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RESEARCH

Steps toward a satellite-based global volcano monitoring and early warning system: from pilot to demonstrator to GVEWERS

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Abstract

The consequences of volcanic eruptions span a broad range. Large explosive eruptions that recur every several hundred to thousands of years can impact global climate, but even small eruptions of a magnitude that takes place multiple times each year someplace on Earth can have devastating effects given the large number of people who live near volcanoes. Ground-based monitoring is inadequate or lacking at many of the world's active volcanoes, but satellite observations can fill important gaps and provide operational awareness of volcanic unrest and eruptions. The need for satellite monitoring of volcanoes has been articulated in numerous international agreements, and for some datasets, like thermal and ultraviolet imagery, daily or sub-daily monitoring has been incorporated into operational volcano surveillance. Utilization of high-resolution synthetic aperture radar (SAR) and optical datasets, however, has lagged. Since 2014, the Committee on Earth Observing Satellites (CEOS) has sponsored a series of projects designed to enhance access to, and utilization of, high-resolution SAR and optical satellite imagery for volcano monitoring. The efforts have culminated in the development of the Global Volcano Early Warning and Eruption Response from Space (GVEWERS) initiative—a global and sustainable program intended to support volcano hazards assessment and mitigation. GVEWERS builds on lessons learned from a decade of CEOS volcano projects while also providing a foundation for continuing to improve the accessibility and exploitation of satellite data for better anticipating and responding to hazardous volcanic eruptions.

Keywords Volcano monitoring · Deformation · Synthetic aperture radar · Remote sensing · Satellite data · Eruption response

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Introduction

Often underappreciated in the wide range of natural hazards that affects Earth—a list that spans locally destructive fires and floods to the global reach of asteroid impacts—is volcanic activity, the consequences of which extend across broad spatial and temporal scales (Cassidy and Mani 2022; Cassidy 2025). A regionally devastating asteroid impact would involve an object larger than 140 m in diameter—a size that collides with Earth on average every few tens of thousands of years (National Research Council 2010; National Academies of Sciences, Engineering, and Medicine 2022). An equivalent-sized volcanic eruption would rate a 7 on the Volcano Explosivity Index (VEI; Newhall and Self 1982) and has a global recurrence that is at least an order of magnitude more frequent—every few hundred to 1000 years (National Academies of Sciences, Engineering, and Medicine 2017; Newhall et al. 2018). Smaller VEI-5 eruptions occur every few years and can have climate impacts with the potential to trigger droughts that lead to famine (Haywood et al. 2013; Cassidy 2025). Even small volcanic events (< VEI-3) that are essentially instantaneous can be destructive, as demonstrated by minor but fatal eruptions at Mount Ontake, Japan (2014; Yamaoka et al. 2016), Fuego volcano, Guatemala (2018; Albino et al. 2020), Whakaari/White Island, New Zealand (2019; Dempsey et al. 2020), and Semeru volcano, Indonesia (2021; Suhendro et al. 2025). Small- to moderate-sized eruptions in the twentieth century, like those of Mount Pelée, Martinique, and Nevado del Ruiz, Colombia, had death tolls in the tens of thousands (Auker et al. 2013). The threat from volcanoes is all the more striking given that over a billion people worldwide live within 100 km of a volcano that has erupted at least once in the Holocene, since about 11,700 years ago (Freire et al. 2019). A built-in advantage for mitigating volcanic hazards, however, is that eruptions can often be anticipated by monitoring data.

Despite the frequency and effects of volcanic eruptions, there has been relatively less global investment in volcano surveillance compared to other hazards (Cassidy and Mani 2022). As of the mid-2010s, only about 35% of the roughly 500 historically active volcanoes worldwide were monitored by ground-based networks of instruments (Brown et al. 2015), even though a key component to forecasting eruptions involves collection and modeling of monitoring data (Sparks et al 2012; National Academies of Sciences, Engineering, and Medicine 2017; Poland and Anderson 2020). The lack of monitoring disproportionately affects developing countries, which is also where the vast majority of injuries and fatalities from volcanic eruptions occur (Sparks et al. 2012; Cassidy 2025).

Fortunately, a comprehensive and global monitoring system for subaerial volcanoes already exists—the constellation of Earth-observing satellites that track weather conditions, landscape evolution, and environmental change. Since the 1960s and 1970s, when Earth-observing satellite data began to become available, space-based remote sensing has detected unrest or eruptions at over 400 volcanoes worldwide (Pritchard et al. 2022). The variety of spatial, spectral, and temporal resolutions provided by current satellite platforms facilitates a deeper understanding of the volcanic processes that pose hazards to people and infrastructure. Although the impactful hazards from submarine volcanoes are difficult to monitor from space (e.g., Maeno 2025), satellite remote sensing provides nearly comprehensive views of all stages of an eruption cycle at subaerial volcanoes, with abilities to characterize ground deformation, topographic and surface cover changes, gas emissions, thermal anomalies, and ash plumes (Pyle et al. 2013; Poland et al. 2020).

Since 2014, the Committee on Earth Observing Satellites (CEOS)—an international consortium of about 60 agencies dedicated to coordinating acquisition of, and access to, comprehensive Earth observation data—has invested in satellite volcano surveillance from space, with national space agencies making available large volumes of traditionally inaccessible satellite imagery over hazardous volcanoes worldwide (Fig. 1). The specific focus of these efforts has been on high-resolution synthetic aperture radar (SAR) and optical imagery, like that from the TerraSAR-X, COSMO-SkyMed, and Pleiades satellite systems, which often require specific funding or proposal submissions. These satellite data are particularly well suited for characterizing recent volcanic deposits, mapping topography, and quantifying centimeter-scale surface displacements. The combination of high-resolution SAR and optical datasets with freely available moderate- and low-resolution satellite images (like those from Sentinel-1 SAR and a variety of optical and multispectral sensors) and partial to fully commercial satellite data (like RADARSAT-2) purchased through government contracts provides an especially comprehensive suite of monitoring tools.

The payoffs from this largely voluntary effort are significant and include: (1) aiding local volcano monitoring agencies in their operations, (2) identifying new phenomena that can be used to forecast future eruptions, (3) stimulating fundamental research into how volcanoes work, and (4) supporting responses to hazardous volcanic activity. In 2024, the effort transitioned from regional and time-limited to a permanent, global, and sustainable program of volcano surveillance, capacity building, and hazards response that aligns with the United Nations' Early Warnings for All (EW4All) initiative (https://earlywarningsforall.org/), which targets the development of life-saving early warning systems related to hazardous natural events for everyone on Earth by the end of 2027 (Tupper and Fearnley 2023). Although global volcano surveillance and eruption response may lack resources, as is the case with many natural hazard monitoring programs, the CEOS efforts demonstrate the payoff of even limited efforts to make satellite data over volcanoes more available, enabling users worldwide to exploit those data for societal benefit.

Satellite data and volcano surveillance

Although utilization of satellite imagery of volcanoes began in the 1960s, space-based remote sensing was only incorporated into operational monitoring by volcano observatories beginning in the late 1980s, aiding in the detection of eruptions even in the absence of ground-based monitoring (e.g., Schneider and Rose 1994; Schneider et al. 1995, 2000; Cameron et al. 2018; Coombs et al. 2024). Modern space-based volcano monitoring includes imaging SO_2 plumes using ultraviolet and infrared remote sensing datasets (Fig. 2A) that are available at sub-daily intervals over most volcanoes

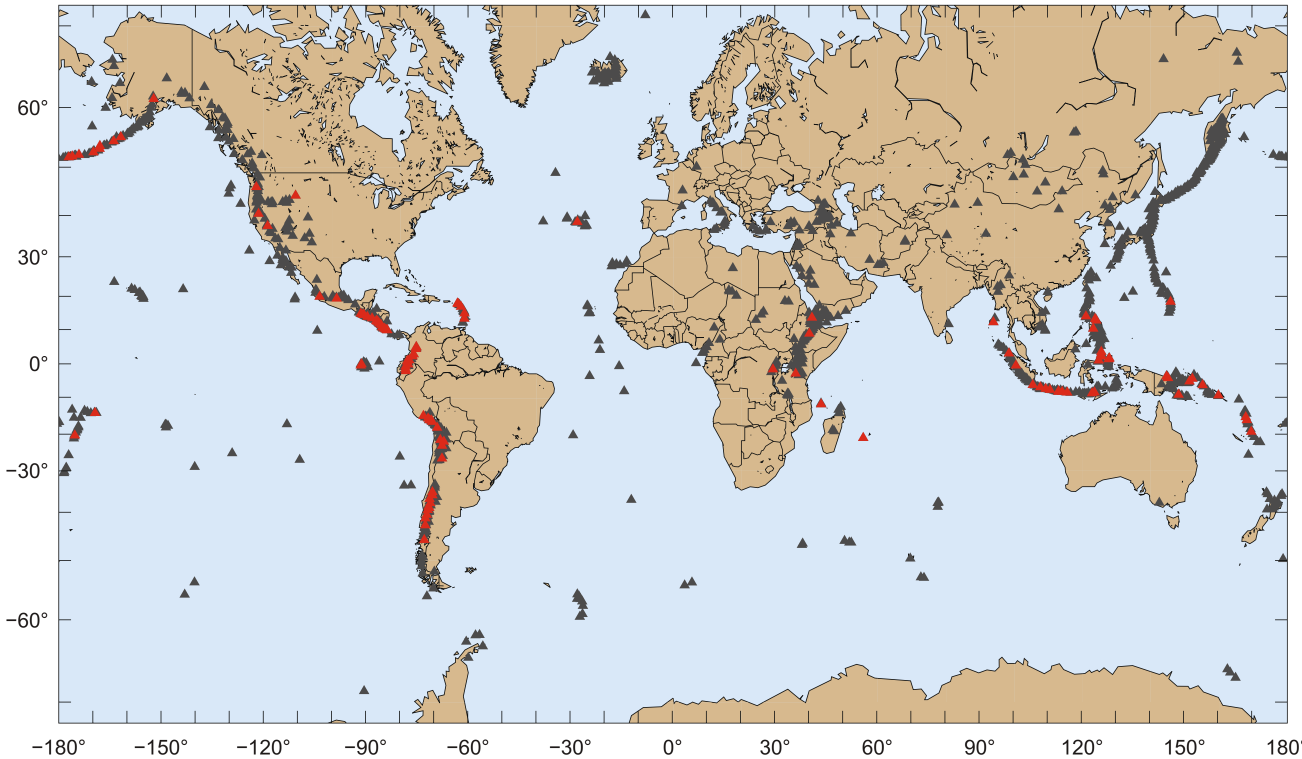

Fig. 1 Map of worldwide volcanoes that are known to have been active in the Holocene (Global Volcanism Program 2025) in black, with red indicating those volcanoes studied and(or) tasked by Committee on Earth Observing Satellites (CEOS) volcano projects (Pilot, Demonstrator, and GVEWERS), including those discussed by Pritchard et al. (2018) and Galetto et al. (2024)

on Earth, thereby providing a means of recognizing gas emissions that might be associated with, or a precursor to, volcanic eruptions (Carn et al. 2017; Theys et al. 2019). Infrared imagery (Fig. 2B) has proven important for not only identifying volcanic activity but also characterizing eruption rates and even providing warnings of future activity based on increases in thermal emissions (Ramsey et al. 2022). These data are used operationally for detecting eruptions around the world (Wright et al. 2004; Wright 2016; Coppola et al. 2016, 2020). Likewise, low-latency multispectral data from a variety of sensors, including those located on meteorological satellites, can provide timely detection of ash plumes (Fig. 2C) that may be hazardous to aviation (e.g., Pavolonis et al. 2015; Mastin et al. 2022; Coombs et al. 2018, 2024). Such imagery is used in combination with other datasets by volcano observatories and Volcanic Ash Advisory Centers to inform civil authorities, aviation agencies, and the public of potential hazards, and to set alert levels (e.g., Barsotti et al. 2024).

Less commonly incorporated into operational volcano monitoring are SAR and high-resolution optical imagery, usually because these datasets are poorly accessible and often require advanced and time-consuming analysis before they can be interpreted robustly. When available in a timely manner, however, the benefits of these resources are clear. Perhaps the best such example is from the 2010 eruption of Merapi volcano, Indonesia, when near-real-time interpretation of high-resolution SAR amplitude data identified high rates of lava dome growth that, along with ground-based monitoring, suggested the potential for an unusually large explosive event. The consequent evacuations probably saved thousands of lives (Pallister et al. 2013). Used in combination, coherence and amplitude data from SAR systems offer a means of mapping new volcanic deposits in hazardous or inaccessible areas (e.g., Poland 2022). SAR data can also be used interferometrically (InSAR) to assess surface deformation (Fig. 2D), which can reveal the characteristics of subsurface magmatic systems and has shown a strong association with eruptive activity (Biggs et al. 2014).

In 2012, the International Forum on Satellite Earth Observation and Geohazards brought together Earth observation and geologic hazards specialists from around the world to the island of Santorini, Greece, to define the satellite data needed by the geohazards community to aid with risk assessment. The resulting "Santorini Report" (Bally 2013) discussed a number of hazards, with recommendations specific to volcanoes including (1) daily satellite monitoring of erupting volcanoes, (2) weekly monitoring of restless volcanoes, and (3) baseline monitoring of quiescent volcanoes. In contrast to many other hazards, like earthquakes and

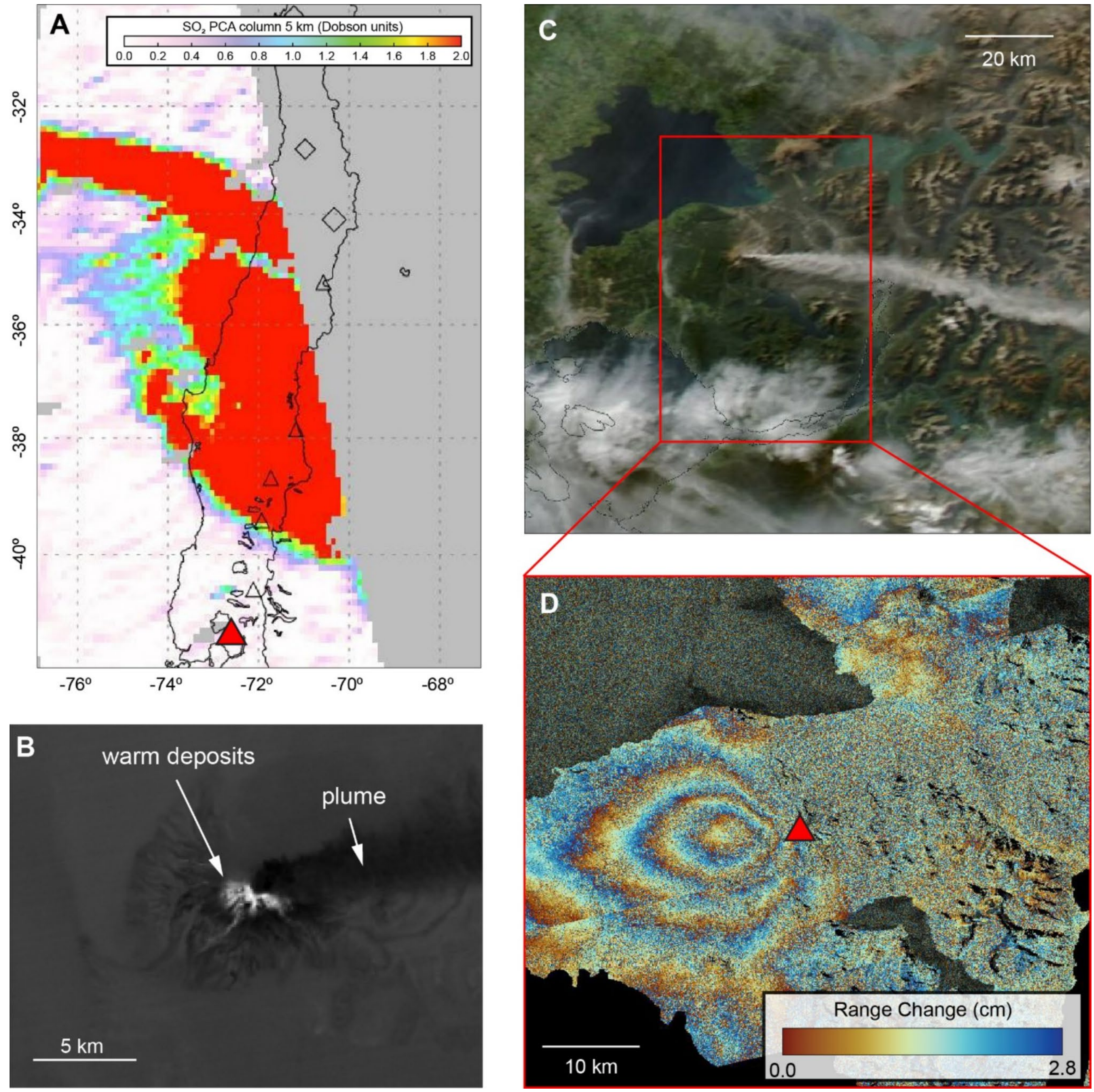

Fig. 2 Satellite views of the April 2015 eruption of Calbuco volcano, Chile. **A** SO_2 column density at 5 km altitude over central Chile on 23 April 2015, measured by the Ozone Monitoring Instrument (PCA, principal component analysis). Calbuco volcano is indicated by the red triangle. By the time these data were collected, the SO_2 plume had detached from the volcano. **B** Thermal infrared image from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument (band 13) on 26 April 2015, zoomed to the area of Calbuco volcano. Light areas indicate warm temperatures and dark areas indicate cooler temperatures. **C** Moderate Resolution Imaging Spectroradiometer (MODIS) true-color image (bands 1, 4, and 3) showing plume emanating from Calbuco volcano on 24 April 2015. **D** Sentinel-1A interferogram showing deflation that occurred coincident with the eruption of Calbuco volcano (red triangle); image spans 14–26 April 2015. Dark regions are water and therefore incoherent. Area covered by image indicated by red box in part C

wildfires, volcanic eruptions are often preceded by measurable unrest in the form of seismicity, ground deformation, gas and thermal emissions, hydrological changes, and other indicators. Detecting and tracking these different forms of unrest can provide a basis for accurate forecasts of eruptions and their hazards and constitutes an early warning system for volcanic activity (e.g., Sparks et al. 2012; National Academies of Sciences, Engineering, and Medicine 2017; Poland and

Anderson 2020). Volcanic hazards are also distinctively dynamic, and satellite monitoring during eruptions can be crucial for forecasting their development and duration (Poland et al. 2020).

Thanks to the growing number of Earth-observing satellites, particularly those with primarily meteorological applications and high-temporal, but low-spatial, resolutions, many of the goals of the Santorini Report with respect to volcanoes have been met (Fig. 3)—for example, daily monitoring of gas and thermal emissions from space is a reality (Wright 2016; Theys et al. 2017; Coppola et al. 2020; Pritchard et al. 2022). SAR observations are also becoming more accessible due to open data from missions like Sentinel-1 and NISAR (Biggs and Wright 2020; Poland and Zebker 2022; Biggs et al. 2026), enabling quasi-weekly measurements at the C and L wavelength bands. Similarly, global topography missions, like the Shuttle Radar Topography Mission (Farr et al. 2007) and TanDEM-X (Kubanek et al. 2021), provide baseline topographic information for nearly all volcanoes on Earth. Lagging behind, however, are high-spatial-resolution SAR and optical datasets that are capable of recognizing ground deformation and major topographic changes that may evolve rapidly or be spatially localized and not easily detectable by moderate-spatial-resolution sensors. Even though high-resolution data can be acquired at time scales that would approach the goals of the Santorini Report, data collection is often sporadic, and imagery is not widely available to volcanologists at the low latencies needed for volcano monitoring. Exploitation of high-resolution SAR and optical datasets is therefore a special focus of volcano remote sensing work sponsored by CEOS.

The CEOS volcano satellite observation program

The importance of satellite data in disaster risk management has been formally acknowledged by both scientific and social-political groups for decades. Since 1999, the International Charter: Space and Major Disasters (Stryker and Jones 2009) has made the satellite resources of over a dozen national space agencies and several commercial satellite operators immediately available for rapid disaster response. The Charter provides a unified system of space data acquisition and delivery to those affected by disasters, although only a few of the 50 or so Charter activations each year are related to volcanoes (https://disasterscharter.org/)—much less than the 60–80 volcanoes that erupt each year (Global Volcanism Program 2025). The Geohazards Supersites and National Laboratories project was initiated in 2008 and formalized in 2012, establishing areas of hazardous natural events as sites of intense study using all available resources, including satellite data (e.g., Poland et al. 2025). The 2012 Santorini conference advocated for global monitoring of geohazards using remote sensing (Bally 2013), and in 2015, the Sendai Framework for Disaster Risk Reduction 2015–2030 emphasized satellite data as a tool for natural hazards preparation and response (UNISDR 2015).

To spur investment from space agencies in disaster prevention and preparation, CEOS established the Working Group on Disasters in 2013. One of the first actions taken by the new working group was to implement three thematic pilots in 2014, focusing on volcanoes, earthquakes, and floods. The goals of these pilot projects were to explore and showcase the value of satellite Earth observations in all aspects of disaster risk management, as well as to link data producers and end users in a sustainable strategy for responding to natural hazards. Although satellite Earth observations span visible, thermal, ultraviolet, and microwave spectra, the Working Group on Disasters emphasized those datasets that were usually not freely available—particularly high-resolution synthetic aperture radar (SAR) and optical imagery. The initial Volcano Pilot project evolved into a larger Demonstrator program and finally to a permanent, sustainable, and global effort to support volcano monitoring and eruption responses using space-based data. This effort meets the goals of the EW4All initiative (Bonadonna et al. 2025) and the Santorini Report (Fig. 3; Bally 2013; Pritchard et al. 2022). In addition, CEOS volcano projects address many of the Sustainable Development Goals adopted by United Nations Member States in 2015 (https://sdgs.un.org/)—particularly goal 17, which emphasizes strengthening the transfer of science and

Fig. 3 Volcano-monitoring goals established by the "Santorini Report" (Bally 2013). Symbols indicate extent to which goals have been met, with "✓" indicating goals that have been achieved, "~" indicating partial (~50%) achievement, and "X" indicating little achievement (~10%)

Strategy for use of satellite data to monitor volcanoes

Global systematic background observations (~1500 Holocene volcanoes)	Weekly observations at volcanoes showing unrest (~100–200 volcanoes per year)	Daily observations at erupting volcanoes (~60–80 volcanoes per year)
✓ ground deformation ✓ topography ✓ temperature ✓ gas emissions	X ground deformation ~ topography ✓ temperature ✓ gas emissions ✓ ash emissions	X ground deformation X topography ✓ temperature ✓ gas emissions ✓ ash emissions

technology to build capacity (e.g., Senger 2024). Finally, CEOS volcano projects have materially contributed to training and growth of scientists, supporting many dozens of early career researchers, including undergraduate, masters, and doctoral students and postdocs, from institutions around the world.

Volcano Pilot project (2014–2017)

The Volcano Pilot was a 3-year effort intended to showcase the benefits of open access to satellite data by focusing on volcanoes in Latin America, from Mexico to Chile and including the Lesser Antilles (Fig. 4). The region was chosen because: (1) it includes about 319 volcanoes that have been active in the Holocene, over half of which are unmonitored by ground-based sensors; (2) the volcanoes are located in a diversity of environments and are characterized by varied styles of unrest and eruptive activity; (3) eruptions in the region are frequent and often impact local residents and regional air travel; and (4) local volcano observatories have a strong need for access to satellite data (Pritchard et al. 2018).

Pilot project aims were to (1) assess the feasibility of integrated, systematic, and sustained monitoring of Holocene volcanoes using space-based observations as described in the 2012 Santorini report (Bally 2013); (2) showcase the applicability and timeliness of space-based observations to the operational community (including volcano observatories and Volcanic Ash Advisory Centers) for better understanding volcanic activity and reducing the impact of eruptions; and (3) build the capacity for use of space-based data at volcano observatories where the uptake of remote sensing data has traditionally been limited.

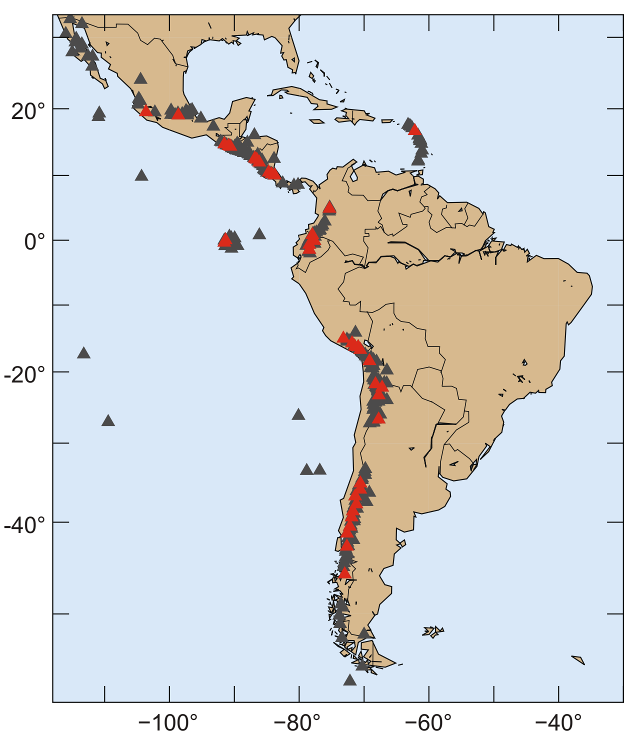

Fig. 4 Holocene volcanoes (Global Volcanism Program 2025) in Latin America, including the Caribbean Sea, in black, with those studied as part of the Committee on Earth Observing Satellites (CEOS) Volcano Pilot project shown in red. Adapted from Pritchard et al. (2018)

Numerous successes demonstrate how the Volcano Pilot met these aims. For example, aseismic deformation was recognized in InSAR data spanning 2012–2015 at Cordón Caulle volcano, Chile—activity that would not otherwise have been known due to a lack of ground-based monitoring and that prompted the installation of several continuous global navigation satellite system (GNSS) stations in the region (Delgado et al. 2016; Euillades et al. 2017; Pritchard et al. 2018). Interferograms and InSAR time series using data from multiple satellites were key to characterizing a previously unknown magma storage area beneath Masaya volcano, Nicaragua (Stephens and Wauthier 2018, 2022). InSAR data also proved critical for interpreting deformation and seismicity at Chiles–Cerro Negro volcanic complex, on the Colombia–Ecuador border, and aided in the determination of the volcano alert level there (Ebmeier et al. 2016; Pritchard et al. 2018). In addition to focusing on specific volcanoes, satellite data were used to research volcanic processes and develop analysis tools and scientific insights that could be applied globally. Specifically, multi-satellite thermal, degassing, and deformation time series provided a means to assess the behavior of open-conduit versus closed-conduit volcanoes (Reath et al. 2019) and contributed to the development of conceptual models of volcanic unrest as an aid in eruption forecasting (Reath et al. 2020). In addition, approaches for mitigating atmospheric artifacts using global weather models, simple statistics, and deep learning were designed and tested using data from Masaya volcano (Stephens et al. 2020; Sun et al. 2020). Capacity-building efforts included short courses and visits to observatories by scientists with expertise in InSAR and other satellite datasets (Pritchard et al. 2018). The Pilot project established that coordinating between multiple space agencies could result in near-daily SAR acquisitions during volcanic crises, and that flexibility in acquisition plans, low latency, and systematic background observations were important to prepare for future episodes of volcanic unrest and eruptions (Pritchard et al. 2018, 2026).

Volcano Demonstrator project (2019–2023)

The success of the Volcano Pilot project encouraged CEOS to expand the effort into a 3-year demonstrator project (extended by an additional year due to delays caused by the COVID-19 pandemic) that sought to work with volcano observatories in Latin America, Africa, and Southeast Asia. The three regions are collectively home to about 735 volcanoes that have been active in the Holocene (Fig. 5; Galetto et al. 2024). The project also increased the number of both data specialists and end users, with a focus on volcanoes in developing nations. In addition to providing support for monitoring and eruption response, the Volcano Demonstrator highlighted the importance of sustained, integrated, and international volcano remote sensing for disaster risk management. The specific goals of the Volcano Demonstrator were to (1) fill gaps in global volcano monitoring where satellite observations were not being fully exploited, in particular through facilitating access to high-resolution SAR and optical imagery; (2) improve understanding of specific volcanoes to aid forecasting and risk reduction in the target regions by supporting research using satellite imagery; (3) characterize links between satellite detection and magmatic processes by contributing to global datasets of volcanic satellite measurements of volcanic unrest and eruption; (4) coordinate tasking and data analysis of the international constellation of satellites to aid with crisis responses, particularly by studying ways in which observation strategies can be optimized to exploit the unique advantages of different types of sensors; and (5) build capacity in processing and interpreting satellite imagery at volcano observatories in developing nations.

Like the Pilot project, the Volcano Demonstrator contributed to responses associated with several episodes of volcanic unrest and eruption. For example, interferograms from high-resolution X-band SAR sensors detected rapid and localized surface motion on the flank of Merapi volcano in late 2020—deformation that was not well understood from ground-based monitoring and that preceded the onset of dome-building in early 2021. This information was incorporated into assessments of the possible course of future activity by Balai Penyelidikan dan Pengembangan Teknologi Kebencanaan Geologi, the volcano observatory in Indonesia that is responsible for monitoring Merapi volcano (Poland and Zebker 2022; Galárraga et al. 2026). High-resolution SAR amplitude data also documented dome growth at La Soufrière, St. Vincent, from December 2020 until the dome's destruction during a major explosive eruption on 9 April 2021, contributing to data available to the University of the West Indies Seismic Research Centre, Trinidad, to support decision-making. Subsequent analysis of those data identified a sudden increase in dome extrusion rate that preceded the onset of the eruption's explosive phase by 2 days (Dualeh et al. 2023)—a research result that provides motivation for low-latency delivery and analysis of high-resolution SAR during eruptions.

Several requests for data spanning episodes of unrest and eruption during the Volcano Demonstrator period were

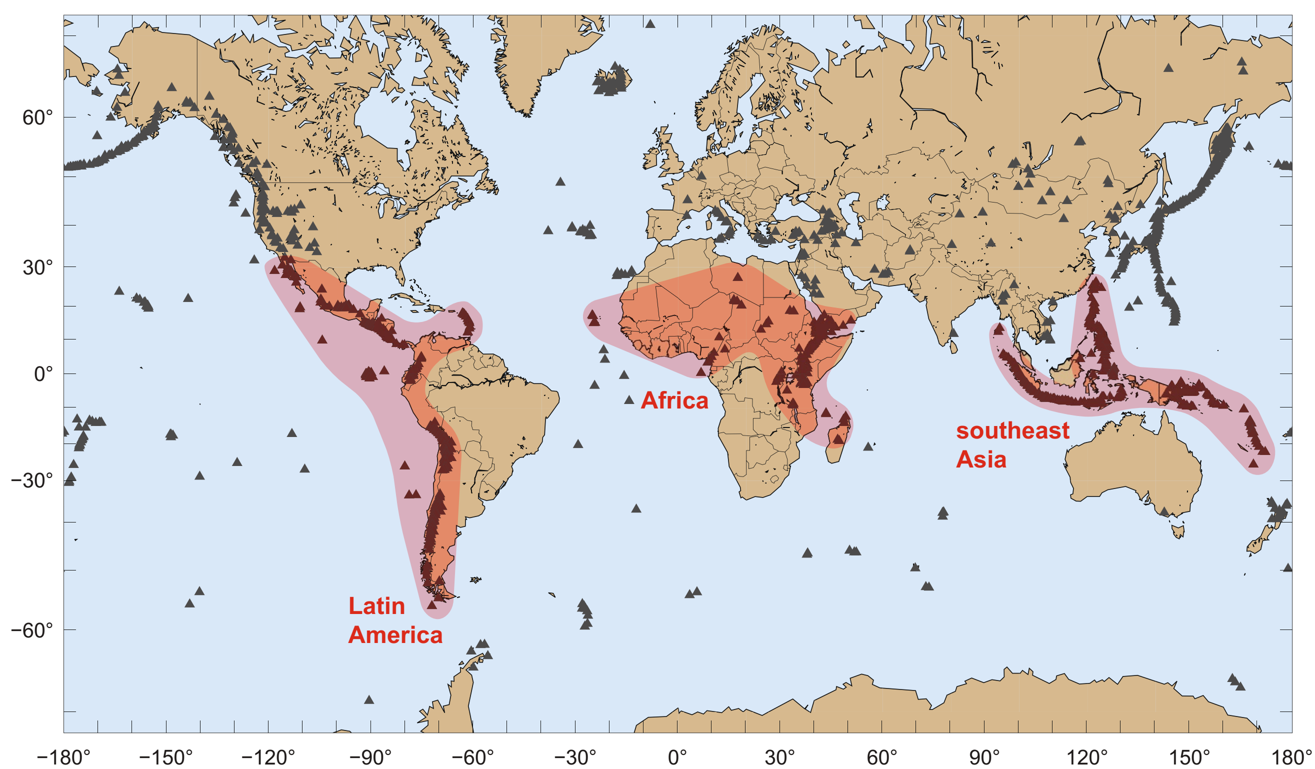

Fig. 5 Map of worldwide Holocene volcanoes (Global Volcanism Program 2025) in black, with red-shaded regions indicating areas covered by the Committee on Earth Observing Satellites (CEOS) Volcano Demonstrator project

motivated by the higher spatial and temporal resolution of X-band SAR datasets (especially TerraSAR-X and COSMO-SkyMed). For example, 48 COSMO-SkyMed images captured 85 days of the 2021 Tajogaite eruption on La Palma, Canary Islands, and were used by local scientists and their collaborators to map lava flow inundation and inform eruption response (Muñoz et al. 2022). In addition, SAR amplitude data captured morphological changes taking place near the eruptive vents (e.g., Walter et al. 2023) that were impossible to observe by other means. Amplitude images also contributed to resolving the December 2018 collapse sequence at Anak Krakatau, Indonesia (Hunt et al. 2021), mapping island morphology following the 2022 Hunga, Tonga, eruption, and identifying changes at the crater of Ambae, Vanuatu, during its eruptive activity in 2021–2023 (Galetto et al. 2024).

Operational use of SAR data for volcano monitoring was implemented in several countries in Latin America, including Colombia, Ecuador, Chile, and Peru. Significant activity captured by these efforts included continued unrest at Chiles–Cerro Negro volcanic complex, as well as periods of unrest and eruption at Sangay volcano, Ecuador, and Nevados de Chillán, Chile. In the southeast Asia region, TerraSAR-X imagery spanning 2019–2022 provided views of deformation at Ambrym caldera, Vanuatu, and COSMO-SkyMed amplitude images were employed to map changes in lava dome and flow activity at Sinabung volcano, Indonesia, in 2021. Work in Africa was complicated by the lack of official institutions dedicated to volcano surveillance in many countries, limitations on travel and in-person workshops imposed by the COVID-19 pandemic, and some restrictions on data acquired over conflict zones. In addition, there were few episodes of volcanic eruption or unrest during the period of the Demonstrator in Africa, but support was provided in response to the 2021 eruption of Nyiragongo volcano, Democratic Republic of the Congo (e.g., Poland 2022; Smittarello et al. 2022), to 2017–2019 lava flow activity at Erta Ale, Ethiopia (Gosling et al. 2026), and to 2021–2022 seismicity and uplift at Karthala, Comoros.

The Demonstrator phase also supported research into past volcanic activity, for example, by providing access to archive high-resolution COSMO-SkyMed and TerraSAR-X imagery that captured localized deformation preceding the 2017 eruption of Mount Agung, Indonesia (Bemelmans et al. 2023), and contributing to multi-sensor studies of trapdoor faulting at Sierra Negra volcano, Galápagos (Shreve and Deldago 2023; LaFemina et al. 2025), and flank instability at Pacaya volcano, Guatemala (Gonzalez-Santana and Wauthier 2021; Gonzalez-Santana et al. 2022).

Concurrent with the Volcano Demonstrator, the U.S. Geological Survey (USGS) Powell Center for Analysis and Synthesis convened a Volcano Remote Sensing Working Group. This effort, which involved an international team of scientists with expertise in volcano satellite data, laid out priorities and best practices for global space-based volcano monitoring, including the acquisition of different data types, data accessibility and distribution, and collaboration and capacity building (Pritchard et al. 2022). The group established a classification scheme for all subaerial volcanoes that have been active in the Holocene, as well as older volcanoes with observed unrest, to guide a data acquisition strategy—particularly important for prioritizing the allocation of limited satellite resources (Pritchard et al. 2022). The Center for Observation and modeling of Earthquakes, Volcanoes and Tectonics (COMET) in the UK adopted the group's categorization to set processing priorities for data collected over volcanoes by the Sentinel-1 satellite system. Biggs et al. (2026) updated this classification by taking into account volcanoes that had recently erupted or had their first detection of unrest, as well as those that had entered phases of quiescence; they estimate that Sentinel-1 data have been used in peer-reviewed studies for 90 out of the 233 subaerial volcanoes classified as a high priority for monitoring. Sentinel-1 and high-resolution X-band SAR data have proven to be exceptionally complementary, often capturing different volcanic processes at the same volcano (e.g., Bemelmans et al. 2023; Walter et al. 2023).

GVEWERS (2024–present)

Following the success of the Volcano Pilot and Demonstrator projects, in 2024 CEOS approved the implementation of the Global Volcano Early Warning and Eruption Response from Space (GVEWERS) initiative. GVEWERS is intended to implement the vision for volcano monitoring that has been repeatedly articulated since the 2012 Santorini conference (Bally 2013; Biggs and Wright 2020; Pritchard et al. 2022; Poland and Zebker 2022). The project aims to provide eruption response and early warning capabilities worldwide with an emphasis on high-resolution SAR and optical satellite data, while also exploring the use of those data in combination with other widely available satellite imagery, including freely available moderate- to low-resolution visible, infrared, and SAR acquisitions. The effort includes no dedicated funding but has secured commitments from several CEOS agencies to provide free access to satellite datasets that are normally restricted or only available for purchase. Data delivery is to users who have established license agreements with individual space agencies (evaluated by the agencies on a case-by-case basis), and distribution and use of derived products, like InSAR displacement maps, is allowed for scientific dissemination and non-commercial purposes in agreement with the intellectual property rights stated in the licenses. GVEWERS is managed on a voluntary basis as a community project with leadership drawn from volcano-monitoring agencies and academia, and the group seeks and accepts input on satellite tasking and data needs from scientists dedicated to volcano monitoring and hazards mitigation worldwide. Previous coordination of volcano monitoring with satellites has been inconsistent, largely driven by short-term efforts related to funded initiatives and without space agency support. GVEWERS aims to establish a permanent organizational framework for space-based volcano surveillance on a global scale by linking satellite data users and providers. In its first 2 years, GVEWERS has expanded the number of volcanoes covered from those addressed by the Volcano Pilot and Demonstrator efforts (Fig. 1). Monitoring priorities follow the guidelines established by Pritchard et al. (2022): frequently to continuously active hazardous volcanoes are targeted for imaging on a daily basis; restless and/or less-hazardous erupting volcanoes are monitored on a weekly basis; and low-hazard quiescent volcanoes are examined on a quarterly to annual basis.

The work of GVEWERS is especially important in settings where local capacity for satellite imagery tasking and analysis is limited, and where new unrest or eruptive activity occurs in areas that lack sufficient ground-based monitoring. To address these gaps, the initiative applies the latest methods and understanding from remote sensing research to volcano monitoring and early warning of eruptions around the world, especially at volcanoes that have not historically been the subject of intensive study. Critical for this goal are the vast archives of past data that can be exploited to better understand the behavior of restless and erupting volcanoes over time. These archives can be used to identify previously unknown signals and processes that may be important to forecasting future hazardous eruptions, as exemplified by focused studies of ground deformation that identified magmatic activity and flank instability processes at Pacaya volcano (Gonzalez-Santana and Wauthier 2021; Gonzalez-Santana et al. 2022), Anak Krakatau (Kim et al. 2024), and Ol Doinyo Lengai volcano, Tanzania (Wauthier and Ho 2024), and by overall exploration of volcano acquisitions collected by the TerraSAR-X, TanDEM-X, and PAZ satellites (Galetto et al. 2024). Further, GVEWERS continues to offer training opportunities in the utilization and interpretation of remote sensing data, especially from high-resolution SAR and optical sensors. These capacity-building and response-preparedness efforts enhance the use and utility of those data for volcanic eruption early warning and response—a critical need for areas with populations and infrastructure that are at risk from volcanic hazards. With these goals, GVEWERS aligns with the EW4All initiative and Sustainable Development Goals of the United Nations (Tupper and Fearnley 2023; Senger 2024; Bonadonna et al. 2025).

Following practices established during the Pilot and Demonstrator, GVEWERS will continue to collaborate closely with the U.S. Geological Survey Volcano Disaster Assistance Program (VDAP), which aims to assist local scientists and managers in responding to volcano emergencies globally and to conduct response-preparedness projects to strengthen volcano monitoring and response (Pallister 2015). The collaboration between GVEWERS and VDAP is mutually beneficial because GVEWERS can provide data and interpretations that would not otherwise be available, and VDAP has the experience necessary to effectively use those insights to support hazards responses even in challenging environments and social-political situations, and also has access to partial and fully commercial data. Collaboration between GVEWERS and COMET also supports global volcano monitoring and eruption response. This partnership has already achieved important success, for instance, providing satellite data spanning repeated magmatic intrusions near Fentale and Dofen volcanoes, Ethiopia, during 2024–2025 described in open-access Event Response Reports (https://comet.nerc.ac.uk/event-response-reports/; Way et al. 2025).

Lessons from a decade of CEOS volcano projects

Satellite imagery is a key component of volcano monitoring, contributing to timely notifications of eruptions that may threaten populations, infrastructure, and air traffic. This is particularly true for low- to moderate-resolution optical, infrared, and ultraviolet data that form the basis for eruption detection and warning systems (e.g., Cameron et al. 2018; Coombs et al. 2018, 2024), like MODVOLC (Wright 2016) and MIROVA (Coppola et al. 2020). High-resolution SAR and optical imagery, however, have often been used as an after-the-fact research tool, despite their potential for contributing to eruption early warning, recognition, and monitoring (Biggs and Wright 2020). The Volcano Pilot, Volcano Demonstrator, and GVEWERS projects, along with numerous complementary efforts, have focused on how these datasets, especially, can contribute to volcano monitoring. Over a decade of intensive efforts has resulted in a number of lessons about their use in responses to volcanic unrest and eruptions.

Support for ground-based monitoring

As stated at the outset of this article, relatively few volcanoes on Earth—less than half—are instrumented by continuous ground-based sensors (Brown et al. 2015). Resources needed to install and maintain equipment like seismometers and GNSS stations are often limited, and conditions on the ground may be unsafe. Space-based datasets can provide insights on which volcanoes most warrant attention and where any monitoring stations may best be located, thereby aiding efficient allocation of resources and enhancing safety for volcano scientists. As an example, campaign and continuous GNSS stations were established at Laguna del Maule, Chile, in response to satellite-detected deformation (Fournier et al. 2010; Feigl et al. 2014; Le Mével et al. 2021). Similarly, satellite observations of ground deformation at Aluto volcano, Ethiopia (Biggs et al. 2011), led to the deployment of a temporary seismic network that detected > 2000 earthquakes within the first 2 years (Wilks et al. 2017). Space-based data can also provide a check on whether ground-based instruments are properly functioning. For instance, InSAR results from post-eruptive periods at Calbuco and Guallatiri, Chile volcanoes, confirmed that ground-based instruments were not working correctly (Pritchard et al. 2018).

Support for responses and volcano alert level determinations

Worldwide, there are over 100 volcano observatories and institutions tasked with providing data in support of volcanic hazards assessment and mitigation (Jolly 2015; Lowenstern et al. 2022). Low-latency data from high-resolution SAR and optical satellite sensors provide additional support when these agencies respond to episodes of volcanic unrest and eruption, particularly with respect to communicating potential public safety impacts. For example, if a strong earthquake or a swarm of small seismic events occurs near a volcano, does the activity reflect a tectonic process, or is it an initial sign of an impending eruption? Even if some ground-based monitoring is present, those data may be conflicting or ambiguous. Satellite remote sensing can often provide a more comprehensive perspective. Data from the Volcano Pilot project were critical in determining that earthquake swarms at several volcanoes—Momotombo (Nicaragua) and Chiles-Cerro Negro volcanic complex, for example—were not associated with magma accumulation, contributing to decisions not to increase the volcano alert level (Pritchard et al. 2018) or to reduce the alert level (Ebmeier et al. 2016). Conversely, satellite data showed that the distal seismic swarm at Mount Agung in 2017 was caused by a magmatic intrusion, which was uncertain from the somewhat ambiguous ground-based data alone (Albino et al. 2019). Data from GVEWERS were communicated to Ethiopian scientists during the 2024–2025 seismic crises in the area of Fentale and Dofen volcanoes (Fig. 6)—essential information for developing a hazards map that helped guide the actions of emergency managers in evacuating local populations (Lewi et al. 2025; Way et al. 2025). These examples demonstrate how high-resolution satellite data are a vital tool for local volcanologists who are responsible for determining the appropriate response to possible volcanic unrest.

The benefit of large data archives

Over many volcanoes, large archives of high-resolution SAR data extend back 10–15 years, enabling comprehensive research into surface deformation over time that can guide future monitoring and forecasting efforts (e.g., Galetto et al. 2024). For example, Wauthier and Ho (2024) examined multiple SAR datasets to identify previously unknown long-term subsidence at Ol Doinyo Lengai volcano and used a high-resolution COSMO-SkyMed interferogram to model shallow magma storage beneath the volcano. An analysis of 12 years of data from Anak Krakatau collected by three SAR satellite systems revealed variable motion of up to meters per year on a detachment fault underlying the volcano's southwest flank—motion that accelerated significantly just prior to the volcano's 22 December 2018 collapse, which caused a tsunami that resulted in 437 deaths (Kim et al. 2024). The fact that detachment fault motion can be detected on a small island with high-spatiotemporal resolution InSAR points to an important monitoring tool for anticipating catastrophic volcano collapse events.

Not all volcanic events can be forecast with satellite data

Although forecasting hazardous volcanic events is a primary goal of volcanology and one of the main motivations for the CEOS volcano projects, forecasts are not possible in all situations. For instance, the deadly phreatic explosion at Whakaari/White Island, New Zealand, was not immediately preceded by significant deformation or other changes detectable by satellite (Hamling and Kilgour 2021). It might be expected that sudden lava flow collapses and phreatic activity would lack precursory warning signs on actionable timespans, but it is also true that significant magmatic eruptions are not always preceded by buildups in pressure that are measurable at the surface. For example, no surface deformation was detected by InSAR in the years before the 22 April 2015 VEI-4 eruption at Calbuco volcano (Fig. 2)—a volcano that is considered to be a closed-conduit system that is likely to support pressurization (Delgado et al. 2017; Reath et al. 2019). Increasingly, volatile overpressure caused by second boiling is considered as a mechanism for eruptions (e.g., Cassidy et al. 2019), and this may trigger activity over timescales that are too short to be reliably detected via satellite. Latency is a persistent issue with remote sensing data that are used for hazards response (Pritchard et al. 2022), although this is improving over time, with many low-resolution datasets available within minutes of acquisition and some high-resolution SAR and optical datasets available within hours. While remote sensing can clearly provide support for anticipating many

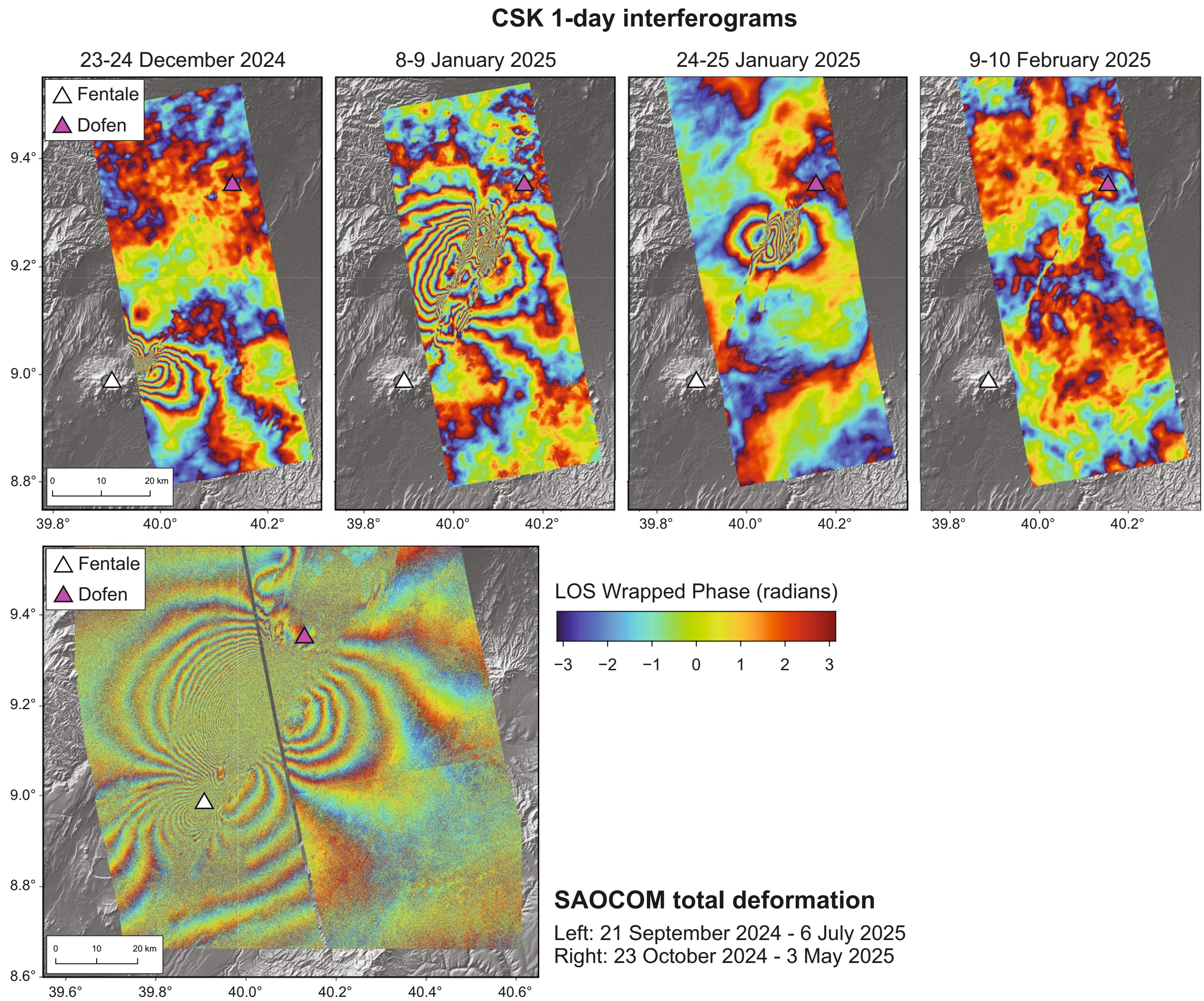

Fig. 6 Top four panels are a series of one-day interferograms acquired by COSMO-SkyMed showing line-of-sight (LOS) deformation due to dike emplacement in the area of Fentale (white triangle) and Dofen (magenta triangle) volcanoes, Ethiopia, in late 2024 and early 2025. Bottom interferograms are from SAOCOM and depict deformation spanning the entirety of the intrusive activity, which was caused by the emplacement of multiple dikes reaching up to 50 km in length. data—©CONAE–COMISION Modified from Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonics Event Response Report 1.5 (https://comet.nerc.ac.uk/event-response-reports/) by W. Zheng, University of Bristol. Product processed by University of Bristol under a license of the Italian Space Agency (ASI); original COSMO-SkyMed Product—©ASI—2024–2025. Product produced from Original SAOCOM NACIONAL DE ACTIVIDADES ESPACIALES (2024–2025)

styles of volcanic activity across a range of timescales, no monitoring system is a panacea, and satellite monitoring is not a replacement for ground-based instrumentation at volcanoes that pose a high threat to local populations and air traffic (Pritchard et al. 2022).

High-spatial resolution is vital

With freely available SAR data provided by Sentinel-1 and NISAR, it may seem that there is little need for other more restricted SAR datasets. Results from high-resolution X-band sensors, like TerraSAR-X/TanDEM-X/PAZ (Galetto et al. 2024) and COMSO-SkyMed (e.g., Kim et al. 2024), and L-band sensors like SAOCOM (Delgado et al. 2024), however, provide evidence to the contrary. At Mount Agung, many centimeters of uplift occurred within the volcano's crater, which is only 900 m across, prior to its 2017 eruption. The rate of deformation increased days to hours before the onset of phreatomagmatic eruptive activity in November 2017. The deformation was obvious in COSMO-SkyMed and TerraSAR-X interferograms, but less apparent in Sentinel-1 interferograms (Bemelmans et al. 2023). Likewise, complex patterns of ground deformation were identified by high-resolution X-band InSAR within about 1.5 km of a lava lake vent at Masaya volcano in 2012—deformation that was limited in terms of its spatial and temporal extent (Stephens and Wauthier 2017). These and numerous other examples demonstrate that surface displacements at volcanoes often are highly localized and occur over short time periods, resulting in deformation that could easily be overlooked by large-scale surveys using moderate-resolution InSAR data (Pritchard et al. 2018, 2022). New commercial SAR data, like the X-band ICEYE satellite system, offer both exceptional spatial resolution (pixel sizes on the order of tens of centimeters) and rapid repeat observations (as little as one day), expanding the scope of volcano deformation and surface change phenomena that can be detected and monitored (e.g., Hjartardóttir et al. 2023; Sigmundsson et al. 2024).

Updated topographic data are vital

Topography is a fundamental geological dataset and is especially applicable to volcanoes. Not only does high-resolution topography facilitate hazards forecasting, but changes in topography can also be used to derive eruption volumes and rates—critical information for hazards assessment (Kubanek et al. 2021). Although qualitative topographic information can be derived from SAR amplitude data and used to support timely monitoring (e.g., Pallister et al. 2013), quantitative topographic data are much more informative (e.g., Dualeh et al. 2023). These data can be calculated from SAR imagery in multiple ways, including by (1) generating interferograms from SAR scenes acquired at different times from similar viewing angles and assuming no net surface deformation in the intervening period (repeat-pass, or monostatic, interferometry; Bürgmann et al. 2000); (2) generating interferograms from two SAR scenes acquired at the same time by two sensors with slightly different viewing angles (single-pass, or bistatic, interferometry; Kubanek et al. 2021); and (3) using topographic errors in repeat-pass interferograms, also assuming no deformation in the time spanned by the images, to determine topographic change since acquisition of the reference digital elevation model (Ebmeier et al. 2012). Bistatic data are most useful in volcanology because they are not compromised by incoherence and work well even in heavily vegetated areas. For example, it was possible to determine the volume of pyroclastic density currents from the 3 June 2018 eruption of Fuego volcano using bistatic TanDEM-X data, despite the rainforest environment (Albino et al. 2020). These data also demonstrated that the flow was predominantly composed of material that had gravitationally collapsed from a location close to the vent. The eroded material increased the volume of the flow (bulking) and probably caused the run-out distance to be larger than previous eruptions during 1999–2017. Topography can also be derived from optical stereo imagery—for instance, from the Pléiades and Worldview satellite systems. Optical images may be compromised by cloud cover but are capable of higher spatial resolution than SAR (e.g., Moussallam et al. 2021; Eiden et al. 2025; Galetto et al. 2025b). Used in combination, SAR and stereo optical imagery provide a powerful means of tracking volcanic activity over time, as demonstrated by Grémion et al. (2023) for dome building at Merapi volcano during 2018–2019, and by Galetto et al. (2025a) for eruptions at Raung volcano, Indonesia, in 2014–2015 and 2021.

SAR data provide more than just deformation and topography

SAR data are most commonly associated with monitoring surface deformation and topography, but the data can also be used to track the emplacement of volcanic deposits. High-resolution X-band amplitude data were important for characterizing changes in the morphology of Bogoslof volcano, in the Aleutian Islands of Alaska—a site of persistent cloud cover—during eruptive activity in 2016–2017 (Fig. 7; Coombs et al. 2019; Poland et al. 2020). Changes in backscatter characteristics and shadow regions in SAR amplitude images can be used to map the extent and thickness of pyroclastic density currents, for example, as demonstrated by Dualeh et al. (2021) at Fuego volcano. Progressive co-eruptive changes in the shapes and extents of shadow regions provide quantitative information about lava dome growth, as documented at La Soufrière in 2021 (Dualeh et al. 2023), and also lava flow thickness, as shown at Reventador volcano, Ecuador (Arnold et al. 2017, 2019). SAR amplitude also offers information on changes in the extent and morphology glacial ice that may be related to volcanic activity, for instance, during eruptive activity at Cotopaxi volcano, Ecuador, in 2015 (Arnold et al. 2018). These approaches can be developed into operational tools to aid volcano observatories in comprehensively mapping the impacts of volcanic events without risking the safety of field personnel and regardless of weather conditions. As an example, coherence between SAR images can be used to track the emplacement of volcanic deposits, especially when combined with cross-polarized amplitude imagery (Poland 2022)—a product referred to as a SAR Volcanic Flow Map and that can be used to map lahars, pyroclastic density currents, and lava flows (Fig. 8).

Multi-sensor fusion achieves high-spatiotemporal resolution over long time spans

There is no one-size-fits-all SAR dataset; rather, comprehensive analyses using data from a variety of sensors

Fig. 7 High-resolution COSMO-SkyMed SAR amplitude images of Bogoslof volcano, Alaska, spanning its 2016–2017 eruption. Morphological changes in the island over time are easy to track and were useful for assessing the consequences of individual volcanic events, exposure of the vent area to the ocean, extrusion of lava domes, and other processes. Product processed by U.S. Geological Survey under a license of the Italian Space Agency (ASI); original COSMO-SkyMed Product—©ASI—2016–2017

can achieve near-daily observations and contribute to extensive time series of observations (Pritchard et al. 2026). For example, SAR data from four different satellite systems spanning wavelengths and spatial resolutions provided decadal-scale perspectives on changes in the characteristics of flank creep at Pacaya volcano (Gonzalez-Santana et al. 2022) and sustained uplift at Corbetti Caldera, Ethiopia (Lloyd et al. 2018). When possible, merging SAR and high-resolution optical datasets can provide powerful insights into volcanic activity. Delgado et al. (2019) combined time-lapse topographic information, which was derived from both TanDEM-X and Pléiades, with InSAR to build a time series of deformation and lava effusion at Cordón Caulle that was used to model magma storage and transport conditions. Eiden et al. (2025) extended this approach to include thermal satellite data, allowing them to develop a model of how magma supply impacts deformation and lava effusion at Nevados de Chillán—insights that would not be possible in the absence of spaceborne high-resolution SAR and optical datasets.

If you build it, they will come

The "lessons" above were largely already understood to be possible prior to the Volcano Pilot, Volcano Demonstrator, and GVEWERS projects. The CEOS volcano projects, however, highlighted how these lessons can aid operational volcano monitoring worldwide. Still, the work above was coordinated largely by academic scientists or in developed nations with extensive capacity to support such work. Would the same data and approaches be useful to volcano observatories in developing countries, where there is greater need to support hazards assessment and operational monitoring? The answer has been a resounding "yes." In Latin America, where the CEOS volcano projects have been active for the longest period of time, volcano observatories

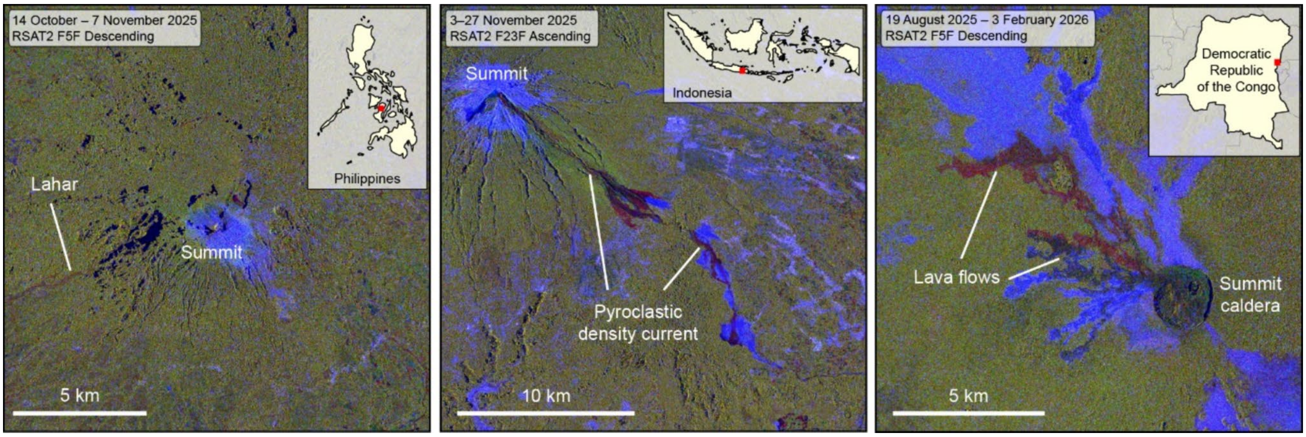

Fig. 8 Synthetic aperture radar volcanic flow maps constructed from cross-polarized amplitude data from different dates (as the red and green channels) and coherence spanning those dates (as the blue channel) acquired by RADARSAT-2. Maps show a lahar at Kanlaon volcano, Philippines (left); pyroclastic density currents at Semeru volcano, Indonesia (center); and lava flows at Nyamulagira volcano, Democratic Republic of the Congo (right). Barren areas are blue, vegetated areas are yellow/green, and volcanic deposits emplaced during the time spanned are red where covering forest and dark where covering unvegetated areas. Dates spanned, imaging geometry, and beam mode are given in the upper left of each image

in Colombia, Ecuador, Chile, and Peru evolved from minimal use of satellite datasets to developing operational capacities for ongoing monitoring, especially of long-term eruptions like those at Nevado del Ruiz (Colombia), Sangay, and Sabancaya (Pritchard et al. 2018, 2022). In addition, many other countries are taking concrete steps, like training students and initiating international collaborations, to develop the capacity to exploit these datasets—for example, Indonesia and Ethiopia (e.g., Grémion et al. 2023; Lewi et al. 2025). The message is clear: space agency commitments to making satellite data more accessible result in more uptake of those data and their use in identifying and responding to volcanic hazards in developing nations. Investing in data availability pays off.

Building on past successes

Concrete progress has been made towards the volcano-specific goals of the 2012 Santorini report (Fig. 3; Bally 2013), primarily in terms of the frequency of volcano observations from space using data spanning the electromagnetic spectrum. Although the utilization of high-resolution SAR and optical data has lagged that of meteorological and moderate-resolution optical/infrared/ultraviolet sensors, there have still been significant advances towards meeting some of the primary goals laid out by Pritchard et al. (2022) with respect to satellite observations of volcanoes. Many of these aims are being met due to work enabled by the CEOS volcano projects, particularly related to the global coordination of acquisitions, rapid distribution of open data, and capacity building, all of which support volcano hazards assessment and mitigation.

There of course remains room for improvement in utilization of remote sensing data for volcano monitoring and eruption early warning. First, not all national space agencies are contributing to fulfilling the vision laid out by the CEOS volcano projects. This is understandable, given the commitment of resources that is necessary to engage with volcano hazards in addition to other applications, like climate, resource, and infrastructure monitoring. The CEOS volcano projects have showcased the benefit of diverse SAR and optical datasets for volcano monitoring and hazards mitigation, demonstrating excellent uptake of such imagery when it is made available. With the emphasis on hazards awareness, monitoring, warning, and response provided by global efforts like EW4All, opportunities continue to emerge for new agencies to contribute to the overall effort. The examples and experiences above demonstrate that additional satellite data are not redundant, even if they offer similar spatial–temporal resolutions or wavelengths as existing data; rather, each dataset offers important capabilities that, especially when merged, can offer exceptional benefit to society.

Second, there is no dedicated funding to support the work of the CEOS volcano projects. Most of the operational efforts are made possible by in-kind contributions of data, as well as resources for processing and interpreting those data, from volcano monitoring institutions and space agencies, and much of the work is shouldered by academic researchers with short-term grants. Long-term institutional efforts, like those of COMET and VDAP, demonstrate the benefits of sustained focus on volcano monitoring and capacity building, and collaboration with those and similar initiatives, including EW4All, are critical for maintaining the momentum and progress of the CEOS volcano projects and ensuring the stability of GVEWERS.

Third, continued capacity building could ensure additional uptake of volcano remote sensing data across the globe. Past experience indicates that capacity-building efforts are best done using a variety of approaches in combination, including the training of students, site visits, development of international collaborations, and topical workshops that are held both in host countries and in conjunction with related scientific conferences, like those sponsored by the International Association of Volcanology and Chemistry of the Earth's Interior (Pritchard et al. 2022). Easy connectivity thanks to video conferencing tools provides a ready way to link volcano observatories and academic scientists so that capacity building and sharing of expertise can be a continuous process, rather than a series of sporadic and unconnected events. Consistent and constructive communication between and among volcano observatories, academic researchers, and space agencies could facilitate coordination of efforts and build a culture of scientific diplomacy that has the potential to save lives, as it did during the 2010 eruption of Merapi volcano (Pallister et al. 2013; Pallister 2015).

Fourth, transitioning data analysis tools from development to implementation could best exploit the large quantities of available imagery. Great progress has already been made in using machine learning approaches to detect anomalies in InSAR data (Anantrasirichai et al. 2018, 2019; Sun et al. 2020; Gaddes et al. 2018, 2019, 2024; Biggs et al. 2022; Dualeh and Biggs 2025; Popescu et al. 2025; Paladino et al. 2026). Some of these tools are already deployed operationally in academic settings but have yet to be widely adopted by volcano observatories. The need for operational data analysis tools extends beyond just recognizing deformation in interferograms. Developing capabilities to rapidly and quantitatively analyze optical and SAR amplitude images could greatly expand the potential of these datasets in volcano monitoring and eruption response (e.g., Gosling et al. 2026). For example, the method for assessing lava dome growth from SAR amplitude images demonstrated at La Soufrière by Dualeh et al. (2023) could be a critical operational tool for timely detection of changes in ongoing eruptions, aiding rapid assessments of volcanic hazards and providing early warning that saves lives.

Conclusions

Volcanic eruptions are a clear hazard to global society but often receive less attention than other threats despite operating on timescales that are much closer to human lifespans and with consequences that can be devastating even from small events. The geosciences community has long recognized the importance of enhanced uptake of satellite remote sensing for volcano surveillance and hazards mitigation. Ground-based monitoring of all threatening volcanoes on Earth is impractical from both logistical and financial perspectives, but a suite of effective volcano-monitoring tools already exists in the form of satellite data. Some datasets, like thermal, multispectral, and ultraviolet imagery, are already openly available, acquired on daily or sub-daily intervals, and used operationally to detect eruptions and their impacts. High-resolution SAR and optical imagery, however, have yet to be robustly incorporated into timely volcano monitoring.

Since 2014, the Committee on Earth Observing Satellites has sponsored a series of volcano projects defined by collaborations between space agencies, academic scientists, and state volcano observatories that aimed to showcase how satellite data—high-resolution SAR and optical imagery in particular—could contribute to global endeavors to assess and mitigate volcanic hazards. These efforts have highlighted the benefits of free and open access to these data and provided a blueprint for their use in volcanology, leading to the GVEWERS (Global Volcano Early Warning and Eruption Response from Space) initiative—a comprehensive and sustainable effort to utilize satellite data to make society safer in the face of growing populations threatened by volcanic activity. While there are still opportunities for better application of satellite data to volcano monitoring, particularly with regard to data availability and exploitation, funding, capacity building, and development of analysis tools, the goals laid out by foundational geohazards visions like the 2012 Santorini report and 2015 Sendai Framework for Disaster Risk Reduction are within reach. With continued interest and investment, monitoring systems that utilize high-resolution SAR and optical datasets may ultimately be used on the same timescales as ground-based datasets like seismology, helping to further the evolution of remote sensing from a research tool to an integrated component of operational volcano monitoring and eruption early warning systems.

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Data Availability All satellite data are available from the source space agencies through signed license agreements. More information is available from https://ceos.org/ourwork/workinggroups/disasters/wgdisasters-activities/volcanoes/.

Declarations

Disclaimer Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Competing interests The authors declare no competing interests.

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