Transcript: Introducing volcanoes and volcanic hazard assessment as part of the METEOR project

Slide 3: In this short talk introducing volcanoes and volcanic hazard assessment as part of the METEOR project I will cover, an introduction to volcanoes including: types of volcanoes, styles and sizes of volcanic eruptions, volcanic hazards with a particular focus on pyroclastic density currents, tephra / ash fall and lahars and volcanic hazard management. I will then go on to discuss the modelling approaches used in the METEOR project, covering: an introduction to Tanzanian volcanoes, Tephra 2 simulations and lahar and pyroclastic density current basin analysis.

Slide 4: At the present time it is estimated that approximately 10% of the worlds population live within 100km of a volcano that is thought to have been active in the last 10,00 years.

These volcanoes are vents or ruptures where lava, gas and ash and can be erupted, connecting the surface of the earth with a magma chamber within the crust. When magma erupts at the surface as lava it can do so explosively. The explosive potential of a volcano is linked to the magma's viscosity or stickiness and the amount of gas contained with the magma. Generally speaking, low viscosity magmas tend to have effusive or runny eruptions – like the famous Hawaiian eruptions. Whereas volcanoes with higher viscosity magmas tend to have explosive eruptions. These explosive eruptions generate more ash than the effusive events. When magma erupts at the surface, as lava, it can form different types of volcanoes depending on the viscosity, of the magma, the amount of gas contained within it, the composition of the magma and the way in which the magma reached the surface.

Slide 5: There are two broad types of volcano – stratovolcanoes and shield volcanoes. Shield volcanoes are volcanoes that produce low viscosity, runny, lavas that spread far from the source forming a volcano with gentle slopes (c.10 degrees). Most shield volcanoes are formed of fluid basaltic lava flows which can flow great distances away from the vent. Mauna Kea and Mauna Loa are shield volcanoes. They are the world's largest active volcanoes, rising over 9 km above the sea floor around the island of Hawaii.

Stratovolcanoes have relatively steep sides and are more cone-shaped than shield volcanoes. They are formed from viscous, or sticky, lava that does not flow easily. The lava therefore builds up around the vent forming a volcano with steep sides (30 – 35 degrees). Stratovolcanoes are more likely to produce explosive eruptions due to gas building up in the viscous magma. Within these broad groups volcanoes can have other features such as fissures, cinder cones, domes and calderas

Calderas are formed when very large explosive eruption empty the volcanoes magma chamber, causing the roof of the chamber to collapse and form a depression, which steep walls. In these eruptions the upper portion of a stratovolcano is removed, leaving the caldera. These can be very large (km's across), a famous example of a caldera forming eruption is the Tambora eruption in Indonesia in 1815, which is widely accepted to have affected global climate in the years following the eruption.

Slide 6: Just like all volcanoes are not the same, the eruptions that occur at volcanoes are not the same. As we have already discussed eruptions can be effusive or explosive, depending on magma viscosity and gas content but this can also cause great variations in the style and size of eruptions.

Hawaiian and Strombolian - These are the least violent types of explosive eruptions. Hawaiian eruptions have fire fountains and lava flows, whereas Strombolian eruptions have explosions causing the release of lava cinders and lava bombs.

Vulcanian eruptions - Vulcanian eruptions are small to moderate explosive eruptions, lasting seconds to minutes. Ash columns can be up to 15 km in height, and lava blocks and bombs may be ejected from the vent.

Plinian eruptions – These eruptions form tall, convective eruptions columns that are a mixture of gas and rock particles and cause widespread dispersion of ash. The have a high rate of magma discharge which can be sustained for minutes to hours. The eruptions have tall columns (20 to 35 km) which may collapse to form pyroclastic density currents (PDC's).

It is clear to see that these eruptions have very different scales and so we must consider how the size (and explosiveness) of an eruption is defined.

Slide 7: The most common measure for the explosiveness of a volcanic eruption is the Volcanic Explosivity Index (Newhall and Self, 1982). This is a logarithmic scale, which takes into account criteria such as the volume of products, eruption cloud height and qualitative observations. The largest eruptions recorded on this scale have a VEI value of 8.

The Hawaiian and Strombolian eruptions discussed on the previous slide have a VEI of 1 to 2, which can be equated to an effusive to 'gentle' eruption with eruption columns reaching a maximum of 5km (for the large Strombolian eruptions). The Plinian eruptions, by comparison would have a VEI value of 5 to 6, depending on their volumes.

There is also a relationship between the size and frequency of eruptions, with larger eruptions happening generally less frequently.

Slide 8: With the range of volcanic types, eruption styles and sizes there are a range of volcanic hazards that need to be considered when performing a volcanic hazard assessment.

These fall into 2 categories: Primary hazards and Secondary hazards. Where primary hazards are produced during the eruption, whereas secondary hazards occur because of the primary hazard. These secondary hazards can occur during an eruption or after an eruption has ended. Both primary and secondary hazards can affect populations at distances of less than 1 km from the summit to 100's of kms away.

Slide 9: Some of the primary and secondary volcanic hazards can be identified here. I will provide a little more detail on the hazards highlighted in red, which are of relevance to the hazard assessment performed for the METEOR project.

Slide 10: Pyroclastic flows, or pyroclastic density currents are fast moving currents of hot gas and rock. They typically travel and speeds of greater than 80km per hour and reach temperatures of up to 700 degrees. Most pyroclastic flows consist of a basal flow that moves along the ground and a turbulent cloud of ash that rises above this.

Pyroclastic density currents can form in different ways: Eruption column collapse. During a large explosive eruption, the eruptive column rises high into the atmosphere. At this altitude the column begins to cool and can become to dense for upward momentum to be preserved, and so the column will collapse back on itself, sending PDCs down the sides of the volcano. During an explosive eruption it is possible to have a 'boiling over' event, where material is erupted without forming a high plume and rapidly moves down slope. Finally PDCs can be generated by the collapse of highly viscous volcanic domes (and lava flows) – as is the case in this image from Mount Sinabung in Indonesia. In this case the viscous material allows the front of the dome or flow to become overly steep until it collapses under gravity.

Generally, PDCs will follow topography such as drainages and low-lying areas – although they have been known to cross over between valleys. The deposits generated by them can less than meter to 200 meters thick, depending on the volume of the flow. Regardless of their mechanism of generation or size, PDCs are extremely destructive and highly deadly for people or livestock that get caught in their way.

Slide 11: 'Tephra' describes all pieces or fragments of rock ejected into the air by an erupting volcano. The largest pieces (those over 64mm) are called bombs – these usually fall near to their source. The smallest fragments however, with a diameter of less than 2mm are termed ash and maybe carried for large distances away from the volcano where they were produced. In the case of the Tambora eruption in 1815 this was up to 1300 km away.

The distance that ash can travel primarily depends on the height of the column, temperature of the air, wind direction and wind speed. Tephra can be an extremely destructive hazard. Pumices for example may still be hot enough to ignite fires at over 30 km from the volcano. The density of ash is such that it has the potential to collapse roofs once accumulation reaches c.30cm. Even small amounts of ash can be dangerous due to the highly abrasive nature of the particles, affecting the health of humans and livestock as well as the function of electronics. In more recent years there has been much interest around the interactions between ash and aviation, as there have been several incidences of commercial airplanes losing engine function after flying through ash clouds. Tephra and ash is the most voluminous volcanic product and therefore should be considered as part of volcanic hazard assessment as a likely proximal and distal impact.

Slide 12: 'Lahar' is a Javanese word that describes the hot or cold mixture of water and rock fragments that can flow down the sides of a volcano (typically entering river valleys). These phenomena generally occur near stratovolcanoes and can occur with or without a volcanic eruption. Eruptions may trigger lahars by melting snow or ice, by ejecting water from crater lakes or due to prolonged rainfall at the time of eruption. They can also be formed when loose volcanic debris is remobilised by rainfall after an eruption has occurred – sometimes this can go on for years after the end of an eruption.

As a lahar moves downslope its size, speed and the amount of material it contains constantly changes. This is because lahars entrain and incorporate materials they come into contact with as they move downslope. A lahar can therefore grow to become up to 10 times their initial size. Lahars can reach speeds of c.200km/hr on steep slopes and may travel many kilometres from the volcano. As slope angles decrease they will slow down and deposit the load. In some cases, these deposits can be 10's of meters thick. The erosion and transportation of loose volcanic debris in these lahar events can leas to severe flooding in areas downstream, they are also capable of destroying bridges and roads and burying houses. In some cases, these deposits may trap people in vulnerable areas, especially if these fresh deposits are too deep, too hot or too soft to cross.

Slide 13: This has been a very brief over-view of a few of the many components of volcanology, primarily I have covered the material that will be most relevant to the following explanation of the METEOR approach to modelling volcanic hazards. I hope its clear from this presentation that volcanoes are themselves complex and multi-hazard systems and that this along with their potential for impacting populations both proximally and distally make volcanic hazard management a challenging problem.

This figure by Tilling shows how all of the different components of research (such as modelling activity and analysing eruptive products) have to be linked to studies of past and present behaviour, volcano monitoring and the promotion of hazard awareness to form a framework for volcanic hazard mitigation. In the METEOR project we have been able to address only a few of these components.

Slide 14: In this next section I will outline the approaches that have been used to model volcanic hazards in the METEOR project.

Slide 15: The first step in conducting the volcanic hazard assessment in Tanzania was identifying which volcanoes this study would focus on. From the records at the Smithsonian Institutes Global Volcanism Program, there are 6 volcanoes that have had activity in the Holocene (approximately the last 10,000 years) in Tanzania. These are: Ol Doniyo Lengai, Meru, Igwisi Hills, Ngozi, Kyejo and Rungwe. These volcanoes are therefore the focus of our study. We aimed to address the 3 primary volcanic hazards: PDCs, Ash fall and Lahars.

As I eluded to in the first part of this talk, to understand these phenomena we need to collect many different sources of data, such as: Eruption histories, volumes of deposits, relevant digital elevation models, the particles size distributions of deposits, plume heights, historic wind speeds and directions and the duration of eruption columns.

Slide 16: In the case of Tanzanian volcanoes, much of this information is not in the record which makes generating robust hazard assessments difficult and in some cases not possible. As a consequence, for assessing tephra / ash fall hazard we have only been able to produce a modelled output for one of the volcanoes on this list.

Rungwe volcano in Southern Tanzania – indicated in the highlighted box is one of the better-studied volcanoes in Tanzania, with a record of at least seven explosive eruptions within the last approximately 4000 years, including VEI 4 and 5 eruptions at approximately 2000 and 4000 year before present (yrs BP), respectively (Fontijn et al., 2010; Fontijn et al., 2011).

Slide 17: We have chosen to model two eruption scenarios for Rungwe volcano based on past eruption history:

A VEI 2 scenario represents a relatively small eruption. Numerous small cones on the caldera and northwest flanks of Rungwe are indicative of such relatively small tephra-producing eruptions (Fontijn et al., 2010).

A VEI 4 explosive eruption scenario based on the Isongole Pumice eruption, which occurred approximately 2000 yrs BP. The Isongole Pumice eruption produced an eruption column of 17.5 km (above the vent) and a volume of 0.25 km^3 of tephra fallout (Fontijn et al., 2010). Based on this, the eruption was classified as a VEI 4, sub-Plinian event.

Ash fall hazard footprints were generated using *TephraProb*, a freely available *Matlab* package developed to produce probabilistic hazard assessments for tephra fallout (Biass et al., 2016). *TephraProb* uses the *Tephra2* tephra dispersion model. *Tephra2* is an open source advection-diffusion model that describes diffusion, transport and sedimentation of tephra (ash) particles released from an eruption column (Connor et al., 2001; Bonadonna et al., 2005). It calculates the total mass per unit area (kg m^{-2}) of tephra accumulation at individual grid locations by solving a simplified mass conservation equation. This equation takes into account the distribution of tephra mass in the eruption column and particle settling velocity, as well as horizontal diffusion within the eruption column and atmosphere after the particle has been ejected from the plume (Connor et al., 2001; Bonadonna et al., 2005; Connor and Connor, 2006).

The model requires a number of inputs representing the vent location, eruption column, wind, grain size and model parameters. The model was run with input parameter ranges for a number of eruption source parameters. The model was run probabilistically, 1000 times for each season (3000 in total), randomly selecting a wind file from a ten-year database for each run. We used different grid extents for the VEI 2 and 4 scenarios, with a larger grid for the VEI 4 scenario.

Slide 18: Here we see the results for both modelling scenario, displaying the 1, 10 and 100 kg/m^2 tephra accumulation thresholds, which equate to thicknesses of approximately 0.1, 12 and 120 cm given the bulk deposit density of 820 kg/m^3.

As a reminder, thicknesses of as little as 1 mm ash fall can cause transport problems, damage to electrical and mechanical components, blockages and clogging of water intake structures and infiltration systems (Jenkins et al., 2015). Each threshold has two datasets for the two seasons modelled: December to March and April to November. In Tanzania, these months were chosen to reflect the variability in wind conditions observed in the once the 10-year global dataset for wind direction.

Slide 19: It is important to note that even though Rungwe is one of the best studied of the Tanzanian Holocene volcanoes, knowledge of its eruption history is still limited; therefore, any modelling of potential future volcanic ash fall hazard is subject to high degrees of uncertainty.

Although we have modelled a VEI 2 and VEI 4 explosive eruption scenario, it is important to note that this is not a forecast and should not be considered a most likely scenario.

A future eruption is unlikely to have exactly the source parameters and wind conditions modelled here. There are a number of factors, which can have a strong influence on the area impacted by ash fall; for example, a finer particle size distribution will lead to a larger area being impacted. Particle size can be strongly influenced by magma composition or the presence of water; therefore, the explosive event does not necessarily need to be larger magnitude than modelled here to have a greater ash fall footprint.

Volcanic eruptions can last from a few hours to days, weeks, months and years. Based on global analysis, the median duration of an eruption is 7 weeks (Simkin and Siebert, 2000). Typically, an eruption comprises volcanic unrest prior to the onset of explosive activity and unrest that can continue after the explosive phase. Many explosive eruptions have multiple explosive events or phases, each lasting minutes to hours. *Tephra2* assumes that the input parameters are representative for the average conditions over the peak eruption duration, and that most tephra is ejected in a short duration explosive event (Connor and Connor, 2006) – this may not be correct.

As well as uncertainties related to the input parameters, there are uncertainties related to the model itself. Due to the complexities involved in modelling atmospheric conditions, *Tephra2* does not take into account horizontal changes in wind conditions away from the vent. A number of assumptions have to be made on diffusion and particle fallout, which will be different for each explosive event depending on atmospheric conditions, mass eruption rate, particle size and particle density

Slide 20: Due to the sparsity of eruption history data for the Tanzanian volcanoes it was also not possible to model specific eruption scenarios for pyroclastic flows or lahars, as we did for the tephra fall.

Instead the areas that are potentially at risk from pyroclastic flows and lahars have been assessed using a drainage basin analysis methodology based on available Earth Observation (EO) data. Essentially in this approach we assume that any pixel that falls within a certain range from the summit of the volcano could be an area that is at risk from either PDCs or lahars or both. This does not mean that these phenomena will affect this area, or indeed that a pixel that falls outside these radii will not experience these hazards. Instead this should be seen as an estimate of where the most likely impact areas are. For more precise volcanic hazard assessment, it would be necessary to collect further data on the eruption histories and parameters at all of these locations.

A simplified workflow for this analysis can be seen in the following slides. The first step in this process is the preparation of the DTM, in this process we used SRTM DTMs resampled to 450m. We then generated buffer zones around each volcano. The diameter of these were informed by global data sets indicating the most likely PDC and lahar run out distances and the potential maximum runout. For pyroclastic flows these values are 3km and 30km from the summit and for lahars these distances were 10km and 100km respectively. It should be noted that these distances are an estimate for modelling purposes and not a forecast.

Once the DTM has been produced the GIS process for extracting PDC basins and lahar basins is slightly different and can be seen here.

Slide 21: The pyroclastic and lahar basin modelling produces outputs like those seen here for Kyejo, Ngozi and Rungwe. All of the volcanic hazard footprints can be reviewed further on the METEOR data portal (https://maps.meteor-project.org/map/vol-basins-tza/#6/-4.903/32.293)

Slide 23: This is the end of this talk introducing volcanoes and volcanic hazard assessment as part of the METEOR project. Further information on all of the concepts discussed here can be found in these key references, which were used in the construction of this talk.