



RESEARCH ARTICLE

FORECASTING MOUNT LEWOTOBI LAKI LAKI VOLCANIC ACTIVITY USING SATELLITE IMAGES

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ABSTRACT

The increased volcanic activity of Mount Lewotobi Laki-Laki in November 2024 had a significant impact on environmental changes. The eruption widely disseminated the gas, as evidenced by the increase in SO₂ levels. Unstable atmospheric circumstances, such as low-pressure cyclogenesis, increase the distribution of SO₂ gas across a larger area. The research analyzes volcanic activity utilizing remote sensing technologies, specifically Sentinel-5P TROPOMI satellite imagery, to monitor SO₂ gas emissions. The results show that volcanic emissions have had a big effect on the local atmospheric dynamics, causing the air pressure to drop to 1007.4 mb, the average temperature to rise to 29.2°C, and the regional weather system to change. These results underscore the importance of incorporating remote sensing technologies into early warning systems and volcanic hazard mitigation. This method enhances preparedness and response strategies by offering a model that is applicable to other volcanic regions through the provision of real-time monitoring.

KEYWORDS

Mount Lewotobi Laki-Laki, Satellite Images, Sulfur Dioxide, Tropomi, Volcanic Activity

1. INTRODUCTION

Mount Lewotobi Laki-laki is an active volcano located on Flores Island in East Nusa Tenggara, Indonesia. This mountain is 1,584 meters above sea level (masl) with a crater diameter of approximately 400 meters (Sumotarto, 2021; Banggor, et al., 2024). According to Andronico et al., Mount Lewotobi Laki-laki's volcanic activity is dynamic and explosive (Andronico et al., 2021). In their research, they highlighted that explosive eruptive activity typically results in the ejection of incandescent material and volcanic ash deposits (Firstov et al., 2019; Cahalan, 2023). This might be the result of a magmatic eruption that creates lava domes, lava flows, and hot clouds of avalanches (Rowe, 2021; Siebert and Roverato, 2021).

During November 2024, Mount Lewotobi Laki-Laki experienced increased volcanic activity, culminating in an eruption on November 4, 2024. This eruption resulted in casualties and widespread evacuations, significantly impacting the surrounding communities. According to the National Disaster Management Agency (BNPB), the effects of the eruption continued for several days, necessitating large-scale displacement efforts to ensure public safety. The activity of Mount Lewotobi Laki-Laki can be tracked using remote sensing technologies. Remote sensing is a technique for gathering physical information about an object without making direct contact (Li et al., 2024; Bazi et al., 2021; Shafique et al., 2022). This technology provides precise observation capabilities at a low cost per unit area, making it an effective solution for gathering and providing correct data (Tuli, 2020; Roh et al., 2021). Several studies, have demonstrated the effectiveness of remote sensing using satellite imagery in monitoring volcanic activity (Chan, et al., 2019; Valade, 2019; Cigna, et al., 2020).

According to Guinn et al., satellite data can be used to observe a variety of signs of volcanic activity, including changes in mountain shape, increased surface temperature, volcanic gas emissions, and ground deformation (Guinn et al., 2024). The benefits of this technology include its broad coverage area, the capacity to acquire data on a regular basis (temporally), and its accessibility, which allows for direct monitoring in remote or difficult-to-reach regions (Anand and Deb, 2024; Khanal et al., 2020).

Remote sensing technology has been extensively employed to monitor volcanic activity, offering valuable insights into environmental changes related to eruptions, including land cover changes, landform deformation, desertification, and deforestation. Nevertheless, the current monitoring methods are still constrained in their ability to quantify gas emissions, acquire real-time data, and achieve spatial resolution (Lucas, 2020; Shen et al., 2019; Wardana and Jumadi, 2015). Despite their effectiveness in detecting seismic activity and deformation, direct monitoring systems are frequently costly and challenging to implement in hazardous volcanic regions (Miller et al., 2022). In contrast, the temporal resolution of conventional satellite-based observations, such as MODIS and Landsat, may not always be sufficient to detect rapid changes in gas emissions. Landsat imaging is a commonly utilized form of imagery (Wulder, 2022; Wulder, 2019). Landsat-8 photography may discern differences in rocks, geological formations, and the distribution of volcanoes through their visual attributes (Tanaka, 2019; Witsil and Johnson, 2020). Moreover, Landsat-7 and Landsat-8 are capable of monitoring alterations in vegetation indices in volcanic regions, which serve as critical markers for evaluating the effects of volcanic activity on ecosystems (Tiabou, et al., 2024; Payne and Egan, 2019).

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Besides Landsat, Sentinel-2A imagery provides terrestrial observation functionalities, encompassing forest monitoring, land cover change detection, disaster management, and the analysis of biophysical parameters such as Leaf Area Index (LAI) and Leaf Chlorophyll Content (LCC) (Chen 2022; Verma, et al., 2022). One of the primary obstacles in volcanic monitoring is the capacity to detect and quantify sulfur dioxide (SO₂) emissions, which are a critical indicator of magmatic activity. The TROPOMI (Tropospheric Monitoring Instrument), mounted on the Sentinel-5P satellite, is capable of detecting atmospheric chemicals like sulfur dioxide (SO₂), carbon monoxide (CO), nitrogen dioxide (NO₂), and ozone (Filonchyk and Peterson, 2023; Mathew, 2024). This data is crucial for real-time monitoring of volcanic emissions and evaluating their effects on the global environment and human health (Stewart, 2022). Previous studies have shown that elevated SO₂ levels often precede explosive eruptions, making gas monitoring essential for early warning systems (Brody-Heine, 2022). The Sentinel-5P TROPOMI instrument provides a significant advance in this area, offering high spatial and temporal resolution for detecting atmospheric SO₂ concentrations. Compared to legacy satellite sensors, TROPOMI allows for more precise tracking of gas plumes and their distribution patterns, improving our understanding of volcanic activity (Corradino, et al., 2024; van Geffen, 2022).

This study aims to address these gaps by utilizing Sentinel-5P TROPOMI satellite imagery to monitor SO₂ emissions from Mount Lewotobi Laki-Laki.

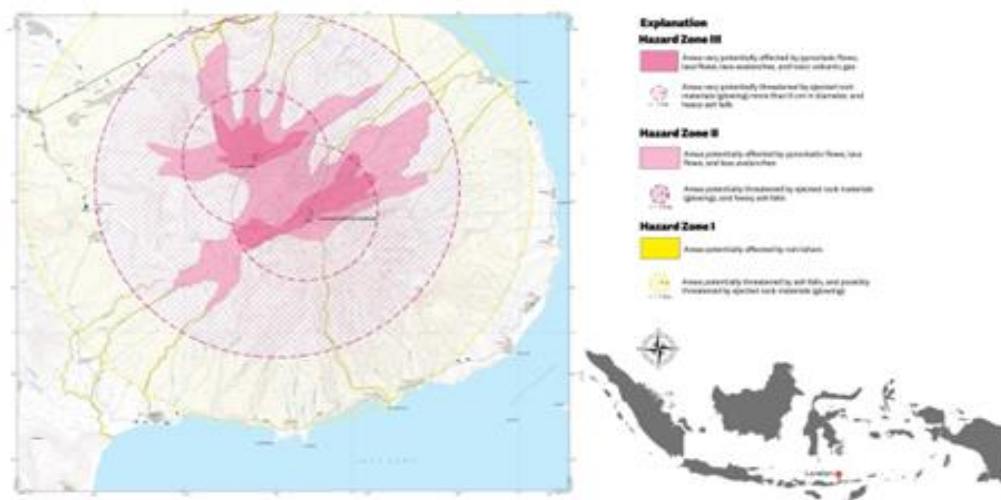


Figure 1: Study Area: Mount Lewotobi Laki-laki.

2.2 Maintaining Absorbing Sulfur Dioxide Index (ASI)

The Absorbing Sulfur Dioxide Index (ASI) was evaluated during the eruption of Mount Lewotobi to monitor the spatial and temporal dynamics of SO₂ emissions. The concentrations of SO₂ from November 1 to November 30, 2024, were quantified using remote sensing techniques, specifically satellite observations. The magnitude, duration, and presence of significant SO₂ emissions that exceeded baseline atmospheric levels were the selection criteria for eruption events that were taken into account in this study. TROPOMI (Sentinel-5P) supplied high-resolution ASI data to monitor the concentration of SO₂ over time and space. Sentinel-5P Level-2 SO₂ products with a spatial resolution of 3.5 km × 7 km and a temporal resolution of one day comprise the dataset employed in this investigation. The Copernicus Open Access Hub was used to procure the data, which encompassed the entire eruption period in November 2024. Atmospheric correction was implemented during preprocessing to reduce interference from water vapor and other contaminants. Pre-defined Sentinel-5P algorithms were employed to apply radiometric corrections during calibration. Prior to conducting additional analyses, the integrity of the data was verified using the SNAP software.

2.3 TROPOMY (Sentinel-5P)

TROPOMI (Sentinel-5P) provides high-resolution ASI data to monitor SO₂ concentrations throughout time and space. Its key responsibilities include atmospheric correction, which eliminates air disturbances such as water vapor and other particles, resulting in trustworthy data. SNAP is also used for data validation, ensuring that the dataset is valid before proceeding with additional analysis. SNAP's simple interface allows for high-resolution data processing, making it simple to identify volcanic aerosol dispersion patterns.

2.4 SNAP (Sentinel Application Platform)

By analyzing variations in SO₂ levels and their correlation with eruptive activity, this research contributes to improving real-time volcanic monitoring and hazard mitigation strategies. The findings will provide a more effective approach to predicting eruptions, ultimately enhancing disaster preparedness for communities in volcanic regions.

2. MATERIAL AND METHOD

2.1 Area Studies

Mount Lewotobi Laki-Laki, situated on Flores Island in East Nusa Tenggara, is a component of the Pacific Ring of Fire volcanic belt. The stratovolcano is characterized by a precipitous cone shape that has been shaped by layers of pyroclastic debris, ash, and magma from previous eruptions. Mount Lewotobi Laki-Laki (1,584 m above sea level) and Mount Lewotobi Perempuan (1,703 m above sea level) are the two primary peaks of the volcanic complex. Figure 1 illustrates a risk zone map of Mount Lewotobi, which is classified according to the severity of the volcanic threat, as determined by historical eruption activity and geological investigations. The hazard zones are responsible for a variety of volcanic activities, such as ashfall, lava flows, lava avalanches, pyroclastic flows, and volcanic ejecta. Mount Lewotobi Laki-Laki is susceptible to catastrophic eruptions and phreatic activity as a result of its location within the Pacific Ring of Fire. The risk associated with each activity varies depending on the specific region.

The Sentinel Application Platform (SNAP) was employed to process Sentinel-5P data, which includes noise reduction techniques and atmospheric adjustments. The spatial distribution maps were generated using the Google Earth Engine (GEE) platform to analyze SO₂ emission trends. The temporal evolution of SO₂ levels during the eruption period was investigated using time-series analysis. Utilizing meteorological data, including wind patterns, atmospheric stability, and air pressure, the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model was implemented to forecast SO₂ dispersion. This method enabled the estimation of potential impact areas and SO₂ transport trajectories.

2.5 PVMBG Data

This research data was obtained from data from the Center for Volcanology and Geological Disaster Mitigation (PVMBG) (<https://vsi.esdm.go.id>). The dataset comprises daily reports on volcanic activity, which encompass eruption chronology, seismic recordings for tremor amplitude and frequency, and visual and morphological observations of crater changes throughout the study period. In order to verify satellite-based SO₂ measurements, PVMBG data were compared to Sentinel-5P outputs. In order to verify critical phases of volcanic activity and sulfur dioxide emissions, this validation procedure entailed comparing detected SO₂ peaks with ground-based eruption reports. The study's reliability is improved by the integration of PVMBG and satellite data, which guarantees that the results of remote sensing are consistent with real-time field observations. Several methodological refinements were implemented to improve the veracity of this study. The Sentinel-5P data was subjected to the Differential Optical Absorption Spectroscopy (DOAS) algorithm to estimate the precise concentration of SO₂. Kriging interpolation was implemented to enhance the spatial resolution of SO₂ emission mapping. The study implemented cross-validation between ground-based PVMBG observations and satellite-derived data to guarantee accuracy and consistency. The study endeavors to offer a

comprehensive and dependable analysis of SO₂ emissions during the Mount Lewotobi eruption in November 2024 by integrating these refinements.

3. RESULT AND DISCUSSION

Mount Lewotobi Laki-Laki is positioned in the subduction zone between the Indo-Australian and Eurasian plates, directly above the oceanic crust. The interaction of the two plates is the primary cause of volcanism, resulting in the accumulation of volcanic material in the area. Figure 2 shows that Mount Lewotobi Laki-Laki's eruptive activity increased in November 2024, indicating that the continuing volcanic process is becoming more intense. Volcanic activity increased beginning on November 4. A big surge occurred in the middle of the month, particularly between November 6 and 13, indicating the peak of volcanic activity. November 12 had the most eruptions, 15 times per day, indicating a period of strong volcanic energy release. After reaching its peak, volcanic activity began to decline between November 14 and 30.

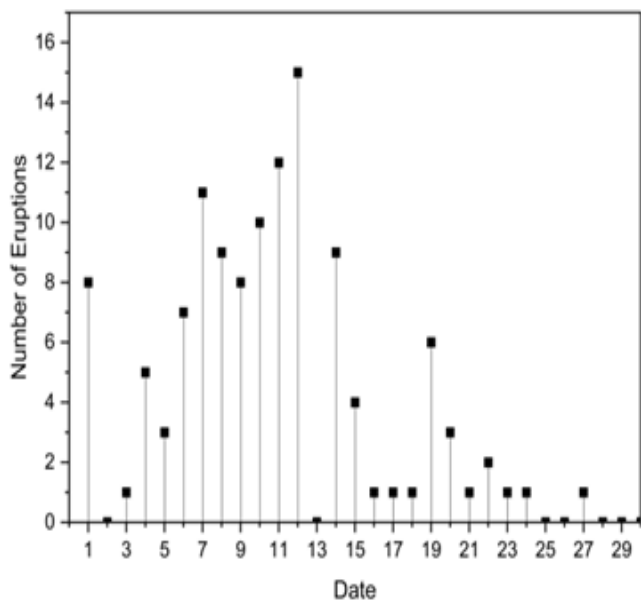


Figure 2: Number of eruptions of Mount Lewotobi Laki-laki during November 2024

Mount Lewotobi Laki-Laki's last eruption occurred in 2002, and it became active again from December 2023 to 2024, with a major rise in activity in November 2024. These findings suggest that Mount Lewotobi Laki-Laki has a long dormant period, which allows for the storage of significant energy within the mountain due to an increase in magma volume and pressure during the dormant period. Mount Lewotobi Laki-Laki's explosive eruption is assumed to be driven by a transition in magma composition from liquid basaltic to thicker andesitic with a high silica (SiO₂) concentration (Fabbrocino, 2024). Explosive volcanic activity offers a substantial concern, particularly given the mountain's proximity to residential areas and agricultural land (Gündüz, et al., 2023).

During the eruption, Mount Lewotobi Laki-Laki underwent morphological and visual alterations (Figure 3). According to Tournigand et al., these changes can result in deformation of the crater region and magma distribution zone (Tournigand, 2025). These variations represent the movement of magmatic fluids, which can cause eruptions and serve as indications for monitoring volcanic activity. Figure 4 shows the results of Mount Lewotobi Laki-Laki's deformation analysis utilizing InSAR and three-dimensional (3D) topographic modeling. The interferogram displays a deformation pattern indicated by color variations that correspond to the phase shift of radar waves. This pattern is created by changes in the distance between the earth's surface and the satellite, which can imply either inflation or deflation. Inflation happens when magma or volcanic gas rises from a reservoir beneath the surface, forcing the ground to expand. Deflation occurs when magma or gas escapes from the reservoir by eruption pathways or subsurface cracks, causing the earth surface to shrink. According to Townsend, the deformation that occurs in volcanoes is produced by the increase of pressure in the magma chamber under the earth's surface (Townsend, 2022). This pressure can be created by the infusion of new magma from the Earth's mantle into the magma reservoir, or it can be reduced by the discharge of volcanic material during an eruption (Caricchi et al., 2021). Deformation photos also reveal variations in the height or distortion of the volcano's surface structure.

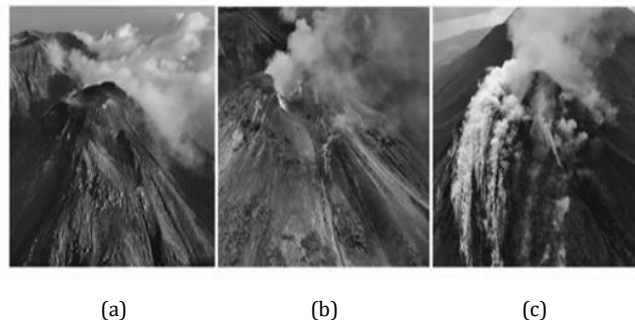


Figure 3: Morphological and visual changes of Mount Lewotobi Laki-laki, (a) October 18, 2024, (b) November 5, 2024, and (c) December 2, 2024.

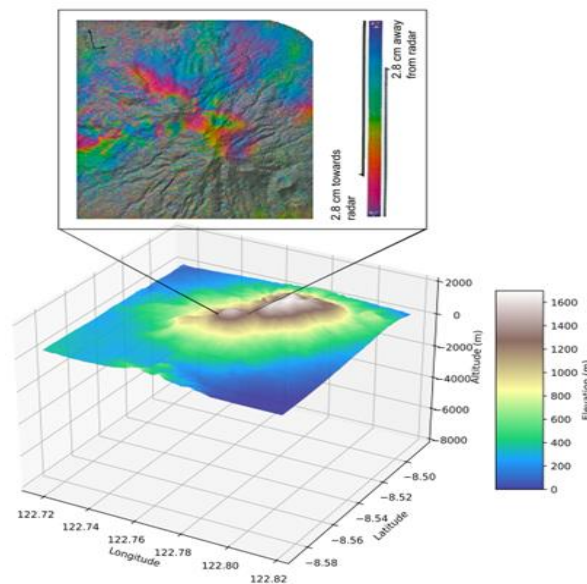


Figure 4: Deformation of Mount Lewotobi Laki Laki.

Figure 5 illustrates how the concentration of sulfur dioxide (SO₂) in the atmosphere fluctuated throughout Mount Lewotobi Laki-Laki's eruption. On November 9, 2024, the peak SO₂ concentration reached 0.012 mol/m². This spike represents the discharge of a substantial amount of volcanic gas into the atmosphere. Lower SO₂ values, observed on November 8 (0.004 mol/m²) and between November 12, 2024, and November 21, 2024, indicate a period of reduced gas emission activity. During this time, previously released gases were free to spread and settle. During the eruption, magma rose to the surface and released dissolved gases into the atmosphere, as evidenced by the increase in SO₂ concentration (Morales-Simfors, 2020). Two other substantial surges occurred on November 11 (0.008 mol/m²) and November 26-27 (0.007 mol/m²). These spikes show that volcanic activity is actively releasing gas into the atmosphere, but at a lower intensity than the big peak on November 9, 2024. This gas release activity may be coupled with lesser magmatic impulses or the occasional discharge of gas from a shallow magma chamber.

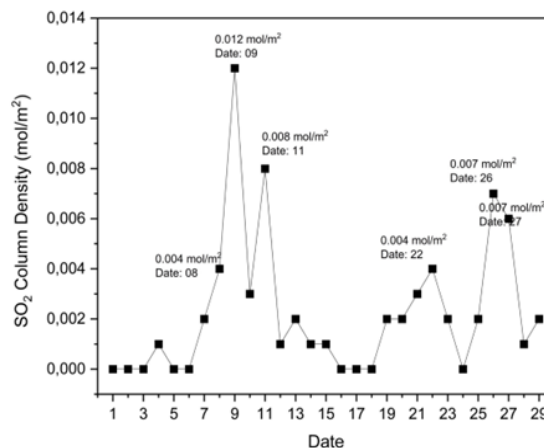


Figure 5: SO₂ concentration during the eruption of Mount Lewotobi Laki-Laki.

When there are more volcanic eruptions, the concentration of SO₂ in the atmosphere rises due to volcanic gases released during the eruption. The correlation between the frequency of eruptions and SO₂ concentration is not necessarily linear. Figures 2 and 5 demonstrate that a high number of eruptions does not necessarily lead to a corresponding increase in SO₂ concentration. This can be produced by a variety of reasons, including eruption intensity, volcano location, and atmospheric conditions. Explosive eruptions with high columns are more likely to inject SO₂ directly into the stratosphere than effusive or low-column eruptions. SO₂ emissions in the stratosphere have a bigger impact on atmospheric concentrations than those in the troposphere (Brody-Heine, 2022)

Figure 6 shows the distribution of sulfur dioxide (SO₂) concentrations in the atmosphere, assessed with TROPOMI data and the HYSPLIT atmospheric model. TROPOMI detects and maps volcanic gas emissions, such as SO₂, providing valuable insights into their impact on the atmosphere (Zhang et al., 2021). The release of SO₂ is often linked to magma movement beneath the surface, making it a reliable predictor of volcanic activity (Biggs, 2021; Egan et al., 2015). Analysis of geographical and temporal gas release patterns using TROPOMI provides a better knowledge of volcanic dynamics, including volcanic activity phases (Basavalingaiah, 2020). Gas distribution can be more properly mapped by incorporating atmospheric models such as HYSPLIT, allowing possible

risks to be identified early and supporting effective disaster mitigation (Faust et al., 2021; Weiser, 2022). Figure 6a depicts the distribution of observed SO₂ concentrations on a low to moderate scale, showing normal gasification activity commonly found in active volcanoes. The huge increase on November 9, 2024 (Figure 6b) suggests the discharge of a large amount of magmatic gas, implying new magma injection into the volcanic system.

The significant expansion of volcanic gas distribution on November 10 and 11 (Figures 6c and 6d) verified a rise in pressure within Mount Lewotobi's magmatic system, indicating a critical phase that could lead to an explosive eruption. The changes in SO₂ concentrations reported on 26 and 27 November (Figures 6e and 6f) represent the intricacy of the magma degassing process, which involves intermittent gas release followed by new pressure building. Unstable atmospheric circumstances, such as low-pressure cyclogenesis, increase the dispersion of SO₂ gas to a larger area (Nadirah et al., 2024). The eruption of Mount Lewotobi Laki-Laki has significant environmental impacts, primarily through the formation of sulfuric acid (H₂SO₄) due to reaction with water vapor in the atmosphere, which then produces sulfate aerosols (Nadirah et al., 2024; Fioletov, 2023). These aerosols not only provide mass and height to the volcanic ash column, but they also cool the atmosphere by absorbing and reflecting solar radiation (Trees et al., 2021).

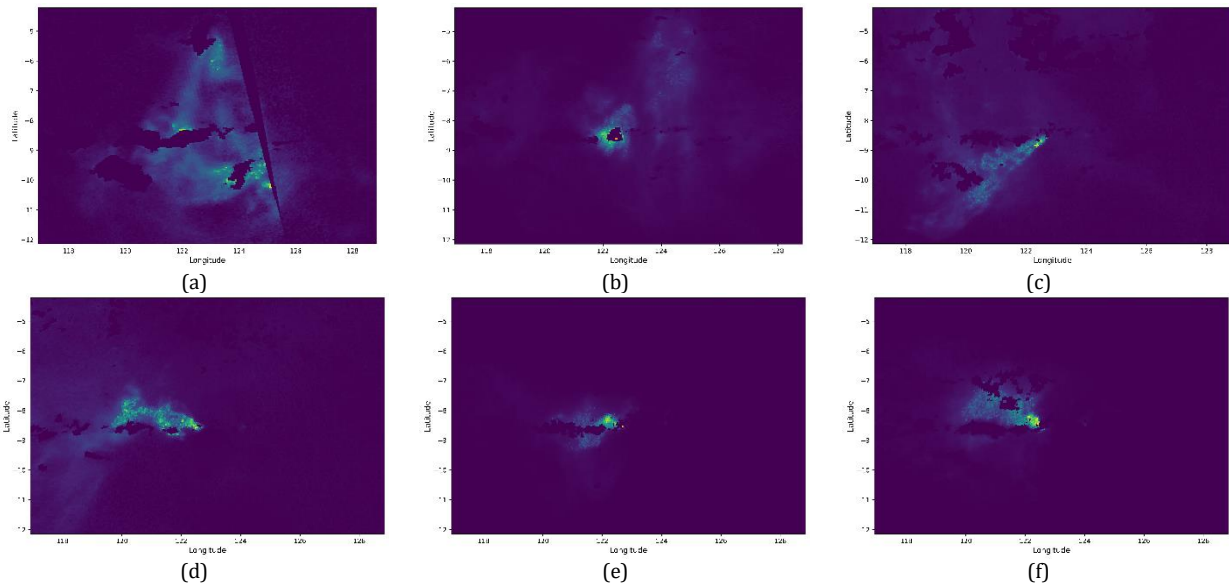


Figure 6: SO₂ concentration, (a) 08 November 2024, (b) 09 November 2024, (c) 10 November 2024, (d) 11 November 2024, (e) 26 November 2024, (f) 27 November 2024.

In addition to atmospheric conditions, stratospheric injection, and wind patterns, the distribution of SO₂ is influenced by these factors. Strong winds at high altitudes can disperse volcanic gases over long distances, thereby reducing the concentrations observed in the vicinity of the eruption site. On the other hand, local accumulations may result from feeble wind conditions. In addition, the direct injection of material into the stratosphere during ongoing eruption phases can significantly alter the distribution pattern of gases, as SO₂ can remain suspended for extended periods, thereby contributing to long-term atmospheric changes. As a result, the relationship between the intensity of eruptions and SO₂ emissions is not entirely linear; rather, it is influenced by dynamic atmospheric processes.

High levels of SO₂ in the atmosphere have impacted local air quality and weather patterns. The Sikka Meteorological Station's data suggest that local weather patterns in November 2024 are directly tied to the nature of the atmospheric layer, which is easily mobile, expandable, and has weight and pressure, resulting in decreasing air density as altitude increases. Understanding weather factors in a certain place is interrelated, with air temperature serving as one of the primary indications of weather conditions. The more energy received by the earth's surface, the higher the air temperature, which in turn affects other weather variables including air humidity and air pressure (Benestad, 2006; Barry and Chorley, 2009). Air density varies according to temperature. The air density increases as one gets closer to the earth's surface and decreases as one gets farther away.

According to the comparison graph of the air pressure weather factors in November 2023 and 2024 against normal conditions (figure 7), there is a rather strong negative anomaly in November 2024, with an average value of 1007.4 mb, 1 mb lower than November 2023. Where this condition has

dropped by 3 megabytes compared to the typical average value of 1010 mb. Negative air pressure anomalies first appeared about mid-November, or in the second decade. This condition declined steadily from the middle of the second decade until the end of the third decade.

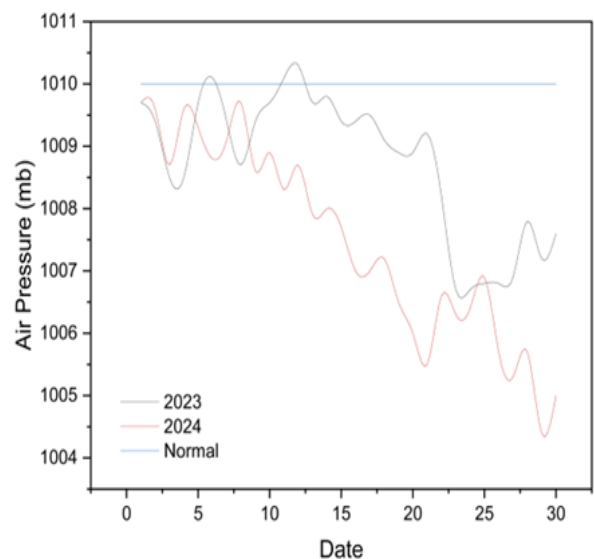


Figure 7: Average Air Pressure Graph for November.

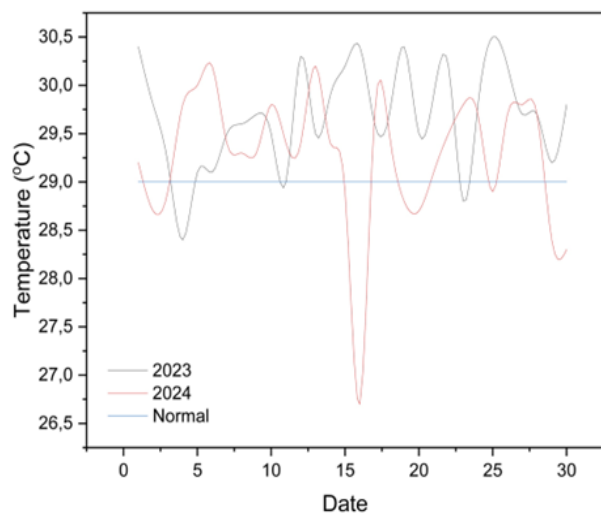


Figure 8: Average Air Temperature Chart for November.

Meanwhile, a comparison graph of air temperature and meteorological factors in November 2023 and 2024 to usual conditions reveals a positive anomaly (Figure 8). The average air pressure reading in November 2024 was 29.2 °C, down 0.7 °C from November 2023 but up 0.2 °C from the usual average of 29.0 °C. The fluctuations in air temperature conditions in the two datasets were mostly constant from the first to the third decade. Based on the link between weather components, air pressure, and air temperature observed in November 2024, the air density was relatively loose, particularly in the third decade or toward the conclusion of the month. This is due to the uneven shape of the earth's surface, which creates fluctuations in air pressure and temperature when particles or molecules are at various concentrations. Because the air density is low, particles and molecules can easily accumulate (Ma, 2024). According to the results of wind monitoring in the third decade of November 2024, the major wind direction shifts from northeast to southeast, with decreasing wind speeds. The impact of the decreasing wind speed causes particles or molecules in the air to float for an extended period (Yang, 2024). This scenario is also supported by the occurrence of an inversion layer, which is a layer that experiences temperature changes at altitudes of roughly 5000 meters. This inversion layer traps rising air and spreads it horizontally, depending on the wind direction and speed.

Furthermore, although changes in air pressure and temperature were observed during the eruption period, their causal relationship with volcanic activity remains complex. Previous studies, such as those conducted by a group researcher have shown that volcanic eruptions can affect atmospheric pressure and temperature fluctuations through aerosol and gas injection (Aubry 2022; Kroll, et al., 2021). However, additional meteorological data and long-term observations are needed to confirm these interactions in the context of Mount Lewotobi Laki-Laki. In terms of SO₂ emissions, comparisons with previous studies explain that SO₂ variability is strongly influenced by magma composition and eruption dynamics (Delbrel et al., 2024; Gonnermann et al., 2013).

The impact of SO₂ on climate and human health requires further investigation. High SO₂ concentrations can contribute to the formation of acid rain and respiratory problems, especially for vulnerable populations. Combining quantitative risk assessments, such as the Air Quality Index (AQI) and satellite-based SO₂ exposure models, will provide a more comprehensive understanding of these impacts. From a disaster management perspective, the study's findings underscore the need to integrate volcanic gas monitoring with early warning systems. By leveraging satellite observations, ground-based sensors, and atmospheric modeling, authorities can develop more effective evacuation plans and reduce health risks to affected communities.

4. CONCLUSION

Mount Lewotobi Laki-Laki's increased volcanic activity in November 2024 implies a major release of energy caused by pressure accumulation in the magma reservoir during the extended dormant era. The main cause of the explosive eruption was a shift in magma composition from basaltic to andesitic with high silica concentration. This process is distinguished by the discharge of volcanic ash, which extends up to 6-7 kilometers from the crater, as well as changes in the mountain's morphology discovered through deformation analysis with InSAR data. The deformation pattern displays inflation from new magma injection and deflation from volcanic material discharge, showing magmatic fluid movement and pressure

accumulation within the magma chamber. The increase in sulfur dioxide (SO₂) concentration in the atmosphere during the eruption period, especially on November 9, 2024, and changes in SO₂ concentration near the end of November 2024, represent complex magmatic dynamics and are crucial markers of increased magmatic pressure. The reaction of SO₂ with water vapor in the atmosphere creates sulfuric acid (H₂SO₄) and sulfate aerosols, contributing to the increase in the mass of the volcanic ash column, local cooling effects in the atmosphere, and threats to air quality, human health, and the agricultural sector.

However, this study has several limitations, especially in measuring SO₂ using satellite data. The accuracy of SO₂ detection can be affected by cloud cover, atmospheric scattering, and variations in sensor resolution. Furthermore, to enhance disaster preparedness, enhancements in volcano monitoring are required. Future research explores the application of artificial intelligence (AI) for real-time data processing, sensor fusion techniques to combine satellite and ground-based observations, and the development of early warning systems with real-time alerts. Improvements in these technologies can significantly improve the accuracy of eruption predictions and enhance risk mitigation efforts.

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