was an atmosphere and climate-related model that required climatic data (Liu et al 2010) at a particular time. The volcanic ash plume course was then modeled at the mount height of 3676 m, representing the height of the volcanic ash plume. The equation to calculate and estimate the volcanic ash plume course was followed by Fay et al. (1995) and Mallia et al. (2018) as follows:

$$Z_{final}(t + \Delta t) = Z_{mean}(t + \Delta t) + W'(t + \Delta t)\Delta t \text{ and}$$
$$X_{final}(t + \Delta t) = X_{mean}(t + \Delta t) + U'(t + \Delta t)\Delta t$$

With U' and W' here correspond to the turbulent velocity components, X_{mean} and Z_{mean} are the mean components of particle positions, and X_{final} and Z_{final} are the final positions in the horizontal and vertical, respectively. The GIS-based volcanic ash plume course method proposed in this study has considered several basic principles. First, this method can be utilized for all types of volcanic ash plume formation regardless of volcanic ash plume parameters, including ash heterogeneity, the dispersion level, the ash plume density, the concentration levels, and the spatial location and spread of smoke-polluted areas. Second, this method used all the available volcano ash plume information. Third, this method emphasizes the use of simple and physically sound criteria for determining the heights at which an intense volcano ash plume has existed (Kovalev et al 2009).

2.3. Estimating the $PM_{2.5}$ emissions

The $PM_{2.5}$ distribution and mapping analysis was followed current methods (Xu & Zhang 2020. Bai et al 2021).The sources of $PM_{2.5}$ were Aerosol Optical Depth (AOD) data produced by MODIS. The result is a thematic layer in the form of shp files of $PM_{2.5}$ distributions sharing the same coordinate and projection with Semeru layers. The $PM_{2.5}$ was denoted as μg/m^3 and its estimation was implemented for period before and after eruption at 03:00 PM on December 4, 2021.

3. Results and Discussion

3.1. Volcanic ash plume course and fallen volcanic material estimation

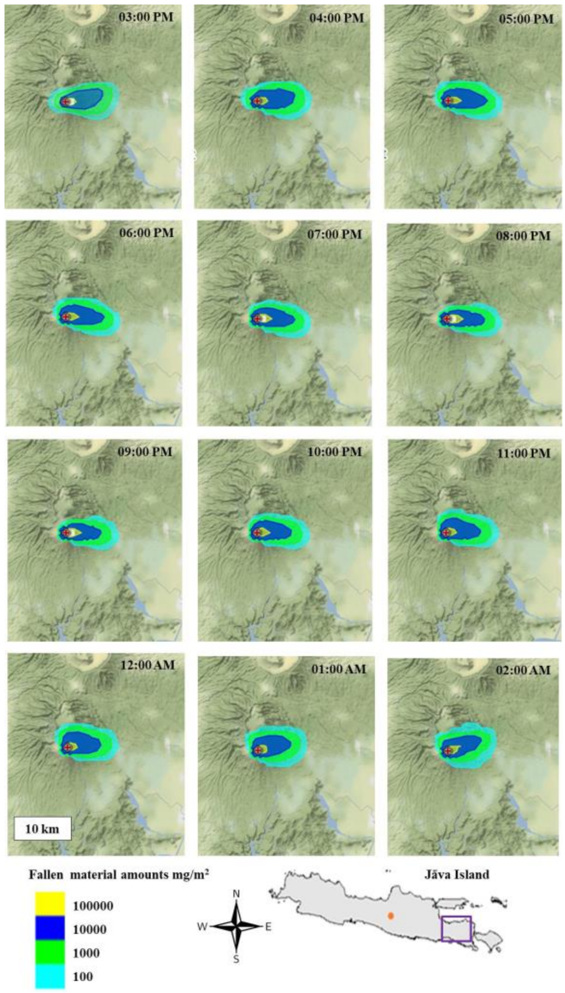

Fig 1 A 12 hour volcanic ash plume course estimation and fallen volcanic material amounts (mg/m^2) of Mount Semeru, East of Java Island from 03:00 PM on December 4, 2021 (eruption time) to 03:00 AM on December 5, 2021.

The results of volcanic ash plume course estimation along with fallen volcanic material amounts (mg/m^2) are available in Figure 1. The plume courses were estimated for 12 hours, starting from 03:00 PM on December 4, 2021, when the eruption happened, to 03:00 AM on December 5, 2021. From the result, it is clearly visible that for 12 hours the volcanic ash plume course was eastward. At the onset of the eruption, the compass bearing of the plume was < 90^0. After 1 hour, the volcanic ash plume direction shifted to > 90^0 or shifted to the south. Regarding sizes, the volcanic ash plume mostly has a width of 10 km and a length of > 10 km. It means that the volcanic ash plume can travel a distance of 0–10 km to the North and South directions, and more than 10 km to the East direction. The size of the volcanic ash plume was large at 02:00 AM on December 5, 2021. The smallest size of a volcanic ash plume was recorded at 09:00 PM on December 4, 2021.

The direction and course of the volcanic ash plume were determined by the wind directions. The influence of wind in determining the ash plume course was in comparison with research on Mount Rinjani previously (Kharisma et al. 2018). The statistics of the estimated ash-charged clouds and their wind directions (Toulkeridis & Zach 2016) are a useful tool in volcanic hazard assessment. Effective early warnings and knowledge about the courses of ash clouds will give enough time to disaster management for the implementation of corresponding mitigation activities.

The volcanic ash plume course also contained fallen volcanic material amounts (kg/m^2). The results and trends of the fallen volcanic material amounts can be observed in Figure 2. The trends and fluctuations of fallen volcanic material amounts were estimated from 03:00 PM to 03:00 AM, or 12 hours.

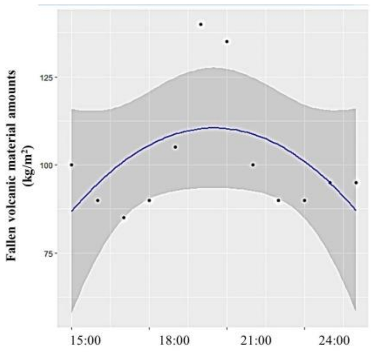

Fig 2 The trends of Mount Semeru fallen volcanic material amount (kg/m^2; 95%CI for shaded area) were estimated from 03:00 PM (15:00) to 03:00 AM (24:00) or12 hour duration.

According to the findings, Mount Semeru's fallen volcanic material amount peaked between 08:00 PM and 11:00 PM. After the eruption, the amount of fallen volcanic material was increasing. Then, after 11:00 PM, the fallen volcanic material's amount was declining.

Besides containing fallen volcanic material, volcanic ash plumes also contain hazardous material, including $PM_{2.5}$. Based on the estimation (Figure 3), the $PM_{2.5}$ content in the atmosphere increased after the eruption. The peak of $PM_{2.5}$ was observed from 01:00 AM to 06:00 AM. The mean of $PM_{2.5}$ before the eruption was 48.5 ± 19.3 (95%CI: 29.2 to 67.8 ug/m^3). While after eruption the mean of $PM_{2.5}$ was 79.4 ± 32.2 (95%CI: 47.2 to 112 ug/m^3). It indicated that the Semeru eruption has increased the $PM_{2.5}$ equals 63.65%. Increasing $PM_{2.5}$ due to the volcano eruption was also observed from other eruption. In comparison, the Kilauea eruption caused the most frequent and severe exceedances of the Environmental Protection Agency (EPA) $PM_{2.5}$ air quality threshold of 35 ug/m^3 on a daily basis in Hawai'i from 2010 to 2018. While the maximum 24-h-mean mass concentration of $PM_{2.5}$ in Kona was 59 ug/m^3 on May 29, 2018, it was one of eight recorded exceedances of the EPA air quality threshold during the 2018 Kilauea eruption.

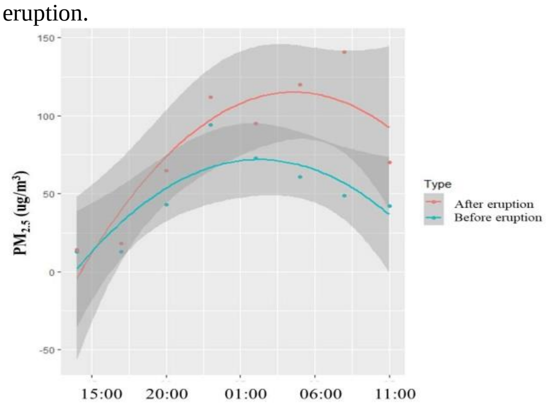

Fig 3 The mean with 95%CI for shaded area of $PM_{2.5}$ trends (ug/m^3) before and after eruption from 03:00 PM (15:00) to 11:00 AM (11:00).

Figure 4 shows the environmental impacts due to the Semeru's volcanic ash plume. Since the course and directions of the course were towards the East and expanded to the Southeast, then the most impacted villages were located in the East and Southeast directions. The landscape around Semeru consisted of forest, plantations, and rural settlements. Then, as can see from the figure, the most impacted landscapes and environmental conditions due to the plume were forests, plantations, and rural settlements.

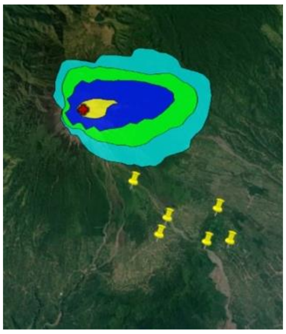

Fig 4 Expanded and courses of volcanic ash plumes, impacted landscape, environment, and villages (yellow markers) due to Semeru's eruption (Background: Google Earth).

Table 1. Areas of fallen volcanic material amount (kg/m^2)

Fallen volcanic material amount (kg/m^2)	Area size (km^2)	%
0.1	28.22	40.50
1	20.06	28.79
10	18.95	27.19
100	2.44	3.5

Conclusions

To our best knowledge, a systematic analysis of the volcanic ash plume courses, $PM_{2.5}$ emissions, and environmental impacts based on the December 4, 2021, Mount Semeru eruption has not been implemented so far. Then, to conclude this research has assessed and confirmed that the east-southeast directions of volcanic ash plumes have caused a village in this region to be impacted due to the fallen volcanic material amounts along with $PM_{2.5}$ threats.

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