Bulletin of Volcanology (2022) 84: 10
https://doi.org/10.1007/s00445-021-01512-w

PERSPECTIVES

Strengthening local volcano observatories through global collaborations

Jacob B. Lowenstern[1] · John W. Ewert[1] · Andrew B. Lockhart[1]

Received: 7 July 2021 / Accepted: 25 October 2021 / Published online: 21 December 2021

Abstract
We consider the future of volcano observatories in a world where new satellite technologies and global data initiatives have greatly expanded over the last two decades. Observatories remain the critical tie between the decision-making authorities and monitoring data. In the coming decade, the global scientific community needs to continue to collaborate in a manner that will strengthen volcano observatories while building those databases and scientific models that allow us to improve forecasts of eruptions and mitigate their impacts. Observatories in turn need to contribute data to allow these international collaborations to prosper.

Keywords Volcano observatory · Volcanic hazards · Collaboration · Future · Assistance · Volcanology

Introduction

Volcano observatories[1] represent the intersection between volcano science and public safety. Though many of the key advances in volcanology emerge from universities and government research laboratories, the impact on society occurs when observatories use those advances to improve forecasts and to protect citizens. Moreover, the most critical advances occur during unrest and eruptions, when observations made with ever more and diverse in situ and remote techniques can be used to develop better models, test hypotheses, and improve forecasts. Observatories play a critical role in making those observations, while also serving as conduits for timely science information to communities near volcanoes as well as to a curious and concerned public (Lowenstern and Ewert 2020).

Over the past 20 years, most observatories have changed how they collect and analyze data, and report information to the public. Specifically, digital data and telemetry (including cellular) have replaced the earlier (and cheaper) analog radios. Satellites increasingly collect critical datasets. Social media provides a less formal, but direct means for messaging about hazards, but with the challenge that other groups and individuals with diverse motivations compete for the ear of the public. In the future, it is clear that techniques utilized during responses to volcanic activity will evolve, as surveillance by satellites becomes ever more widespread, and databases accumulate global volcano information that can inform local forecasts. As global data and remote monitoring expands, how will this progress impact the contract between volcano observatories and the communities they serve? This brief paper considers the history of volcano observatories, their current status, and their future role in disaster-risk reduction.

A very short history of volcano observatories

At the present time, forty-two countries with active volcanoes have one or more volcano observatories conducting various types of systematic observations (Table 1). The first official observatory was created at Vesuvius in 1841 in

Editorial responsibility: J.H. Fink

This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

✉ Jacob B. Lowenstern
jlwnstrn@usgs.gov

1 U.S. Geological Survey, Cascades Volcano Observatory, 1300 SE Cardinal Court, Vancouver, WA 98683, USA

[1] A volcano observatory is an entity or institution responsible for monitoring activity at a volcano (or volcanoes) with the goal of understanding volcanic processes and hazards and communicating information relevant to volcanic status and hazards.

response to the ~ 9-year-long eruption that began that year. Geological surveys, university professors, and professional societies added to volcano science throughout the nineteenth century, mostly by making detailed observations of volcanic phenomena at volcano hotspots in Italy, Indonesia, Japan, and the Caribbean. Over an approximately 6-month period in 1902, the eruptions of Mont Pelée, Martinique, Soufrière St. Vincent, and Santa Maria, Guatemala, captured the world's attention with sudden and horrifically large loss of human life by mechanisms mysterious and misunderstood by the scientific community and the public. These eruptions, and others in the first 20 years of the twentieth century, spurred the development of long-term, place-based systematic observation and research at volcano observatories and geological mapping of young, but non-erupting, volcanic systems (Tilling et al. 2014). The founding of the first observatories at Vesuvius, Kīlauea, Asama, and Mont Pelée was by academic institutions, and nearly all scientific effort in volcanology was devoted to observing, analyzing, characterizing, and cataloging volcanic phenomena with the greatest emphasis given to developing the ability to accurately predict eruptions and develop engineered mitigation strategies.

The large and deadly eruption of Kelut volcano Java, Indonesia, in 1919 (over 5000 fatalities), was the catalyst to form the Netherlands East India Volcanological Survey, which later became the Volcanological Survey of Indonesia (VSI). VSI was the first national-scale volcanological service by which all volcanoes in a country were studied and kept under observation. VSI's mission was to study how the population near volcanoes could be protected from eruptions. This would be accomplished by: "(1) studying the type of the volcano (*Classification*[2]); (2) finding out a possibility to predict an eruption (*Forecasting*); (3) investigating the menaced regions (*Hazard and risk mapping*); (4) developing a system to warn and evacuate the population of these regions (*Public warning and communication*); and (5) trying to reduce the effect of an eruption (*Engineering mitigation measures*)." (Neumann van Padang 1983). In time, many more volcano observatories would be established, often in response to deadly eruptions, in other countries. The mission profile developed by VSI endures as the *modus operandi* of most current volcano observatories.

Diverse administration and organization of volcano observatories

Today, most volcano observatories are established as governmental institutions, often collaboratively with academic institutions, but with the majority of operational support coming from national governments. Some have an entirely operational mission, whereas others are tasked also with research and scientific understanding. It is a challenge to count the number of existing volcano observatories because many are tied to national research centers. For example, there are 77 observatories in Indonesia alone, bolstered by a large roving staff based in Bandung at CVGHM headquarters (institution abbreviations spelled out in Table 1). Only a few employees may work at the volcano observatory full-time. PHIVOLCS (Philippines) has a similar setup, but for only six volcanoes. Italy monitors about a dozen volcanoes from two primary observatories (Vesuviano and Etneo), with additional support from other INGV offices. The U.S. Geological Survey (USGS) operates 5 volcano observatories, though one of them is entirely virtual and without an onsite office (the Yellowstone Volcano Observatory). Japan's volcano warnings are issued by JMA, the meteorological service, but at least a dozen government organizations and universities contribute to monitoring, assessment and research. The observatories in Ecuador, Costa Rica, and the Caribbean are run by universities that adhere to agreements with civil-defense agencies. Table 1 lists our compilation of the observatories for the world's volcanically active countries.

Priorities and capabilities of volcano observatories

As with the initial five goals of the VSI from 100 years ago, volcano observatories still focus on a wide range of activities. In those countries that are most volcanically active, workflow often revolves around VSI's item #4: monitoring systems and public warnings, combined with #2: forecasting. Figure 1 illustrates how the observatory collects data from disparate sources and distributes value-added information and assessments to stakeholders such as municipal and national authorities, the private sector, aviation community, media, and public. Messaging may occur via official alerts such as VANs (Volcano Activity Notice) and VONAs (Volcano Observatory Notice for Aviation), as well as via websites, social media, apps, press conferences, interviews, and many other means. Different observatories have vastly different capabilities, however—not only in terms of their monitoring networks, but also their ability to put out messages, and in their readiness to incorporate outside data and collaborations. Some observatories in 2021 have no Internet presence, no official social media accounts, and only minimal infrastructure to collect and distribute data. Nevertheless, they may still have governmental responsibility, active liaisons with civil defense, and considerable local experience and credibility responding to volcanic unrest. In some cases, observatories have advanced infrastructure, but their capabilities are challenged by administrative turnover, loss of staff to opportunities elsewhere, poor funding, or changing responsibilities due to competition with other governmental

[2] Italics denote the authors interpretation of the original activities based on contemporary definitions.

Table 1 Volcano observatories of the world by country/region

Country	Organization(s)	Website*	# of facilities	Comments
Antarctica	U.S. National Science Foundation Spanish Instituto Geográfico Nacional	https://www.nmt.edu/research/organizations/erebus.php	2	NSF facility at McMurdo Station IGN facility at Deception Island
Argentina	Observatorio Argentino de Vigilancia Volcánica (OAVV)	https://oavv.segemar.gob.ar/	2	Buenos Aires and Neuquen
Cameroon	Institut de Recherches Géologiques et Minières (IRGM)	https://www.irgm-cameroun.org	1	Observatory semi-active
Canada	Natural Resources Canada (NRCAN)	https://chis.nrcan.gc.ca/volcano-volcan/index-en.php	0	Responsible for response but minimal monitoring
Cape Verde Islands	Observatório Vulcanológico de Cabo Verde (OVCV), Departamento de Ciência e Tecnologia, Universidade de Cabo Verde (Uni-CV)	https://www.facebook.com/Observat%C3%B3rio-Vulcanol%C3%B3gico-de-Cabo-Verde-OVCV-175875102444250/about/	1	Only a FB page found
Chile	Servicio Nacional de Geología y Minería (SERNAGEOMIN)/ Southern Andes Volcano Observatory (OVDAS)	https://www.sernageomin.cl/red-nacional-de-vigilancia-volcanica/	1	Main observatory in Temuco with additional staff and monitoring in Santiago and regional SERNAGEOMIN offices
China	Chinese Earthquake Authority	https://www.volcano.ac.cn	6	
Colombia	Servicio Geológico Colombiano (SGC)	http://amenazas.sgc.gov.co/ovsm/	3	Observatories in Manizales, Pasto and Popayan
Comoros	Observatoire Volcanologique du Karthala (OVK) Centre National de Documentation et de la Recherche Scientifique des Comores	http://www.cndrs-comores.org/observatoires/ovk/	1	Observatory in Moroni, Grand Comore Isl
Costa Rica	Observatorio Vulcanológico y Sismológico de Costa Rica, Universidad Nacional (OVSICORI-UNA) Universidad Costa Rica-Red Sísmica Nacional y Observatorio Sismológico y Vulcanológico Arenal-Miravalles (OSIVAM)	http://www.ovsicori.una.ac.cr https://rsn.ucr.ac.cr/ https://rsn.ucr.ac.cr/actividad-sismica/ultimos-sismos/20-actividad-sismica/centros-de-regsitro/2-boletines-ova-osivam	2	Two separate observatory institutions. Both participate in the Comité Asesor Técnico en Vulcanología (CATv) as part of the Comisión Nacional de Prevención y Atención de Emergencias (CNE)
Dem. Republic of Congo	Goma Volcano Observatory	No public URL	1	No website. Equipment co-operated with European partners
Ecuador	Instituto Geofísico-Escuela Politécnica Nacional (IG-EPN)	https://www.igepn.edu.ec	1	Central observatory in Quito
El Salvador	Ministerio de Medio Ambiente y Recursos Naturales (MARN)	https://www.snet.gob.sv/	1	Central observatory in San Salvador
Ethiopia	Institute for Geophysics, Space Science and Astronomy (IGSSA) at Addis Ababa University Afar Rift Consortium (AFC)	http://www.aau.edu.et/igssa/academics/ http://www.see.leeds.ac.uk/afar/index.html	1	IGSSA operates the national seismic and geodetic networks. AFC is a UK university group with ties to Addis Ababa University
France	Institut de Physique du Globe de Paris (IPGP)	http://www.ipgp.fr/fr/observatoires-volcanologiques-sismologiques	3	Martinique, Guadalupe, Reunion

Table 1 (continued)

Country	Organization(s)	Website*	# of facilities	Comments
Greece	Aristotle University of Thessaloniki Institute for the study and monitoroing of the Santorini Volcano (ISMOSAV) Instsitute of Geodynamics, National Observatory of Athens	http://geophysics.geo.auth.gr/index_en.html https://www.santorini.net/ismosav/ http://www.gein.noa.gr/en/	3	No single institute or consortium appears to have authority for volcano monitoring and hazard mitigation in Greece. Additional responsibility for hazard mapping with IGME: https://www.igme.gr/index.php/en/
Guatemala	Instituto Nacional de Sismología, Vulcanología, Meteorología e Hidrología (INSIVUMEH)	https://insivumeh.gob.gt	4	Headquarters in Guatemala City. Small outposts at Pacaya, Fuego and Santiaguito
Iceland	Iceland Met Office (IMO)	https://en.vedur.is	1	Central observatory in Reykjavik
Indonesia	Pusat Vulkanologi dan Mitigasi Bencana Geologi (PVMBG) English: Centre of Volcanology and Geological Hazard Mitigation (CVGHM)	https://magma.vsi.esdm.go.id	77	Main Observatory in Bandung. Separate major facility in Jogyakarta for Merapi Volcano
Italy	Istituto Nazionale di Geofisica e Vulcanologia (INGV)	www.ingv.it	2	Two main obseratories for Etna and Vesuvius plus other volcanoes
Japan	Japan Meteorological Agency (JMA)	https://www.jma.go.jp/bosai/map.html#5/34.5/137/&contents=volcano&lang=en	4	JMA operates 4 regional Volcano Observatory and Information Centers (VOIC)
Mexico	Centro Nacional de Prevención de Desastres (CENAPRED) University of Colima Universidad de Ciencias y Artes de Chiapas (UNICACH)	https://www.gob.mx/cenapred https://portal.ucol.mx/cueiv/Sismico.htm https://monitoreo.unicach.mx/index.php?p=page&v=NA = =	3	Central observatory in Mexico City. CENAPRED partners with universities for Colima and El Chichón
Lesser Antilles (English-speaking)	University of the West Indies/Seismic Research Centre (UWI/SRC) Includes Montserrat Volcano Observatory	https://uwiseismic.com/ http://www.mvo.ms/	2	Headquarters in Trinidad. Staffed observatory also in Montserrat. Covers active volcanoes on Dominica, Grenada, Montserrat, St. Kitts, Nevis, St. Vincent and the Grenadines
Nicaragua	Instituto Nicaragüense de Estudios Territoriales (INETER)	https://web-geofisica.ineter.gob.ni/vol/dep-vol.html	1	Central observatory in Managua
New Zealand	GNS, Ltd	https://www.gns.cri.nz https://www.geonet.org.nz/	3	Major offices in Wellington, Wairakei, and Auckland
Panama	Instituto de Geociencias – Universidad de Panamá	https://www.panamaigc-up.com/	1	IG-UdP has authority for national seismic and volcano monitoring
Papua New Guinea	Rabaul Volcano Observatory	No public URL	5	Headquarters at Rabaul with observatory outposts at Karkar, Ulawun, Manam and Lamington
Peru	Instituto Geológico Minero y Metalúrgico (INGEMMET) Instituto Geofísico del Perú (IGP)	http://ovi.ingemmet.gob.pe/ https://www.igp.gob.pe/servicios/centro-vulcanologico-nacional	2	Two observatory institutions
Philippines	Philippine Institute of Volcanology and Seismology (PHIVOLCS)	https://www.phivolcs.dost.gov.ph/index.php/volcano-hazard/volcano-advisory	8	Central observatory in Manila

Table 1 (continued)

Country	Organization(s)	Website*	# of facilities	Comments
Portugal	Centro de Informacao e Vigilancia Sismovulcanica dos Acores (CIVISA)	http://www.ivar.azores.gov.pt/civisa/Paginas/homeCIVISA.aspx	1	Ponta Delgada, Azores
Russia	Kamchatka Volcanic Eruption Response Team (KVERT) Sakalin Volcanic Eruption Response Team (SVERT)	http://www.kscnet.ru/ivs/kvert/index?lang=en http://www.imgg.ru/en/	1	Kvert-Remote monitoring from Petropavlovsk-Kamchatsky SVERT-Remote monitoring of Kuril Islands volcanoes from Sakalin Island
Saudi Arabia	Saudi Geological Survey	https://sgs.org.sa/en	1	Headquarters in Jeddah
Solomon Islands	Seismology& Volcanology Network	https://www.mmere.gov.sb/index.php/alias-about-us/technical-divisions/geological-survey.html	1	Headquarters in Honiara
South Korea	KMA: Korean Meteorological Administration	https://web.kma.go.kr/eng/weather/kma_service/volcano.jsp	1	Headquarters in Seoul
Spain	Instituto Geográfico Nacional (IGN) INVOLCAN-ITER	https://www.ign.es/web/ign/portal/vlc-area-volcanologia www.involcan.org	2	IGN headquarters in Madrid with a field office on Tenerife; INVOLCAN-ITER office on Tenerife
Taiwan	Taiwan Volcano Observatory	http://dmip.tw/lfive/2017/	1	No current website.
Tanzania	Tanzania Volcano Observatory	tzvolcano.chordsrt.com/about	0	Monitoring through collaboration with US university partners
Turkey	Disaster and Emergency Management Authority (AFAD)	https://deprem.afad.gov.tr	1	AFAD is National Seismic Network
USA	United States Geological Survey (USGS)	https://volcanoes.usgs.gov	5	One of the five observatories is virtual (no building). Also monitors volcanoes of the Northern Mariana Islands
Vanuatu	Vanuatu Meteorology and Geohazards Department (VMGD)	https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/current-volcanic-activity	1	Regional Observatory in Port Vila

and private organizations. Despite apparently common goals, the fundamental characteristics, scope, resources, and products of volcano observatories are widely variable.

A changing landscape of eruption forecasting and volcano response

Potential external collaborators have two increasingly useful tools to help local observatories with volcano crises: remote sensing and global datasets. In addition to these assets, observatories can sometimes call upon assistance from other countries near and far.

Remote monitoring and assessments

Over the past two decades, an exciting yet daunting reality for all observatories is the advancement of technology and accumulation of knowledge, which make it simultaneously easier and harder to manage an eruption response. The most obvious change is the (literally) skyrocketing increase in satellite data that can be used to track deformation, gas output, thermal flux, and atmospheric ash dispersion, and surface change (Pritchard and Simons 2002; Reath et al. 2019; Poland et al. 2020). These satellite-collected data can provide rapid insights that often cannot be obtained from ground-based measurements due to clouds, hazards, expense, and other challenges. Satellite images combined with seismic data were critical to effecting evacuations that are credited with saving thousands of lives in 2010 at Merapi (Pallister et al. 2013). In 2020, low-latency, freely accessible Sentinel-1 InSAR data provided important insights to PHIVOLCS during a dike-fed eruption at Taal volcano (Bato et al. 2021), offering particularly valuable insights given that some ground-based monitoring was compromised by ash accumulation on solar panels.

Many volcanoes still have no nearby instrumentation, such that eruptions may be detected by infrasound or lightning networks hundreds or thousands of kilometers distant from the volcano, or by weather satellites before an alert has been issued by the pertinent volcano observatory.

The remote-monitoring equipment may be owned by other countries, and the data may be reduced and analyzed by workers half-way around the world. This complicates any workflow envisioned in Fig. 1. In particular, the public may receive information and analysis directly from a satellite working group unassociated with the volcano observatory. National space agencies may publicize images or data and disseminate simple assessments that might run counter to local knowledge and experience. Foreign scientists may be interviewed by news media based on their interpretation of the data. In our experience, most volcanologists defer to the local volcano observatory, and attempt to follow established guidelines (IAVCEI Subcommittee for Crisis Protocols et al. 1999, IAVCEI Task Group on Crisis Protocols et al. 2016; Pallister et al. 2019); however, if the volcano observatory has not released alerts or information statements, it becomes challenging for the volcanological community to mirror any local assessment.

Global datasets

In the above section, we briefly outlined how critical datasets are increasingly collected by groups that may or may not have a close connection to the observatory. Another key area requiring collaboration is the compilation, archiving, and distribution of global volcano data (e.g., WOVODAT: Costa et al. 2019; and the Global Volcanism Program 2013)

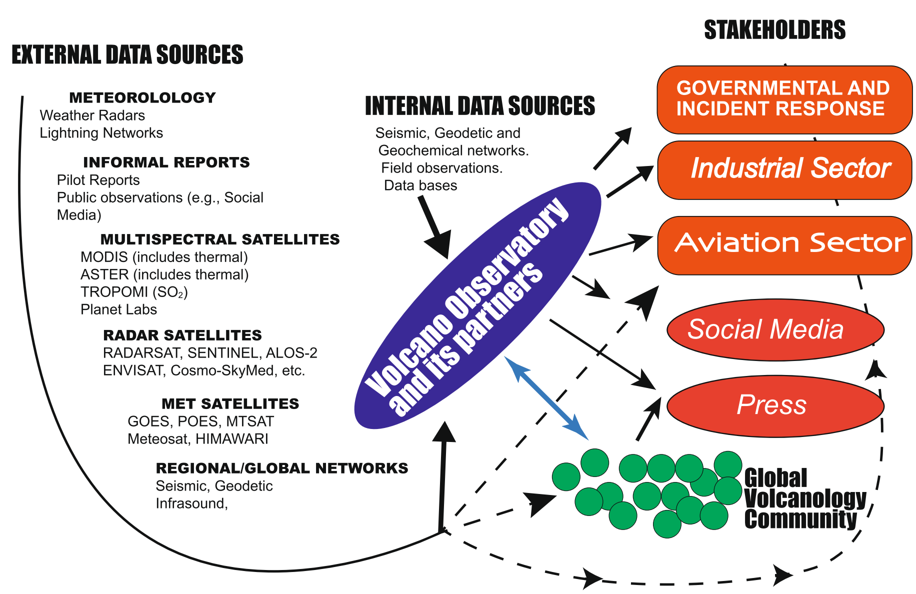

Fig. 1 A schematic for the complex manner by which information is distributed to the public and other stakeholders during volcanic unrest. Bold arrows represent preferred means of information flow, but it is apparent and inevitable that many stakeholders will receive information directly from external data sources or the global volcano community without vetting or interpretation by the observatory (dashed arrows). The blue two-way arrow represents the communication and collaboration between the observatory and other volcanologists

or regional data (e.g., GeoDIVA; DGGS Staff and Cameron 2004). These data are an important source of information that can be used by volcano observatories to aid in eruption forecasts. Crucial questions can be addressed, particularly when a volcano without historical activity becomes restless. The growth and utility of these databases in turn rely on integration of ground-based observational, geophysical and geochemical data originating from observatories around the world. Thus, ideally, all observatories would collaborate with the data-base compilers, and would offer timely, relevant data that has been vetted, and compiled in an accessible format. Clearly, this is a huge reach both for small observatories and for the databases that are operated by small staffs with non-permanent sources of funding. Some observatories with research staff may seek to protect their opportunity to publish the results of their work and will be unwilling to distribute the data to others. Others may want to avoid being judged for the quality of the data or the accuracy of their assessments or may not fully appreciate how observations from their volcanoes fit into a global context. For these reasons, there can be resistance to growth of these global resources. As an example, we have encountered volcano observatories that do not share data with the IRIS seismic database.

Regional support

Another recent change is the number of regional and international groups that exist to foster collaboration, communication, and research. In Europe, the FUTUREVOLC program was a 26-partner consortium focused on geologically active areas in Europe. In Latin America, ALVO supports countries by organizing meetings and facilitating workshops in Spanish. The INVOLC group seeks to support volcano observatories and volcano science in resourced-constrained nations, whereas the NSF-supported CONVERSE in the USA seeks enhanced cooperation between the academic community and volcano observatories during eruptions.

All of these groups aim to increase the amount of international collaboration between scientists and observatories, with the goal of broadening the capabilities and resources available to all. And overall, we think they hint at a future where volcano responses increasingly take advantage of expertise, models, computer systems, and data provided from sources beyond the local volcano observatory. Nevertheless, the observatory should and must remain the focal point for the response, given its ties, credibility, and indeed obligations to the local and national governments and populations, as well as its knowledge of landscape, volcano behavior, history, and culture.

Communicating risk to decision-makers

Ultimately, local and national authorities (together with scientists) must make critical decisions regarding evacuation and mobilization of resources. To do so, they need information stripped of scientific jargon, with clear scenarios and relative likelihoods (Mileti and Sorenson 1990). Creating scenarios and estimating probabilities (even if highly uncertain) requires collaboration among volcano scientists and communications experts (often social scientists). Moreover, the information must be provided within the context of local political, societal, and geographical realities. One critical protocol for CVGHM during the 2017 Mount Agung crisis was the numerous briefings with Hindu priests (the key local influencers) as part of socialization (Syahbana et al. 2019).

The role of social media has grown rapidly for the distribution of hazards information during crises. Increasingly, observatories use social media at the expense of more permanent and authoritative statements posted to observatory archives. Moreover, the public may not always recognize the authoritative source (or origin) of hazards observations within a blizzard of tweets and posts. This places more pressure on the global community to support the local observatory to prioritize accurate information. Yet, it also requires that the global community know and trust the local observatory.

Looking ahead and strengthening local volcano observatories through global collaboration

Whether we consider the natural environment or society, the only thing that is constant is change. We are in a time of rapid change—changing climate and changing societal norms that will require observatories to adapt. Climate change may eventually decrease the likelihood of primary lahars on now-glaciated volcanoes, but prolong non-eruptive lahar hazards owing to more intense rainfall events. Social media may continue to produce polarizing effects on societies and erode confidence in scientific authority. But access to broadband communications, cloud computing, and inexpensive data storage, coming with decreasing costs may enable observatories to develop more and closer ties with colleagues that are not co-located to aid in response to volcano crises and pursue collaborative research projects.

Volcano observatories, regardless of scale or experience, must consider how to provide the most useful information to decision makers. Often, this requires careful planning in anticipation of volcanic unrest (Pallister et al. 2019; Newhall et al. 2021; Lowenstern et al. 2021). It is important that external scientists and scientific groups contributing to a volcano crisis recognize the limitations of their understanding of local conditions, social structures, and priorities. They should be aware that their scientific viewpoint, data, and models may sometimes have limited applicability toward making timely decisions for public safety. In our view, the global volcano community needs to clarify how to best assist observatories during volcanic crises. At the same time, local observatories need to recognize that part of their success will depend upon their ability to integrate knowledge coming from afar. They need to plan not only for their interactions with local authorities, but also how they can collaborate and benefit from their colleagues abroad.

Acknowledgements We appreciate reviews by M. Poland and two anonymous reviewers for the journal. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Author contribution JL wrote the first draft and Fig. 1. JE researched most of Table 1, wrote the section on the history of volcano observatories, and had the concept for Fig. 1. AL discussed the initial concept and provided initial guidance and edited and amended the manuscript during all revisions.

Funding The authors are funded by the USGS Volcano Hazards Program and an Interagency Agreement with USAID.

Availability of data and material Not applicable for this section.

Code availability Not applicable for this section.

Declarations

Ethics approval and consent to participate Not applicable for this section.

Consent for publication Not applicable for this section.

Conflict of interest Not applicable for this section.

References

Bato MG, Lundgren P, Pinel V, Solidum R, Daag A, Cahulogan M (2021) The 2020 eruption and large lateral dike emplacement at Taal volcano, Philippines: insights from satellite radar data. Geophys Res Lett 48:e2021GL092803. https://doi.org/10.1029/2021GL092803

Costa F, Widiwijayanti C, Nang TZW, Fajiculay E, Espinosa-Ortega T, Newhall C (2019) WOVOdat – the global volcano unrest database aimed at improving eruption forecasts. Disaster Prev Manag 28(6):738–751. https://doi.org/10.1108/DPM-09-2019-0301

DGGS Staff, Cameron CE (2004) Alaska GeoSurvey News — the geologic database of information on volcanoes in Alaska (GEO-DIVA): a comprehensive and authoritative source for volcanic information. Alaska Div Geol Geophys Surv Newslett 2004:8. https://doi.org/10.14509/14592

Global Volcanism Program (2013) Volcanoes of the World, v. 4.10.0 (14 May 2021). In: Venzke E (ed) Smithsonian Institution. Downloaded 27 May 2021. https://doi.org/10.5479/si.GVP.VOTW4-2013

IAVCEI Subcommittee for Crisis Protocols, Newhall C, Aramaki S, Barberi F, Blong R, Calvache M, Cheminee J-L, Punongbayan R, Siebe C, Simkin T, Sparks RSJ, Tjetjep W (1999) Professional conduct of scientists during volcanic crises. Bull Volcanol 60:323–334

IAVCEI Task Group on Crisis Protocols, Giordano G, Bretton R, Calder E, Cas R, Gottsmann J, Lindsay J, Newhall C, Pallister J, Papale P, Rodriguez L (2016) Toward IAVCEI guideline on the roles and responsibilities of scientists involved in volcanic hazard evaluation, risk mitigation, and crisis response. Bull Volcanol 78(31):1–3

Lowenstern JB, Wallace K, Barsotti S, Sandri L, Stovall WK, Bernard B, Privitera E, Komorowski JC, Fournier N, Baligizi C, Gareabiti E (2021) Guidelines for volcano-crisis operations: recommendations from the 2019 Volcano Observatory Best Practices meeting. J Appl Volcanol (in press)

Lowenstern JB, Ewert JW (2020) Volcano observatories reduce risk around the globe Here's how we can support them. Temblor. https://doi.org/10.32858/temblor.085

Mileti DS, Sorensen JH (1990) Communication of emergency public warnings: a social science perspective and state-of-the-art assessment. Oak Ridge National Laboratory Report ORNL-6609 for the Federal Emergency Management Agency. https://doi.org/10.2172/6137387

Neumann van Padang M (1983) History of the volcanology in the former Netherlands East Indies. Scr Geol 71:1–76, 25 figs., 4 pls, enclosure, Leiden

Newhall C, Pallister JS, Miller DC (2021) A Checklist for Crisis Operations within Volcano Observatories, Volcanic Hazards, Risks and Disasters. In: Papale P (ed) Forecasting and Planning for Volcanic Hazards, Risks, and Disasters, Chapter 13. Elsevier. pp. 493–544. https://doi.org/10.1016/B978-0-12-818082-2.00013-5

Pallister J et al (2013) Merapi 2010 eruption—chronology and extrusion rates monitored with satellite radar and used in eruption forecasting. J Volcanol Geotherm Res 261:144–152. https://doi.org/10.1007/s00445-016-1021-8

Pallister J, Papale P, Eichelberger J et al (2019) Volcano observatory best practices (VOBP) workshops — a summary of findings and best-practice recommendations. J Appl Volcanol 8:2. https://doi.org/10.1186/s13617-019-0082-8

Poland MP, Lopez T, Wright R et al (2020) Forecasting, detecting, and tracking volcanic eruptions from space. Remote Sens Earth Syst Sci 3:55–94. https://doi.org/10.1007/s41976-020-00034-x

Pritchard ME, Simons M (2002) A satellite geodetic survey of large-scale deformation of volcanic centres in the central Andes. Nature 418:167–171

Reath K, Pritchard M, Poland M et al (2019) Thermal, deformation, and degassing remote sensing time series (CE 2000–2017) at the 47 most active volcanoes in Latin America: implications for volcanic systems. J Geophys Res Solid Earth. https://doi.org/10.1029/2018JB016199

Syahbana D et al (2019) The 2017–19 activity at Mount Agung in Bali (Indonesia): intense unrest, monitoring, crisis response, evacuation, and eruption. Sci Rep 9:8848. https://doi.org/10.1038/s41598-019-45295-9

Tilling RI, Kauahikaua JP, Brantley SR, Neal CA (2014) The Hawaiian Volcano Observatory—A Natural Laboratory for Studying Basaltic Volcanism. In: Poland MP, Takahashi TJ, Landowski CM (eds) Characteristics of Hawaiian volcanoes: U.S. Geol Surv Prof Paper 1801, 64 pp. https://doi.org/10.3133/pp18011