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How artificial intelligence can enhance monitoring of volcanoes from space

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Summary. — The ability to collect and analyze satellite data in near real-time (NRT) is fundamental for monitoring volcanic hazards and identifying the needed mitigation actions. This capability depends mainly on the availability of satellite data, which can range from a few minutes (SEVIRI, MODIS) to several days (MSI, OLI). Volcanology has embraced artificial intelligence (AI), incorporating both Machine Learning (ML) and Deep Learning (DL), allowing computers to learn from historical data and build a knowledge base of volcanic processes. An AI-based platform has been developed for NRT monitoring of volcanic activity, utilizing satellite imagery and offline analysis. ML and DL algorithms automatically evaluate volcano status from extensive multi-spectral satellite data flows. Built-in modules work together towards a common goal and are activated based on AI logic. These modules are adept at diverse tasks, from forecasting eruption initiation to quantifying erupted products using satellite thermal measurements. This platform represents an unprecedented convergence between technological innovation and the scientific community's experience overcoming limitations of traditional approaches by inferring knowledge from large amounts of heterogeneous satellite data. It enables informed, timely, and sophisticated management of volcanic activity, significantly contributing to enhancing safety measures and minimizing the impact of volcanic events on communities and infrastructure.

1. – Introduction

Real-time monitoring of volcanic activity significantly enhances our understanding of volcano dynamics, aiding in timely activity detection, precise eruption forecasts, and the implementation of preventative measures to minimize risks and damages. Active volcanoes pone unique challenges for direct observation and thermal measurements, particularly during eruptive phases. Under this perspective, the application of satellite remote sensing techniques offers an invaluable solution, serving as a powerful tool, especially

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advantageous for observing high-temperature volcanic features from a distance. By capturing spatial data on thermal patterns and volcanic activities, satellite remote sensing aids in forecasting and identifying emerging volcanic threats, offering crucial insights that guide preventive measures. Leveraging diverse satellite data categories, crucial spatial and temporal information can be retrieved to assess the state of the volcano [1]. The advent of AI has transformed traditional volcano monitoring, from two main perspectives: from one hand, it allows machines to perform tasks that typically require human intelligence. On the other hand, advanced AI techniques like ML and DL give the ability to machines to learn from experience without being explicitly programmed [2, 3]. In modern volcanology, platforms play an essential role in monitoring eruptive events, providing real-time processed data and images [4]. A significant advancement has been made with HotVolc [5], enabling users to obtain immediate and dynamically processed data, significantly improving reactivity and effectiveness in interpreting volcanic information. Here, we propose a novel platform for volcano monitoring from space empowered by AI logic, representing a milestone that will change the landscape of volcano hazard monitoring. It automatically activates built-in modules coping together towards a common goal, *i.e.*, volcano hazard assessment. A change of paradigm is proposed to overcome the limitation of single-task existing platforms by designing a multi-task modular one entirely driven by data. What distinguishes it from other platforms is its intelligence behind modules' interaction. This innovative approach allows for the extraction of valuable insights from diverse sources, enhancing the platform's ability to comprehensively analyze volcanic activity. Such intelligent integration not only improves the effectiveness of mitigation strategies but also contributes to a deeper understanding of volcanic processes. Innovative ML and DL algorithms are developed to automatically assess the status of the volcano and characterize ongoing eruptions from massive flows of satellite data, converting it into useful knowledge.

2. – Data source

The utilization of various satellite data sources represents an invaluable asset, significantly enhancing our ability to monitor volcanic activity by combining enhanced temporal and spatial resolution. We integrate a range of freely accessible satellite datasets, comprising visible (VIS), infrared (IR) and radar data, each characterized by distinct spatial, temporal, and spectral features. The spatial resolution can range from 20, 30, or 60 meters depending on the bands used, while the temporal resolution can range from 15 minutes (SEVIRI) to 5, 10, or more days (MSI, OLI). Specifically, we harness geostationary satellite sensors like SEVIRI (Spinning Enhanced Visible and InfraRed Imager) aboard Meteosat satellites, as well as several mid-to-high spatial resolution polar satellite sensors, including MODIS (Moderate Resolution Imaging Spectroradiometer) on Terra and Aqua satellites, VIIRS (Visible Infrared Imaging Radiometer Suite) on Suomi-NPP and NOAA-20 satellites, SLSTR (Sea and Land Surface Temperature Radiometer) on Sentinel- 3A and Sentinel-3B satellites, and high spatial resolution sensors like MSI (MultiSpectral Instrument) on Sentinel-2, and OLI (Operational Land Imager) on Landsat 8, and Sentinel-1 Synthetic Aperture Radar (SAR).

3. – AI-based platform

The use of AI, specifically ML and DL, is the cornerstone in the development of the proposed advanced volcanic monitoring platform. Its modules act both independently and collectively, representing an example of a System of Systems. The outcome, *i.e.*, the status of the volcano, is determined by a combination of all modules.

The advanced volcanic monitoring platform is structured into four key sections (*Forecasting*, *Detecting*, *Tracking* and *Quantifying*) as shown in fig. 1. Each section is designed to address specific needs and objectives in volcanic activity monitoring and analysis, while sharing a common unique goal, automatically assessing and describing the status of the volcano. The platform operates synergistically and recursively, with different modules activated sequentially in response to developments in volcanic activity. It provides continuous NRT monitoring of multiple volcanoes, offering a quick overview of their status with a color-coded icon indicating green, orange, or red based on the activity state determined by the outcomes of the Forecasting and Detecting modules.

The primary objective of the Forecasting section is to issue warnings in the event of changes occurring during the unrest phase. Eruptions are often preceded by various indicators detectable from space, including subtle increases in surface temperature. Advanced algorithms of DL, *i.e.*, CNN [6], were adopted to extract subtle to large volcanic thermal features segment the image. Forecasting module will produce either "advisory state" class if any change is detected or "normal state" class otherwise. In this case, an orange icon will be displayed together with the thermal time series showing such a trend. When the eruption officially begins, the system transitions to the crucial Detecting phase. This phase automatically switches the activity state to "watch state" based on all available satellite thermal data, using the Anomaly Detection ML algorithm, specifically Isolation Forest [7]. During this phase, the platform is designed to accurately and promptly detect anomalous volcanic thermal activity and recognize any volcanic hazard phenomena. The Volcanic Radiative Power (VRP) time series, depicting the evolution of emitted radiance, will automatically appear. This model activates "Lava Flow", "Volcanic Cloud", and "Pyroclastic Deposits" based on the analysis of the available satellite data based on the scheme shown in fig. 1. As an example, the platform can detect the onset of a lava flow and then quantify its geometrical features (*e.g.*, area, length) thanks to sophisticated detection algorithms supported by advanced ML and DL techniques, *i.e.*, cascading models based on Random Forest and Squeezenet [8]. Once any volcanic phenomenon is detected through the activation of the "Detecting" module, the system automatically transitions to the next tracking phase. Space-based imagery tracks activity over time, providing information on the emplacement of volcanic deposits, the presence and characteristics of ash plumes, and potential changes in the eruption's nature. This tracking implementation focuses on the spatial-temporal evolution of eruptive products

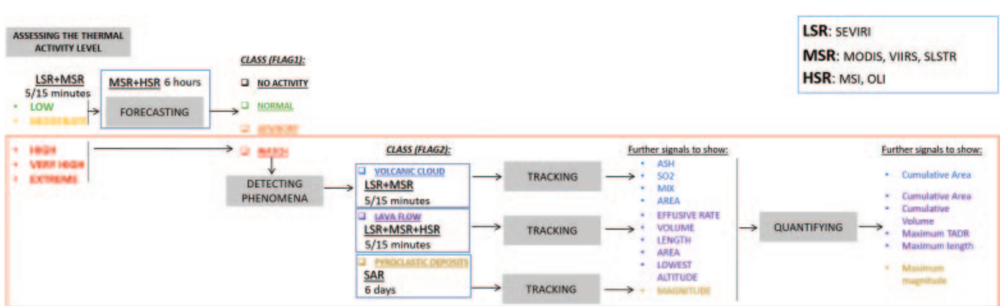

Fig. 1. – Workflow AI-based platform.

(ash clouds) using an ML approach, specifically Support Vector Machine (SVM) [9], to discriminate between the spectral features of volcanic clouds components based on training data. Finally, after guiding users through each phase of volcanic activity, we reach the last crucial section: Quantification. This section represents the culmination of monitoring, collecting, and providing precise measurements and characterizations of volcanic activity. It offers detailed assessments of hazard magnitude, such as the amount of material emitted and the altitude reached by the lava flow. This information guides a ML model to determine if the phenomenon poses limited hazards, maintaining the activity state as "watch", or if it requires as shift to "warning". The outcomes of each module will be integrated into an ML model to assess the type of eruption, such as strombolian activity, major explosion, paroxysm, and effusive activity. Finally, an offline mode will allow users to select the volcano of interest and explore historical data. Users are introduced to an intuitive and interactive interface that offers considerable flexibility in navigating through different volcanic parameters over time.

4. – Conclusions

Our proposed platform demonstrates an innovative contribution, introducing a new way for thinking about volcano monitoring from space. Thanks to AI, a NRT description of volcanic behavior is automatically contextualized by merging spatiotemporal information from various satellite sources with advanced ML models. The significance of this work extends far beyond; it represents an engineering innovation that integrates AI methodologies to address complex and dynamic challenges, ranging from eruption prediction to designing solutions for risk mitigation. This fusion of volcanology and engineering, supported by AI, bridges the gap between understanding natural processes and technological innovation, opening the door for highly advanced systems capable of dynamically adjusting to changing conditions in volcanoes. This approach not only sparks scientific interest due to its contribution to predictive accuracy but also revolutionizes volcanology by enabling the development of evacuation and protection strategies driven by real-time data.

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