PREDICTING CHANGES IN THE BEHAVIOR OF ERUPTING VOLCANOES, TO REDUCE THE UNCERTAINTIES ASSOCIATED WITH THEIR IMPACT ON SOCIETY AND THE ENVIRONMENT

Human vulnerability to volcanic eruptions is increasing[1], with a concomitant increase in the economic costs associated with volcanic unrest. During the 2010 eruption of Eyjafjallajökull, Iceland, ash clouds grounded aircraft for eight days, costing airlines ~US$1.7 billion, with the cancellation of ~100,000 flights[2] affecting 10 million passengers. At a local scale, the June 2014 lava flow erupted at Kilauea volcano, Hawaii, extended 17 km within three months, extending to within 500 m of the town of Pahoa, resulting in months of uncertainty for residents. The total cost of this small eruption was ~US$14.5 million, primarily for constructing emergency access roads. On average, 50 to 60 volcanoes erupt each year[3].

Key challenges for the coming decade include predictions of the beginning, and end, of eruptions, evolution of lava flows, dispersion of volcanic gas and ash clouds, impact on air quality, and post-eruption hazards such as landslides and mud flows. Timely prediction is necessary if emergency managers are to formulate effective mitigation strategies in near-real-time.

1. WHAT ARE THE KEY CHALLENGES FOR THE COMING DECADE?

i) **FORECASTING WHEN AN ERUPTION WILL BEGIN.**
Before an eruption fresh magma moves close to the surface, typically resulting in precursory seismicity, deformation, and degassing (primarily H_2O, CO_2, and SO_2)[4]. Enhanced shallow hydrothermal activity may result, manifesting as thermal, mineralogical and degassing anomalies at the surface. Excepting earthquakes and infrasound, these precursory signal can be measured from space (Figure 1). Multi-temporal measurements of their co-variance over multi-annual time scales will allow the changes that take place as volcanoes worldwide enter periods of heightened unrest to be determined. A key challenge will be to discriminate the patterns that precede eruptions (i.e. arrival of lava at the surface) from those that precede failed eruptions (e.g. magma intrusion at shallow depths with no eruption)[4].

ii) **FORECASTING WHEN AN ERUPTION WILL END.**
During lava-flow forming eruptions, effusion rates typically increase rapidly to a peak, and then wane over a longer period of time until the eruption ends[5]. During these eruptions, and those that produce lava domes, gas emission rates also decrease as supply of fresh magma from depth wanes. Dome-forming eruptions may last years, making long-term measurements of lava effusion and gas emission rates essential for recognizing secular declines. Determining how satellite measurements of effusion rate[6] and degassing[7] (combined with models of volcanic behavior[8]) can be used to predict eruption cessation is an important challenge. Space-based deformation

measurements will provide an important constraint from which partitioning of magma and lava between the surface and the subsurface can be constrained.

iii) **PREDICTING VOLCANIC HAZARDS, AND MAKING THE INFORMATION AVAILABLE TO DECISION MAKERS IN NEAR-REAL-TIME.**

Mitigating volcanic hazards to aviation: Recent advances in ash transport and dispersion modeling have combined remote sensing estimates of mass concentration with models of the physico-chemical evolution of ash[9] and meteorological models. Key challenges include incorporating variations in ash composition, size, and shape into the estimates of mass loading, and validating ash retrievals, to predict the time-space evolution of ash clouds, and the concentration of ash at each point in space. Collaborations with the aerospace sector are required to define tolerable thresholds for safe flight.

Mitigating lava flow hazards: It is important to forecast which areas downslope are likely to be inundated by lava flows and their time-rate of advance. A key challenge is to predict these quantities for long-duration eruptions, where multiple flow units can advance during the same eruption, in response to changes in the mass flux driving flow propagation. Effusion rate is a key variable in parameterizing numerical lava flow simulations[10], and can be estimated from space.

Mitigating health effects of persistent degassing: SO_2 is converted to (respirable) aerosol as it moves from the vent. A challenge is quantifying how efficiently (and under what environmental conditions), this conversion takes place[11], such that atmospheric dispersion models can more accurately predict aerosol pollution, allowing health professionals to monitor for its effects and target mediation efforts.

The societal benefit of meeting these challenges is obvious. Mitigating these hazards requires rapid delivery of information to decision makers. Satellite data must be available within hours of overpass (via direct broadcast), in a format (or via a well-considered suite of higher level data products) that decision makers can utilize. Onboard processing and product generation will minimize the time between data acquisition and product delivery.

iv) **HOW HAZARDOUS ARE VOLCANOES THAT SHOW NO OBVIOUS SIGNS OF ACTIVITY?**

Populations will increase around dangerous volcanoes that are dormant, or have no record of activity. Volcanic landslide hazards can be identified by mapping the surface expression (e.g. hydrothermal alteration) of structural weaknesses. Unconsolidated pyroclastic deposits can be remobilized by water, forming mud flows. Mapping the distribution of such deposits (in relation to topography) is a prerequisite for their hazard evaluation, and can be expedited using satellite remote sensing[12].

v) **How does global volcanism perturb the Earth system?** Subtle changes in ecosystems are increasingly used as metrics of environmental change. What subtle effects do volcanic gas emissions have on landscapes at local and regional scales?13 Large eruptions can influence climate on sub-decadal time scales, by perturbing Earth's radiative balance, and lowering global temperatures, countering the role that anthropogenic greenhouse emissions play as agents of warming. Recent research has suggested that a gradual increase in stratospheric aerosol loading since 2002 is the result of smaller tropical eruptions, not coal burning in Asia, as previously thought[14]. It is important to determine the magnitude of the volcanic forcing, to quantify its relative contribution to the global climate system.

2. Why is this the right time to address these challenges and why are satellite observations fundamental to achieving these goals?

Addressing these challenges is timely. Earth's population is increasingly vulnerable to volcanic hazards. Encroachment into areas vulnerable to eruptions is pronounced in emerging nations, where in-situ monitoring networks are still lacking[4]. Economic systems and infrastructure are integrated as never before, but have low resiliency to disturbances: reducing the uncertainties associated with eruptions is increasingly important, as they can have regional and global consequences. Computational models that seek to predict volcanic behavior have increased enormously in complexity and capability[15], and require ever increasing volumes of data that space-based technologies are now well placed to provide.

Satellite observations are fundamental to meeting these challenges as they can provide measurements of key eruption variables, with uniform fidelity, for all volcanoes on Earth, encompassing all eruption styles and their temporal variability. Furthermore, volcanic processes are dynamic and decision-makers require data in near-real-time; satellites, via direct broadcast (and onboard processing) can provide this information for eruptions anywhere on Earth. The concept of a space-based volcano observatory may even be realizable in the near future. Systems that use low spatial but high temporal resolution satellite sensors to autonomously re-task higher spatial (but lower temporal) resolution sensors already exist[16]. Integrating more space-based sensors into these systems, to maximize the amount of important data acquired during often short-lived eruptions, is both an opportunity and a challenge. The proliferation of UAVs and autonomous in-situ technologies will allow more complete validation of satellite measurements (and integration, via "sensor-webs") than ever before, enhancing their collective value.

With respect to meeting the challenges identified, InSAR measures deformation, and current and proposed SAR missions (e.g. NISAR) will provide these measurements. However, no global mapping mission is in operation (or development) that will provide measurements in the 0.3 to 14 μm range needed to meet the challenges identified. Volcanic aerosols (and CO_2)[17] can be quantified using hyperspectral visible-to-short-wave infra-red (VIS-SWIR) measurements. Lava flow cooling[18] and effusion rates[6] can be quantified using SWIR and mid-wave infra-red (3-5 μm) measurements (the high temperatures require that these measurements resist saturation[19]). SO_2 and ash can be quantified using long-wave infrared (LWIR, 7-14 μm) data[20], (although retrievals benefit from simultaneous hyperspectral VIS-SWIR measurements, for atmospheric correction). LWIR measurements allow the composition and texture of rocks to be determined using measurements of their temperature and emissivity[21], and provide precise measurements of the temperature of low temperature hydrothermal systems.

Space-based systems upon which volcanologists rely are beyond their planned mission lifetimes. While progress has been made in quantifying volcanic behavior from space, volcanologists have had to cede spatial and spectral detail to buy higher temporal sampling, or vice versa. A future challenge for observing volcanism from space is to bridge this gap, providing data with sufficient spatial resolution to resolve, for example, crater lakes <100 m in diameter, at the wavelengths described in the preceding paragraphs, and at the high temporal resolutions (and duty cycle) required to study dynamic volcanic phenomena across the globe. Current technologies allow for acquisition of high spatial resolution data (<100 m), between 0.3-14 μm, for the entire globe, night and day, at temporal resolutions of less than one week.

3. WHICH SCIENTIFIC COMMUNITIES WILL BE INVOLVE IN MEETING THESE CHALLENGES

Meeting these challenges will involve interactions between geologists, physicists, chemists (geochemists and atmospheric chemists), atmospheric scientists (particularly dispersion modelers), computer scientists, and mathematicians.

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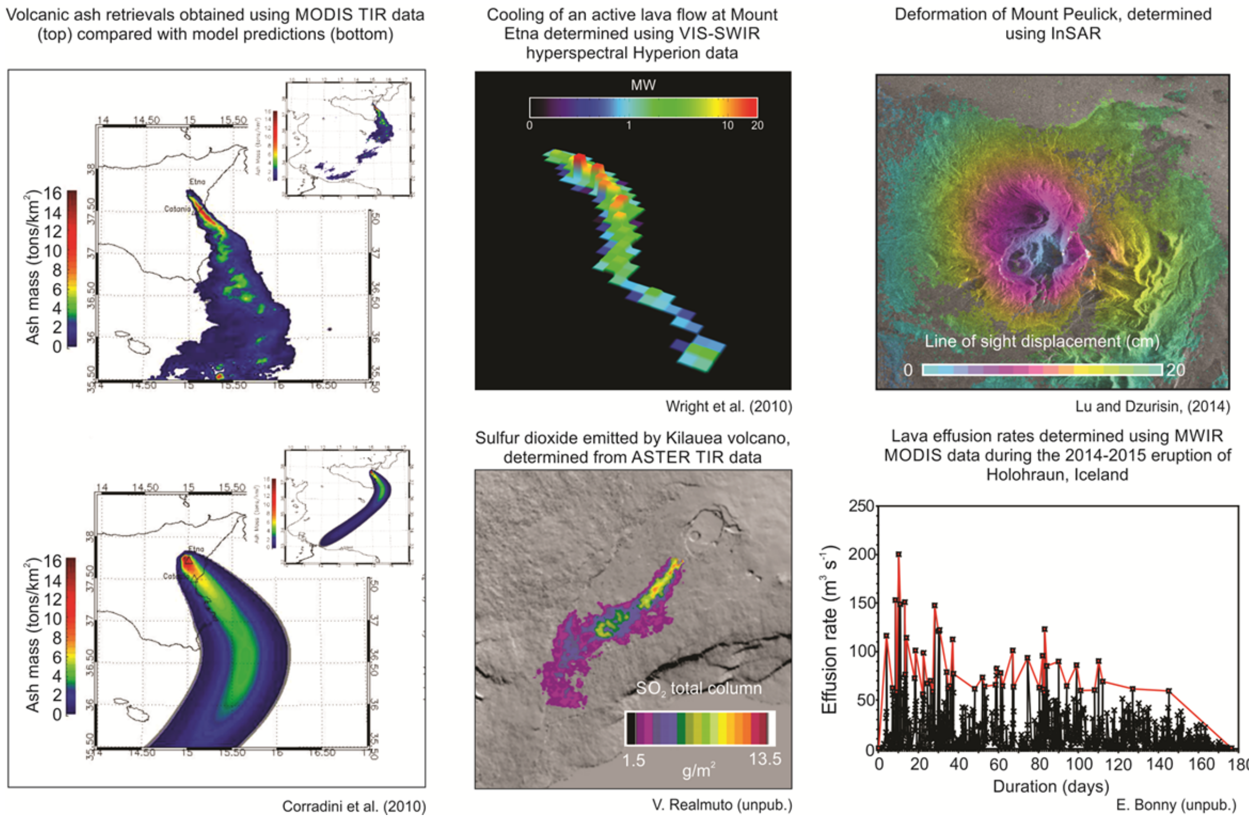
Figure 1



Volcanic ash retrievals obtained using MODIS TIR data (top) compared with model predictions (bottom)
Ash mass (tons/km^2)
16
14
12
10
8
6
4
2
0
Etna
Catania
Corradini et al. (2010)
Cooling of an active lava flow at Mount Etna determined using VIS-SWIR hyperspectral Hyperion data
MW
0
1
10
20
Wright et al. (2010)
Deformation of Mount Peulick, determined using InSAR
Line of sight displacement (cm)
0
20
Lu and Dzurisin, (2014)
Sulfur dioxide emitted by Kilauea volcano, determined from ASTER TIR data
SO_2 total column
1.5
g/m^2
13.5
V. Realmuto (unpub.)
Lava effusion rates determined using MWIR MODIS data during the 2014-2015 eruption of Holohraun, Iceland
Effusion rate ($m^3 s^{-1}$)
Duration (days)
0
20
40
60
80
100
120
140
160
180
50
150
200
250
E. Bonny (unpub.)