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PERSPECTIVES

Future impacts of climate-induced compound disasters on volcano hazard assessment

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Abstract
The growing frequency of climate change–related hazards such as wildfires, floods, landslides, and drought increases the chances that they will coincide in space and time with volcanic eruptions. The cascading effects of the resulting compound disasters are much harder to predict than eruptions alone. Successful response to current volcanic events draws on the collective knowledge of past patterns gained by volcanologists and other disaster management professionals, allowing them to map out strategies for preparation, monitoring, evacuation, and recovery. In the coming decades, interpretations of such familiar patterns of events will be complicated by compound hazards. To respond effectively to future events, volcanologists will need to expand their knowledge of non-volcanic hazards and more intentionally incorporate social science perspectives into disaster planning and management.

Keywords Climate change · Compound disasters · Cascading effects · Volcanic eruptions · Societal impacts

Introduction

Ever since the foundational work of Hutton (1788) and Lyell (1837), geologic forecasts have been based on an implicit assumption of uniformitarianism—"the past is the key to the future." In volcanology, this means we base hazard assessments on our understanding of earlier eruptions, enhanced by field measurements and theoretical models. Many aspects of volcanic activity are relatively predictable—with a few notable exceptions (e.g., Krauskopf 1948), explosive or effusive products tend to come out of volcanoes, and certain eruptive sequences commonly repeat themselves. However, the accelerating pace of human-induced climate change and development pressures such as fracking (Nyberg et al. 2018) and urban expansion (Iglesias et al. 2021) into locations with active volcanism may increase overall hazard vulnerability in such areas. While the fundamentals of plate tectonics, mantle plumes, and magma dynamics are not noticeably affected by global warming, the odds are steadily increasing that volcanic activity will co-occur with other unrelated hazard events.

As we move into the third decade of the twenty-first century, the tendency for isolated disasters to evolve into scenarios involving multiple coincident hazards is becoming stronger, posing increasingly serious threats to the lives and livelihoods of millions of people (Cutter 2018; AghaKouchak et al. 2018), while complicating the jobs of emergency managers. In this paper, we discuss a range of co-occurrences of volcanic activity with other natural and anthropogenic hazards. We conclude that these accelerating changes will make it increasingly necessary for volcanologists and social scientists to collaborate, with the goal of producing the transdisciplinary knowledge required to prepare for and respond to this new and complex reality.

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

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Background: volcanic eruptions coinciding with other disasters

Successful response to volcanic eruptions often depends on recognizing patterns of sequential hazardous events. Bearing this in mind, observatory staff focus on the occurrence of volcanic hazards and emergency managers anticipate the risk that may likely accompany different stages of an eruption (Tilling 2008). Learning to identify eruptive sequences, their variations, spatial distributions, and the physical explanation for their behaviors is a major part of today's volcanological training, which commonly combines geology, geophysics, geochemistry, and civil engineering.

While forecasting the onset, magnitude, duration, frequency, and severity of hazards associated with volcanic sequences may be difficult, scenarios that combine eruptive phenomena with other geologic activity, like landslides and earthquakes, are even more challenging. Connections between volcanic and seismic activity have long been recognized (Carr and Stoiber 1973; Gudmundsson and Saemundsson 1980); improvements in global instrumentation and compilations of large geological data sets have, in the past 25 years, revealed considerably more correlations (Linde and Sacks 1998; Alam et al. 2004; Manga and Brodsky 2006). Some eruptions have likely been triggered by nearby earthquakes (e.g., Cordón Caulle, Chile 1960; Barrientos 1994), and in a few cases, seismic activity has led to unrest of volcanic systems over 1000 km away, as when the 1992 Landers earthquake in southern California was followed by small magmatic earthquakes at volcanoes throughout the American West (Hill et al. 1993).

Eruptions that melt glaciers have been responsible for some of the deadliest volcanic disasters. Glacial melting triggered by a relatively small eruption of Nevado del Ruiz in Colombia in 1985 generated a series of massive lahars that killed over 22,000 people in towns and villages tens of kilometers downstream (Pierson et al. 1990). Non-eruptive volcanic risks can also occur. For example, New Zealand's worst natural calamity, the 1953 Tangiwai disaster, occurred when the unanticipated collapse of a tephra dam released Ruapehu Volcano's summit lake. The resulting lahar destroyed a railroad bridge just as a passenger train was approaching; 151 people were killed when the locomotive and several cars of the train plunged into the river below (Lecointre et al. 2004).

A third class of compound hazard that is even more difficult to prepare for are those in which a natural event like a volcanic eruption takes place at the same time and location as a societally driven calamity like famine, war, or pandemic. In 2002, extremely fast-moving lava flows advanced down the flanks of Nyiragongo Volcano (Allard et al. 2002) into the Congolese city of Goma, destroying over 12,000 homes and much of the central business district. The impacts of direct inundation by lava flows were aggravated when a petrol depot blew up, causing most of the 45 deaths. More than 300,000 people fled from the eruption into neighboring Rwanda, but most returned within a week because the area was already filled with refugees from the genocide that had devastated the region 7 years earlier. Attempts to provide aid to the people of Goma were hampered by ongoing military activity in the Congo, driven by conflicts among warring factions over mineral rights. A subsequent analysis of the eruption by French, English, and American volcanologists indicated that early warnings of volcanic hazards could not be acted upon due to the civil unrest (Baxter et al. 2002).

We can thus identify three types of co-occurring volcanic hazards: those causatively connected to eruptions, like landslides, lahars, and triggering earthquakes; other simultaneous yet unrelated natural disasters, like storms, floods, wildfires, and droughts; and non-geologic crises caused by human actions, including war, famine, and pandemics. These categories are not fully independent, nor are they decoupled from anthropogenic climate change, which can manifest through "natural" events. Also, note that we are not considering the converse case of sulfur-rich volcanic eruption clouds contributing directly to the short-term mitigation of global warming through increased reflection of sunlight back into space, as occurred at Mount Tambora, Indonesia, in 1815 (Stothers 1984), El Chichon, México, in 1982 (Bluth et al. 1992), and Mount Pinatubo in the Philippines in 1991 (Graf et al. 1996).

There is no agreement among scholars as to whether these situations should be described as cascading, compound, or coincident disasters since it is commonly unclear whether an initial disruptive event causes others that are adjacent in space or time (Virmani 2012; Pescaroli and Alexander 2016; Gill and Malamud 2016; Sakamoto et al. 2020). In addition, disciplinary training and culture shape how people perceive or describe such events. Here, we use the expression "compound disaster" to describe cases in which one or more related or unrelated hazards or shocks co-occur in ways that generate secondary or tertiary impacts that disrupt normal functioning of society (Cutter 2018). In other words, "compound" refers here to the accumulating effects of a series of hazards without implying any causal connection among them.

Such scenarios are likely to become more common and severe due to the intersecting factors of climate change, urbanization, demographic shifts, mass migration, and poor land use practices (Gill and Malamud 2017; Cutter 2018; Feng & Xiang-Yang 2018; Iglesias et al. 2021). These shifting patterns of risk have begun to complicate eruption responses, making both the forecasts of hazards and the development of mitigation and communication plans less accurate and reliable. Volcano observatories and other government agencies are unlikely to have the requisite on-staff expertise to address all of the possible combined scenarios, making it imperative that relevant collaborations be established and maintained prior to the onset of an eruptive episode.

Our main point is that climate change is increasing the frequency of natural hazards, such as floods, storms, and heatwaves (IPCC 2021) with a greater chance that such events could co-occur with volcanic eruptions within the next few decades, requiring enhanced levels of coordination, planning, and funding to adequately deal with these complicated scenarios. In the next section, we highlight two theoretical approaches that describe how researchers, government agencies, and nonprofits can optimize the ways they respond to expanding, coincident hazards, and compound risks and disasters. While the details of these theories will not be explored fully here, they demonstrate how volcanologists can benefit from collaborating more closely with scholars and practitioners from a wide array of disciplines, including the social sciences.

Critical awareness theory and an all-hazard approach

Theories about hazards and disasters have evolved in the past few decades, paralleling changes in strategies for preparedness and response. Earlier, more naturalistic views held that the biophysical environment was the sole cause of disasters, with attention focused primarily on naturally occurring events and techno-managerial reactions thought to be most effective. Today, social scientists and practitioners have a multi-dimensional understanding that accounts for the complex interrelationships between society and nature and the myriad strategies required for preparedness, mitigation, response, and recovery.

While no single theory fully explains the nexus of compound disasters and societal response, we find two frameworks to be useful: critical awareness theory (CAT) and an all-hazard approach (AHA). CAT identifies how social knowledge of hazards (i.e., the frequency with which experts, scholars, and the public discuss hazard issues with each other), risk perception (i.e., how people interpret risk in relation to their social conditions), and hazard-specific concerns (i.e., a sense of obligation to act to mitigate a disaster) all interact to motivate preparedness (Gotham 2007; Paton 2003). On the other hand, AHA delineates personal and society-level processes (community participation, collective efficacy, empowerment, and trust) that interact with general knowledge of hazards to facilitate decision-making under conditions of uncertainty (Paton 2013). Combining these two theories can yield a clearer understanding of how to mitigate, respond, and prepare for coinciding or compound disasters, thereby minimizing potential loss of lives and property in the future.

Consideration of how volcanic eruptions have been perceived in the USA before and after the reawakening of Mount St. Helens, WA, in 1980 (Lipman and Mullineaux 1981) can help illustrate these two approaches. Before the St. Helens cataclysm, American volcanologists, disaster managers, politicians, and the public had much greater awareness of less explosive but more common Hawai'ian-style eruptions than they did for the more violent but less frequent activity found in the Cascades' stratovolcanoes. Based on CAT, one could say professionals and the public were better-prepared for Hawaiian-style eruptions than for Cascadian ones—because they had more knowledge of the risks and were more comfortable discussing and planning how to respond. Under these same circumstances, an AHA would suggest that perception of risk, knowledge of evacuation strategies, and concern for the well-being of neighbors all would have been more apparent in places like Hawai'i where eruptive activity was part of the collective memory, than in Washington or Oregon. Furthermore, AHA suggests that while each type of hazard has specific inherent characteristics, there should be a baseline of certain common ways that society responds to them all. For example, when active, the Cascade volcanoes can exhibit a wide range of eruptive behavior, all requiring common protocols regarding communication, hardening of infrastructure, identification of evacuation routes, and the setting up of emergency management strategies.

We note that the problem of compounding events is not completely new. In the past, we have seen a diversity of dangerous phenomena co-occur with volcanic eruption. For example, the 1980–1986 eruption of Mount St. Helens included explosive surges, pyroclastic flows, mudflows, landslides, melting of glaciers, and growth of a lava dome, each of which required a different preparedness strategy. Before 1980, most people in the USA were unaware of all these individual hazards, let along how they might interact. After 1986, it became possible to invoke an all-hazard approach because the public experienced compounding events such as the Mount St. Helen eruption.

The example of Mount Pinatubo in the Philippines further illustrates how the theories proposed in this section may be applied. The cataclysmic phase of the Pinatubo eruption in 1991 took place just before the arrival of a typhoon. The combination of heavy rain following massive deposition of volcanic ash and pumice led to extremely voluminous mudflows, along with the collapse of thousands of structures on Luzon Island in response to heavy water-laden ashfall. Most of the 300 fatalities from the eruption were caused by collapsing roofs (Global Volcanism Program 1991). Because Mount Pinatubo had not erupted in over 600 years, the affected population, as well as the Philippine Institute of Volcanology and Seismology (PHIVOLCS), had limited awareness of the dangers they faced. PHIVOLCS and the U.S. Geological Survey team that was collaborating with them had a particularly challenging time advising populations to both flee and avoid sheltering in structures whose capacity to withstand heavy ash loads had not been evaluated. Subsequent planning for other volcanic eruptions in the Philippines has drawn on a CAT approach and has emphasized educating the public about the range of risks they may face, thus enhancing preparedness for future hazards. For instance, weeks before the 2020 Taal eruption, PHIVOLCS warned residents of a potential "explosive eruption" and urged the evacuation of 40,000 residents within a 14-km radius, thereby saving numerous lives (Cartier 2020).

Discussion: implications for the coming decade

In the twenty-first century, awareness of volcanic eruptions has grown due to a proliferation of coverage by cable news and social media, coupled with ubiquitous cell-phone video capabilities and the public's fascination with colorful and violent images of nature. In parallel, popular knowledge about climate-induced crises including hurricanes, floods, wildfires, ice storms, droughts, and disease outbreaks has expanded rapidly. Yet the public's willingness and governments' ability to prepare for these increasingly frequent events or to support recovery efforts are compromised by political, psychological, and economic influences. *Partisan politics* continue to deeply divide the government and public on the severity of environmental crises (Dunlap et al 2016). *Compassion fatigue* (Adams et al. 2008) limits the amount or duration of attention individuals and groups can devote to news about bad outcomes for others. *Static* and *dynamic economic resilience* (Rose 2007) shapes the allocation of resources and the repair and restoration of capital stock needed for long-term recovery.

On the other hand, the expansion of satellite-, aircraft-, and ground-based surveillance networks, sensor miniaturization, cloud computing, and artificial intelligence mean that emergency authorities' ability to predict and react to natural calamities is steadily increasing. The immediate implication of these developments for the science and practice of volcanology is that the profession may benefit from shifting its view of itself from being a standalone sub-discipline of geology specializing only in eruptions, to instead becoming a key component in the broader socio-ecological and technical system dealing with a range of natural hazards that require preparation, response, and recovery. In practice, this means the increasing likelihood of the co-occurrence of eruptions with climate-related calamities like floods, wildfires, and storms should also be incorporated into volcanological training.

In the second "Looking Backward and Forward" AGU session in 2010, it was suggested that "in the coming decade, climate change will become so prominent that only volcanic research related to [its effects] will be funded by federal agencies" (Fink 2010). This prediction, made during the climate-friendly Obama administration in the USA, did not anticipate the anti-science, pro-fossil-fuel agenda of the Trump administration, which pushed federal climate research into the shadows, and invalidated, or at least postponed, the earlier forecast. The re-emergence of federal climate science during the Biden administration, coupled with increased policymaker, media, and corporate attention on the accelerating pace of climate-related disasters, signifies a reversal of the previous trend. This recent history highlights the increasingly complex political landscape in which volcanologists and many other applied natural scientists find themselves.

In contrast to the broad, anti-scientific political baggage associated with human-induced climate change (e.g., Pettenger 2016), controversies about volcanic eruptions tend to be more localized, centering on post-hoc issues, like whether a particular response was adequate (Wilson et al 2012), whether scientists took excessive risks (Kerr 1993), or whether tourists were given sufficient access (Heggie and Heggie 2004). As compound disasters that combine volcanic activity with coincident climate-induced phenomena increase in frequency, publicity about the overlap may draw volcanologists into the unfamiliar political crosshairs now trained on other scientific fields, ranging from sociology to meteorology and even epidemiology. Alternatively, the public's acceptance of scientific explanations for the volcanic components of these compound disasters may help offset skepticism about climate-caused events.

In conclusion, we can posit that in the coming decade, climate change and other natural and human-caused phenomena will make the jobs of volcano scientists increasingly more complicated. Therefore, now is the time to prepare for an uncertain future of compounding hazards.

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