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Research paper

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Thermal and ground deformation monitoring for early detection of volcanic eruptions: a case study of Taal volcano, Philippines

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Summary

Volcanic eruptions, such as those of Krakatau and Pinatubo, are uncontrollable natural phenomena with the potential for widespread destruction, including the global climate. Early detection of volcanic activity is crucial for mitigating risks and preventing loss of life. This study focuses on the Taal volcano, located in the Batangas region of the Philippines, which erupted in January 2020 after being dormant for 43 years. Using satellite remote sensing data, the study employed the Land Surface Temperature (LST) analysis, the Normalized Temperature Index (NTI), and ground deformation monitoring using radar-based the Small Baseline Subset (SBAS) InSAR techniques to detect early warning signs of volcanic unrest.

Keywords

Taal Volcano • Land Surface Temperature (LST) • Normalized Temperature Index (NTI) • ground deformation • Sentinel-1 • volcanic eruption • early warning systems

1. Introduction

Volcanic eruptions, such as those of Krakatau and Pinatubo, are uncontrollable natural events that can cause massive destruction, including the global climate. The eruption of Krakatau in Indonesia released volcanic aerosols into the stratosphere, reaching altitudes of up to 34 km, affecting weather patterns globally for many years [USGS 2021]. The 1991 eruption of Mount Pinatubo in the Philippines intensified monsoon rains in

Asia, lowered global temperatures by 0.5°C, and contributed to ozone depletion [Wolfe 2020]. The resulting climatic effects resulted in significant casualties despite evacuation efforts [Chen et al. 2020]. Eruptions of this magnitude, rated at level 6 on the Volcanic Explosivity Index (VEI), cause significant atmospheric disruptions [Newhall and Self 1982]. At the lower end of the scale (VEI 0), non-explosive eruptions, characterized by ash plumes, occur daily around the world [Global Volcanism Program 2024]. However, at the upper extreme (VEI 8), an eruption could lead to global devastation, potentially wiping out life on Earth [Greicius 2021].

To mitigate the risks associated with volcanic eruptions, numerous observatories have been established in volcanic regions to monitor changes that may indicate an imminent eruption. These observatories, often government- or university-affiliated, use seismic, geodetic, and gas emission data to detect ground deformation and seismic activity caused by magma movement beneath the surface [Wright 2015]. As magma ascends, it heats and displaces groundwater, causing the surrounding ground to deform and rise [Wan and Dozier 1996]. Scientists also monitor changes in gas emissions, gravity, and magnetic fields to detect deviations from normal volcanic activity [Massimetti et al. 2020]. However, according to the Smithsonian Institution's Global Volcanism Program, even the most advanced monitoring systems can only predict eruptions a few days in advance [Zhuo et al. 2021].

Developing more effective forecasting methods is essential for enabling timely evacuations of people and livestock in affected areas. Forecasting methods must be reliable enough in order to avoid unnecessary panic or false alarms, as inaccurate predictions could undermine public trust [Ganci et al. 2011]. In addition to ground-based monitoring, satellite data analysis has become increasingly important [Suarez-Herrera et al. 2021]. NASA's Jet Propulsion Laboratory (JPL) has developed a method for detecting thermal changes well before other signs of volcanic activity become evident [Lazecky et al. 2020]. This method identifies increases in heat emissions over a volcano, signaling an impending eruption. After analyzing 20 years of satellite data, the researchers observed consistent patterns of rising surface temperatures over active volcanoes [Trepińska 2022].

The Global Volcanism Program (GVP), which maintains data on active volcanoes worldwide, estimates that there are currently 1,324 active volcanoes globally [Pogoda 2017]. In the Philippines alone, 23 active volcanoes are being monitored. For instance, Taal Volcano in the Batangas region of Luzon was closely monitored before its eruption on January 23, 2020 [PHIVOLCS 2021]. The volcano is surrounded by Lake Taal, and although it had been dormant since 1977, it erupted with a VEI of 4 [MIROVA 2021]. To protect people and infrastructure from volcanic hazards, the Philippine Institute of Volcanology and Seismology (PHIVOLCS) monitors volcanic activity using broadband and short-period seismic measurements, GPS, and CO_2 emissions [Coppola et al. 2008]. PHIVOLCS' data will be used in this study to compare ground-based monitoring results with satellite data analyses [COMET 2021].

The MIROVA system uses MODIS satellite imagery to calculate Land Surface Temperature (LST) as part of its volcanic ground temperature research [OpenScienceLab.

2020]. MODIS data, with 1 km spatial resolution, can be compared with other satellite imagery, such as Sentinel-2 [Chan and Konstantinou 2020]. The article *Volcanic Hot-Spot Detection Using SENTINEL-2* compares data across eight volcanoes, analyzing the correlation between ground temperatures near the volcanic site [Lewandowski 2021].

MOD11 data, utilizing the Split Window Algorithm, has been applied to volcanic thermal studies [Rothery et al. 2020]. Research on Mayon Volcano in the Philippines utilized the MOD11 data to observe temperature increases linked to volcanic activity [PHIVOLCS 2020]. The Normalized Temperature Index (NTI) analysis, part of the MODVOLC system, detects thermal anomalies and offers real-time updates [Zhou and He 2021]. Studies applying the NTI on Stromboli and Copahue have demonstrated the effectiveness of this method in predicting eruptions [Chen et al. 2020, Jones and Harris 2019].

Ground deformation analysis using InSAR data from Sentinel-1 is conducted by COMET's Volcanic and Magmatic Deformation Portal [Trepińska 2022]. OpenScienceLab employs the SBAS technique to generate time series interferograms, detecting deformation before an eruption [Greicius 2022].

Taal Volcano is equipped with a ground-based network that includes GPS stations and temperature sensors in Lake Taal [Wan and Li 2008]. Satellite data, especially valuable for monitoring remote volcanoes, provides critical insights into volcanic activity [Coppola 2021].

2. Methods and data

In this study, remote sensing techniques and satellite data analysis were applied to monitor land surface temperature and ground deformation in the region surrounding Taal Volcano. Specifically, the methods used include the Land Surface Temperature (LST), the Normalized Temperature Index (NTI), and the Small Baseline Subset (SBAS) technique for ground deformation analysis.

2.1. Data

Various satellite data sources were utilized to perform thermal and ground deformation analyses.

2.1.1. MODIS Data

The study used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the MOD11A2 (for LST) and MOD021KM (for NTI) datasets to analyze surface temperature and detect thermal anomalies. The data covers the period from January 1, 2018, to July 31, 2022, and has a spatial resolution of 1 km. The MODIS datasets provide information on surface temperature and emissivity every 8 days, allowing for the tracking of long-term thermal changes.

- MOD11A2: 8-day average surface temperature dataset used for analyzing long-term thermal variations.

- MOD021KM: dataset contains measurements in emissive bands, allowing for the calculation of the NTI index for volcanic activity monitoring.

2.1.2. Sentinel-1 Data (SBAS)

Radar data from the Sentinel-1 satellite was used for ground deformation analysis, specifically applying the Small Baseline Subset (SBAS) method. The data, consisting of second-level processed interferograms, was sourced from the ASF Data Search portal [Greicius 2021] and exported to the AWS cloud platform. This approach significantly simplifies the analysis of large datasets, eliminating the need for local computational resources and the manual process of downloading data. Sentinel-1 interferograms, with a spatial resolution of up to 10 meters, enable precise monitoring of ground deformation.

Time series analyses were conducted on 92 interferograms spanning three time periods: the year 2018, from November 15, 2018, to January 9, 2020; and the post-eruption period in 2020. These analyses were performed on the OpenScienceLab platform [Wright 2015], providing a comprehensive overview of the ground deformation patterns before, during, and after the Taal Volcano eruption.

2.2. Methods

Three main analytical methods were applied in this study to identify thermal anomalies and ground deformation in the Taal Volcano region.

2.2.1. LST Method (Land Surface Temperature)

Surface temperature (LST) was calculated using the *Split Window* algorithm, which relies on the difference in brightness temperatures across two spectral bands. This algorithm requires information on water vapor content, atmospheric transmissivity, and surface emissivity to accurately determine surface temperature.

For the LST analysis, it was assumed that areas near Taal Volcano would heat up more than distant areas. To identify thermal anomalies, the average temperatures in two zones – one with a diameter of 8 km and a larger one with a diameter of 32 km – were compared (Fig. 1). A temperature difference of 1 K or more between these zones was considered a possible indicator of volcanic activity.

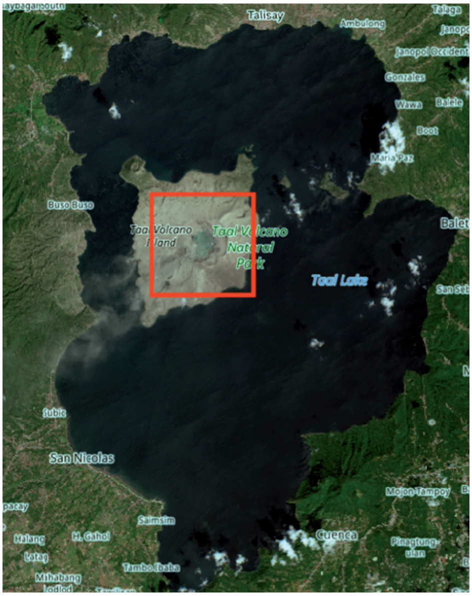
2.2.2. NTI Method (Normalized Temperature Index)

The NTI is calculated based on Planck's law, which describes the relationship between spectral radiation and surface kinetic temperature. In the NTI calculations using MODIS data, the B21, B22, B6, B31, and B32 bands were used. The NTI values were compared to the threshold values of –0.8 for nighttime data and –0.65 for daytime data. Values exceeding these thresholds indicated increased volcanic activity.

The NTI was calculated for four strategically selected pixels covering the main crater and part of the volcanic island, allowing for the monitoring of temperature changes in areas most susceptible to eruptions (Fig. 2).

Source: Authors' own study

Fig. 1. Representation of the 8 km buffer (red) and the 32 km – 8 km buffer (blue), showing the land area for which the LST values were determined and compared. In the top right corner, the map of the Philippines highlights the location of Taal Volcano in red



Source: Authors' own study

Fig. 2. Visualization of the location of four MODIS data pixels on a Sentinel-2 image, analyzed to determine the NTI (red) [PHIVOLCS 2020]

The NTI was calculated using the algorithm employed by MODVOLC [Wright 2015]. Based on bands 22 and 32, the following formula (1) was used:

$$NTI = \frac{L_{22} - L_{32}}{LL_{22} + L_{32}} \tag{1}$$

2.2.3. SBAS Method (Small Baseline Subset)

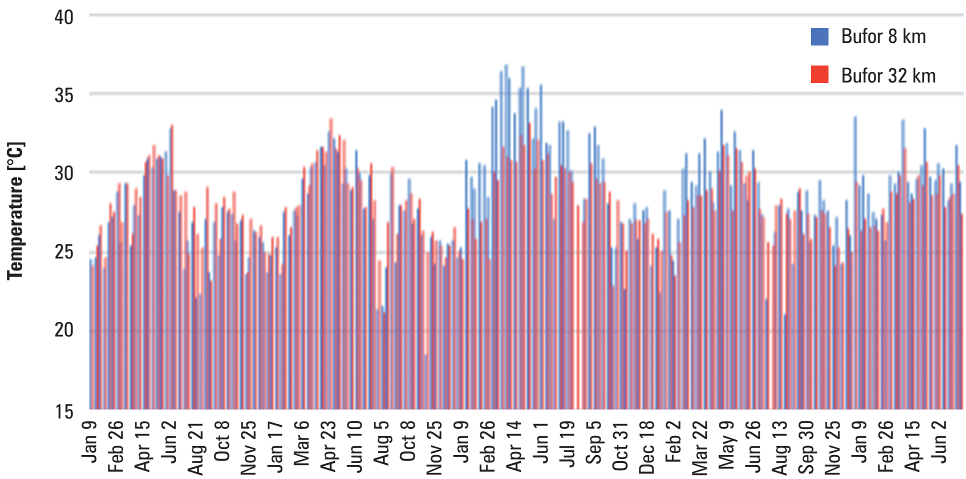
The SBAS method allows for the monitoring of ground deformation over time by generating time series from radar interferograms. Temporal and spatial filtering, used in this technique, enhances the precision of deformation measurements. Interferograms are generated based on Sentinel-1 radar data using specific temporal and spatial baseline parameters to maintain signal phase coherence.

The SBAS interferograms were generated using second-level processing data, which enabled the detection of surface deformation near the volcano days before the eruption. Time-series analyses were compared with the first image in the stack and reference points.

3. Results and discussion

3.1. LST Analysis results

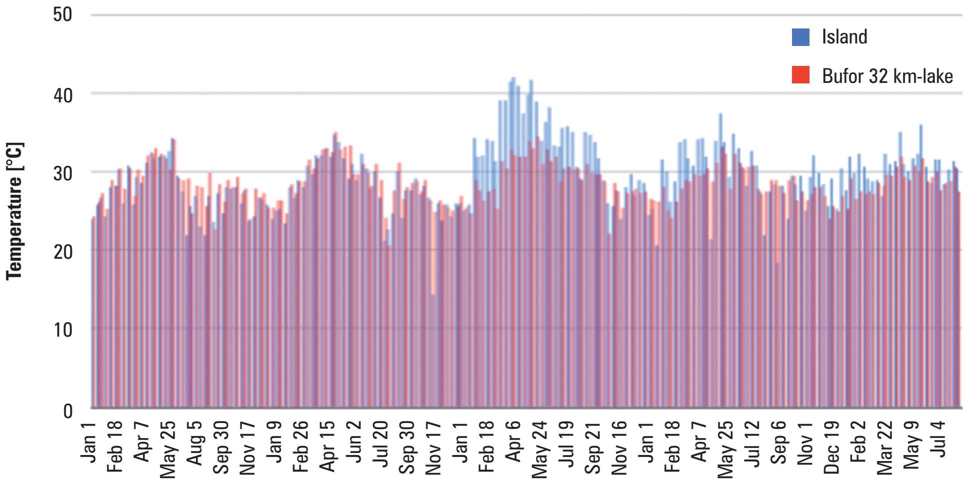
The LST analysis revealed an increase in surface temperatures in areas adjacent to Taal Volcano prior to the eruption. In thermal imagery that includes water temperature, an increase in ground temperatures was observed 3 days before the eruption when compared to distant areas (Fig. 3).



Source: Authors' own study

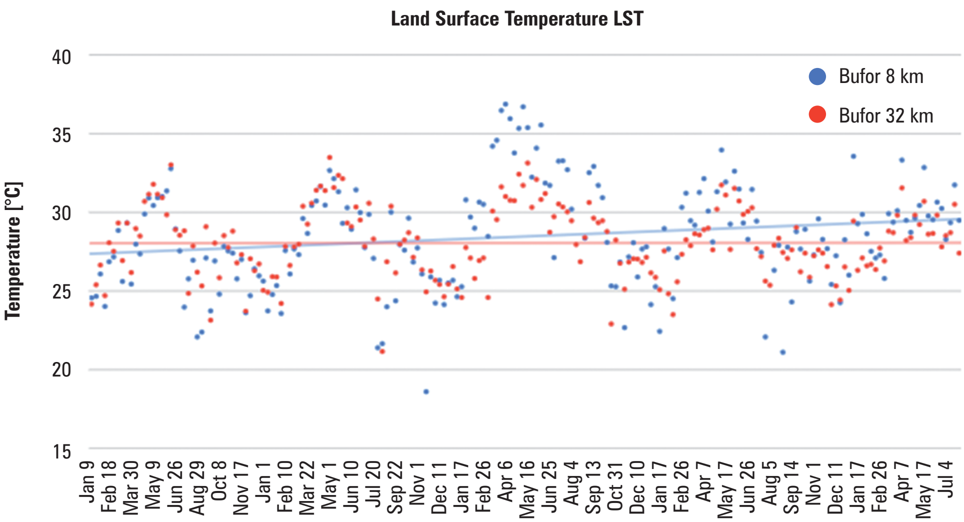
Fig. 3. Bar graph of temperatures generated from MOD11A2 data on the Google Earth Engine platform for two areas: an 8 km buffer zone and a 32 km buffer zone, as shown in Figure 1

Excluding water temperature, the increase in ground temperature was observed 11 days before the eruption (Fig. 4). The eruption began on January 12, 2020, and lasted until January 23, 2020. The presence of large water bodies, such as Lake Taal, significantly impacted recorded temperatures.



Source: Authors' own study

Fig. 4. Bar graph of temperatures excluding Lake Taal's temperature, generated from MOD11A2 data on the Google Earth Engine platform



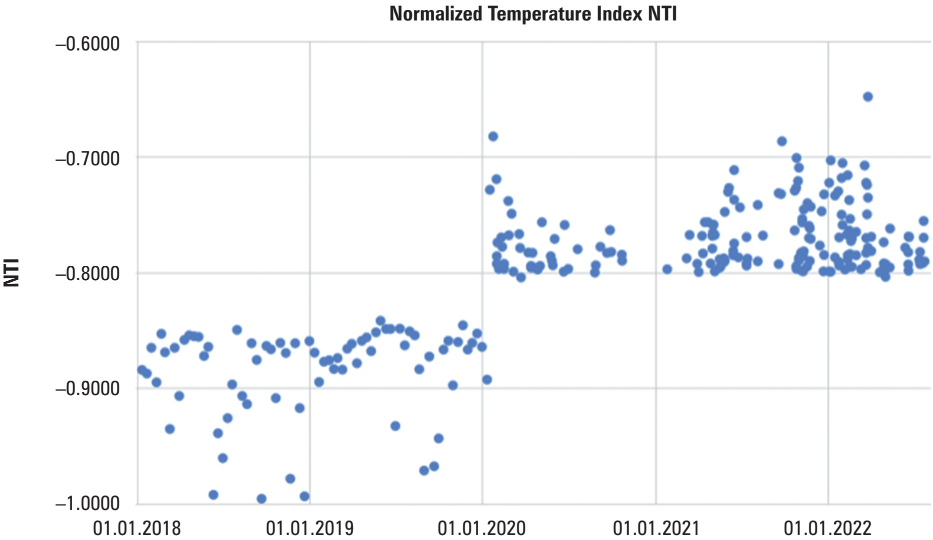
Source: Authors' own study

Fig. 5. Scatter plot of temperatures for the areas marked in Figures 3 and 4, with trend lines indicated by straight lines

The temperature trend lines for both adjacent and distant areas indicate a more pronounced temperature increase in the regions closest to the volcano. The intersection of these trend lines occurred in May 2019, corresponding to in situ measurements from the ground monitoring station, which recorded a temperature increase in the main crater in April 2019 (Fig. 5).

3.2. NTI Analysis Results

The NTI analysis (Fig. 6) shows no volcanic activity prior to January 16, 2020, followed by significant volcanic activity after this date. The highest NTI value occurred on the day of the eruption, reflecting a sharp increase that persisted throughout the monitored period. This indicates continuous volcanic activity post-eruption.



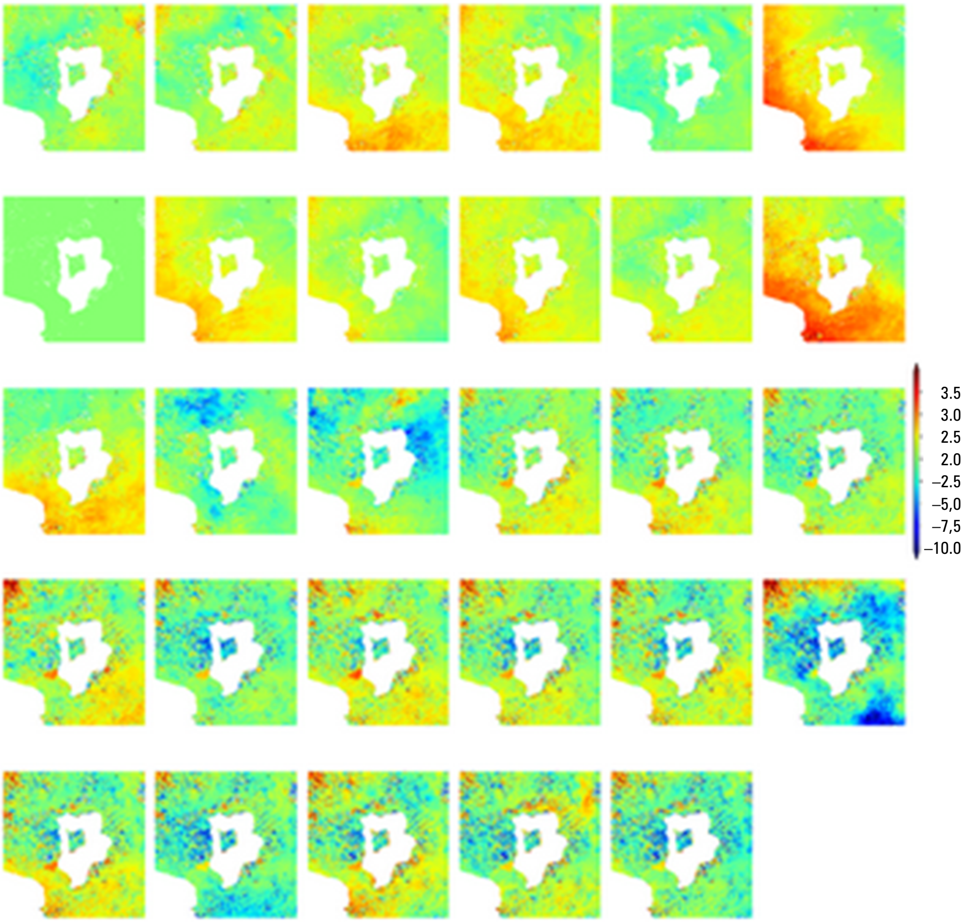
Source: Authors' own study

Fig. 6. Graph of the NTI values from January 1, 2018, to July 31, 2022

3.3. SBAS Analysis Results

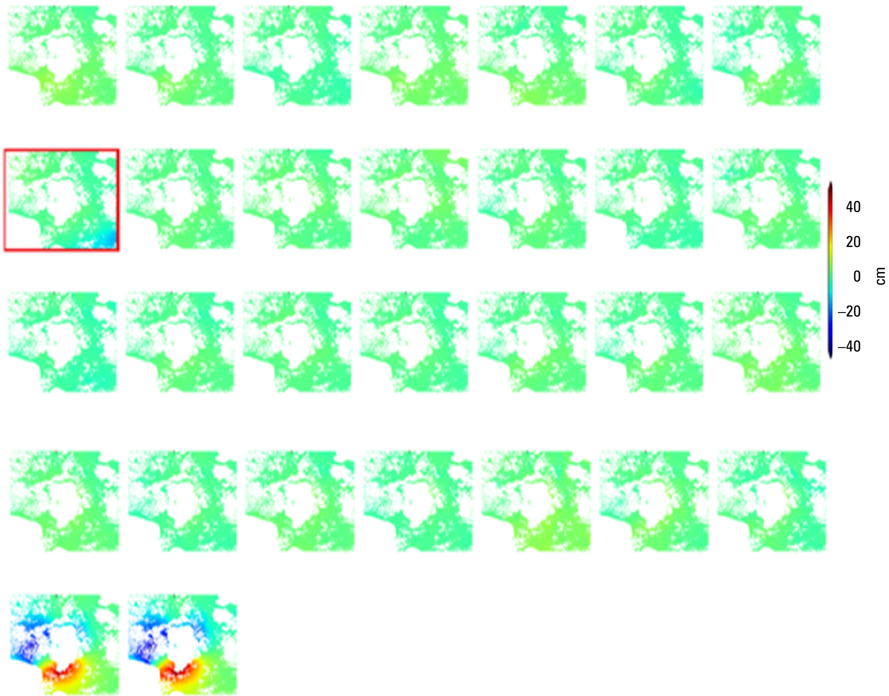
Ground deformation measured using SBAS data from Sentinel-1 indicated substantial deformation, ranging from deflation of –0.40 m in the northern region to inflation of +0.40 m in the southern region. These deformations occurred within a short time frame, approximately 14 days before the eruption. Prior to this, minor inflation and deflation of the ground were observed, consistent with reports from the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and the COMET Volcanic and Magmatic Deformation Portal.

In 2018, ground deformations ranged from –10 cm to +7.5 cm, while in 2020, deformations varied between –15 cm and +10 cm across the study area. These fluctuations could be attributed to the tectonic setting, as the Philippines lies at the convergence of the Pacific and Eurasian tectonic plates, which results in significant seismic activity. Throughout 2019, continuous minor inflation was recorded, with a rapid increase in the southern part of the volcano just before the eruption, indicating magma movement (Figs. 7–9).



Source: Authors' own study

Fig. 7. Ground deformation images for the year 2018, based on 29 interferograms



Source: Authors' own study

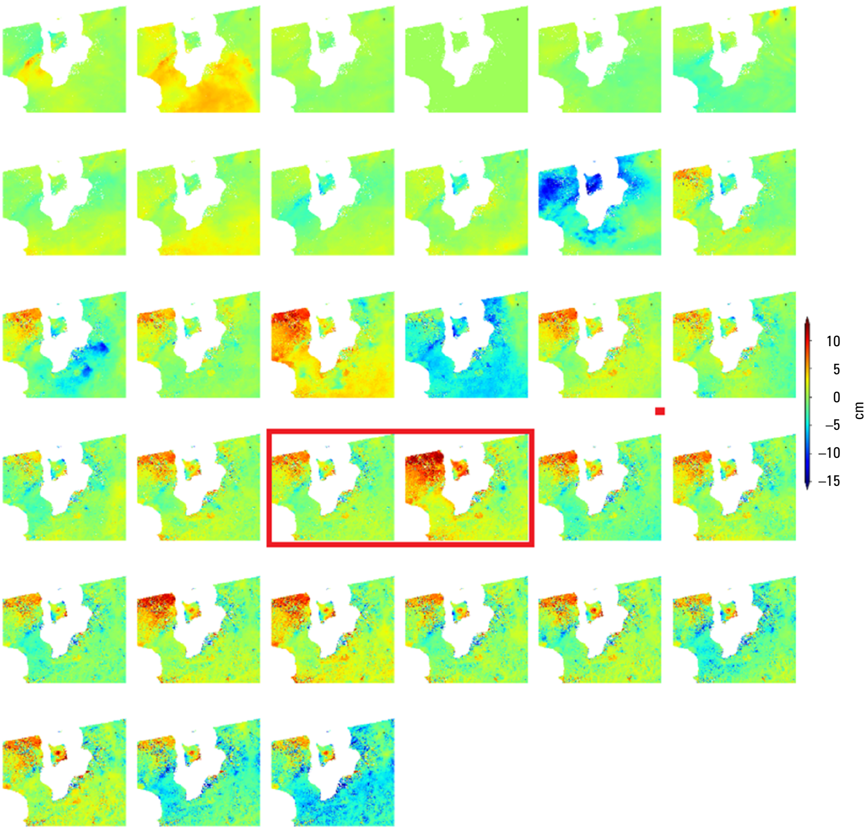
Fig. 8. Ground deformation images for the period from November 15, 2018, to January 9, 2020, based on 30 interferograms. The deformation marked with a red frame indicates displacement in the lower right corner, potentially caused by low coherence

4. Discussion

The results from the LST, NTI, and SBAS analyses provide strong evidence of the efficacy of satellite-based remote sensing for early detection of volcanic activity. The significant rise in surface temperatures, particularly in areas near the Taal Volcano, indicated magmatic activity well in advance of the eruption. The observed trend line intersections in May 2019, followed by temperature increases recorded in April 2019, further highlighted the value of LST monitoring as an early warning tool.

The NTI analysis added further confirmation of volcanic activity. Although the NTI did not show clear signals before January 2020, it demonstrated a pronounced increase in values immediately after the eruption. This suggests that NTI is a valuable complementary tool to the LST, especially for confirming ongoing volcanic activity.

Ground deformation patterns identified through SBAS interferometry revealed significant inflation, particularly in the southern region of the volcano, as magma moved beneath the surface. The ground deformation observed before the eruption was consistent with typical volcanic inflation patterns, further supporting the role of SBAS as a key method for monitoring volcanoes prone to explosive eruptions.



Source: Authors' own study

Fig. 9. Ground deformation images for the year 2020, post-eruption, based on 33 interferograms. Two deformations marked with red frames indicate inflation, coinciding with the volcanic eruption

The comparison of these different remote sensing techniques – LST for thermal anomalies, NTI for surface temperature anomalies, and SBAS for ground deformation – underscores the importance of integrated monitoring approaches. Combining these methods allows for a more comprehensive assessment of volcanic unrest and increases the likelihood of detecting critical warning signs.

5. Conclusion

Volcanic eruptions pose a substantial threat to human life, infrastructure, and the environment, making early detection vital for risk mitigation. This study demonstrates the effectiveness of satellite-based methods – Land Surface Temperature (LST), Normalized Temperature Index (NTI), and Small Baseline Subset (SBAS) – for monitoring volcanic activity and providing early warning signals.

In the case of Taal Volcano, the LST analysis detected significant thermal anomalies months before the eruption, showcasing its potential for early volcanic activity detection. NTI, while effective in identifying thermal anomalies, was most useful in confirming ongoing volcanic activity after it had already begun. The SBAS ground deformation analysis provided insights into magma movement beneath the volcano, serving as a reliable predictor of imminent eruptions.

The study emphasizes the importance of considering local geographical factors, such as large water bodies like Lake Taal, which can affect temperature readings and satellite data interpretation. Continuous satellite monitoring, integrated with ground-based data, is essential for improving early detection and mitigating risks in high-risk volcanic regions. The findings suggest that these remote sensing methods can complement traditional monitoring systems and be applied to other volcanic areas, significantly enhancing global early warning systems and disaster preparedness efforts.

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