Dispersal and Deposition Modelling of Ash from Soufrière Hills Volcano, Montserrat

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Abstract

Ashfall is a notorious hazard that can have a variety of effects on agriculture and infrastructure and, most notably to aviation and human health. This study discusses the creation of a conceptual model to aid in modelling the dispersal and deposition of ash from Soufrière Hills Volcano on the island of Montserrat. It includes a discussion of assumptions and boundary conditions of the model as well as a detailed diagram of the conceptual model, complete with parameters, units and equations. The two main processes contained within the model are the dispersal and deposition of ash, the outputs obtained from running the model, if created, would be the total amount of fine ash contained in the eruption column, distance travelled by ash and ash thickness at surface.

Soufrière Hills, Montserrat, Volcanic Ash, Modelling, Dispersal, Deposition, Conceptual

Introduction

Soufrière Hills Volcano is an active volcano located on the island of Montserrat which is a British Overseas Territory and part of the Lesser Antilles island chain in the Caribbean (Figure 1) (Montserrat Volcano Observatory, 2010). Soufrière Hills began erupting in 1995 after a long period of dormancy stretching from the 17th Century, and caused a large amount of social and economic disruption by completely destroying the capital Plymouth (Global Volcanism Programme, 2010). This eruption lasted 8 years and released a total of 1.2×10^8 m^3 of material; the most recent eruption which started on the 15th April 2005 and is ongoing to this day sees the continuation of a highly eruptive phase of the

Figure 1: Location of Montserrat and nearby populated areas

volcano.

This is creating a variety of hazards such as ashfall which is the focus of this study (Global Volcanism Programme, 2010). Ashfall is a notorious hazard of volcanic activity; in particular the volcanic ash of Montserrat is more dangerous to human health than other more famous eruptions such as Mt. St. Helens in 1980, this is because of a high content of cristobalite within the ash (up to 24%) which is a high temperature crystalline silica polymorph that has been shown in various studies to effect the lungs and breathing (Horwell *et al.* 2003; Lee and Richards, 2004).

Aviation can also be adversely affected by dispersal and deposition of ashfall, when air traffic enters into an eruption cloud it can potentially clog the engines and cause engine failure and also reduces visibility due to its abrasive nature. It is therefore important to forewarn airports and pilots when they are about to enter an eruption cloud, this is usually done in the form of SIGMET (Significant Meteorological Information) reports (Guffanti *et al.* 2005). It has been shown that even small amounts of ash and/or small exposure times can result in engine damage (Peterson and Dean, 2008). In the case of Montserrat, the airport which is 9 km north of the volcano is not open to major airliners however monitoring still needs to occur in case ash moves into the path of an international route or interferes with lighter air traffic. The disruption ash can cause to aviation was clearly seen after the eruption of Eyjafjallajökull, Iceland on the 14th April 2010; over 100,000 European and International flights were cancelled up to the 20th April 2010 affecting a total of 23 European countries (Schumann *et al.* 2010).

Other effects of even the smallest amounts of ash can cause disruption of agriculture (in the short term), clean-up costs and disruption to communication (Hurst and Smith, 2004). Ash also has effects on local residents and their buildings, at differing levels of ashfall intensity roof collapse and even complete building collapse can occur (Spence *et al.* 2008). Tephra fallout can occur for four reasons, of which all occurred at Montserrat, these are; magmatic explosive eruptions, dome-collapse/pyroclastic flows/rockfalls, ash-venting and phreatic explosions (Bonadonna *et al.* 2002b). It is therefore of great importance to be able to predict and forewarn residents of Montserrat and surrounding islands of the relative risks during periods of increased activity and/or ashfall to prevent and reduce the risk of harmful effects being felt by the population, industry and aviation. Therefore, this paper sets out to describe and explains the creation of a conceptual model for the dispersal and deposition of volcanic ash. Throughout this study the example of Soufrière Hills Volcano will be used, however, the model could potentially be used in other locations as well.

Existing Ash Dispersion Models

It is the job of 9 VAAC's (Volcanic Ash Advisory Centres) globally to assess the hazard of volcanic ash to aviation. Soufrière Hills volcano is within the monitored airspace of the Washington DC (USA) VAAC area (Guffanti *et al.* 2005). Soufrière Hills Volcano is under the jurisdiction of the Montserrat Volcano Observatory (MVO) which publishes regular assessments of hazard and risk (ESSC, 2009). These centres use real time information and models to predict the dispersal of ash but generally limit deposition to fallout areas as including fallout thickness in a model would add unnecessary variables (Guffanti *et al.* 2005). Volcanic ash dispersion models are generally known by the term VATD (Volcanic Ash and Dispersion/Tracking Model) (Mastin *et al.* 2009). An example of a model such as this is

HYSPLIT 4 (HYbrid Single-Particle Lagrangian Integrated Trajectory) model which can be used for multiple purposes other than solely volcanic, such as the dispersal of PM_{10} (desert dusts), $PM_{2.5}$ (wildfire smoke) and radioactive clouds following pollution episodes. Despite being labelled as a Lagrangian model, HYSPLIT 4 is actually run in combination with the Eulerian approach to modelling. The model is available as software which is downloadable; the software produces a graphical output of eruption cloud which shows spread and concentration of ash (Draxler and Hess, 1998; NOAA Air Resources Laboratory, 2010). PUFF is an example of a model which is used solely for tracking volcanic ash, and it is used for young ash clouds that are less than 48 hours old. PUFF was initially created to run as a dynamic software package which allows quick usage and is special designed to be used in emergency situations, on young eruption clouds. It was developed for use in the Northern Pacific region, after the economic damage caused by the eruption of Redoubt, Alaska in 1989/1990 (Searcy *et al.* 1998). PUFF is available online to users; the output is in the form of a graph which follows individual “puffs” over a specified time period. Additional information for currently erupting volcanoes such as Chaitén (at time of writing – 24th October 2010) can be downloaded into Google Earth and overlain onto the surface; this includes a 2D airborne spread, 2D fallout areas and a 3D view. PUFF was created using the programming languages C and C++(Alaska Volcano Observatory, 2010). FALL3D is a Eulerian based model for the tracking and deposition of ash, its main areas of focus are for past and current eruptions. FALL3D was created using the code FORTRAN-90 and is best used on the operating systems Unix, Linux and Mac (Istituto Nazionale di Geofisica e Vulcanologia, 2010). Examples of applications of this model are to the eruption of Etna in 2001 (Costa *et al.* 2006) and Chaitén in 2008 (Folch *et al.* 2008). Other examples of VATD’s which are based on similar ideals as the discussed models are NAME (Ryan and Mayron, 1998), CANERM (D’Amours, 1998) and MEDIA (Sandu *et al.* 2003).

Hypotheses and Perceptual Diagram

The model which is going to simulate the dispersal and deposition of ash has been called the ‘Dispersal and Deposition of Ash’ (DDA). It is hoped that DDA will improve on models such as PUFF to include a greater accuracy at a more local level and a longer time frame whilst still allowing the option of applying the model over a wider region to increase functionality of the model. The hypotheses of this model prior to creation of the perceptual diagram are listed below:

H1. Large eruption rate equates to more ash released into the atmosphere and subsequently a larger spread of ash.

H2. Longer eruption duration equates to more ash released into the atmosphere and subsequently a larger spread of ash.

H3. Higher eruption column equates to a larger spread of ash.

H4. High atmospheric wind speeds equate to a further spread of ash.

The rationale behind each of these hypotheses (H1, H2, H3 and H4) is linked and relatively simple as they apply to the majority of eruptions which produce eruption plumes. As per equations given in Parfitt and Wilson (2008) and Mastin *et al.* (2009), more eruptive material will mean more dispersible ash is released. Similarly longer eruptions will release more ash, with the potential for more to spread over a larger area. Higher eruption columns will give ash more time to spread, also settling time of particles will be longer. The larger the wind speeds acting upon a column will determine the extent of ash spread, as well as direction and distance (Carey and Bursik, 2000).

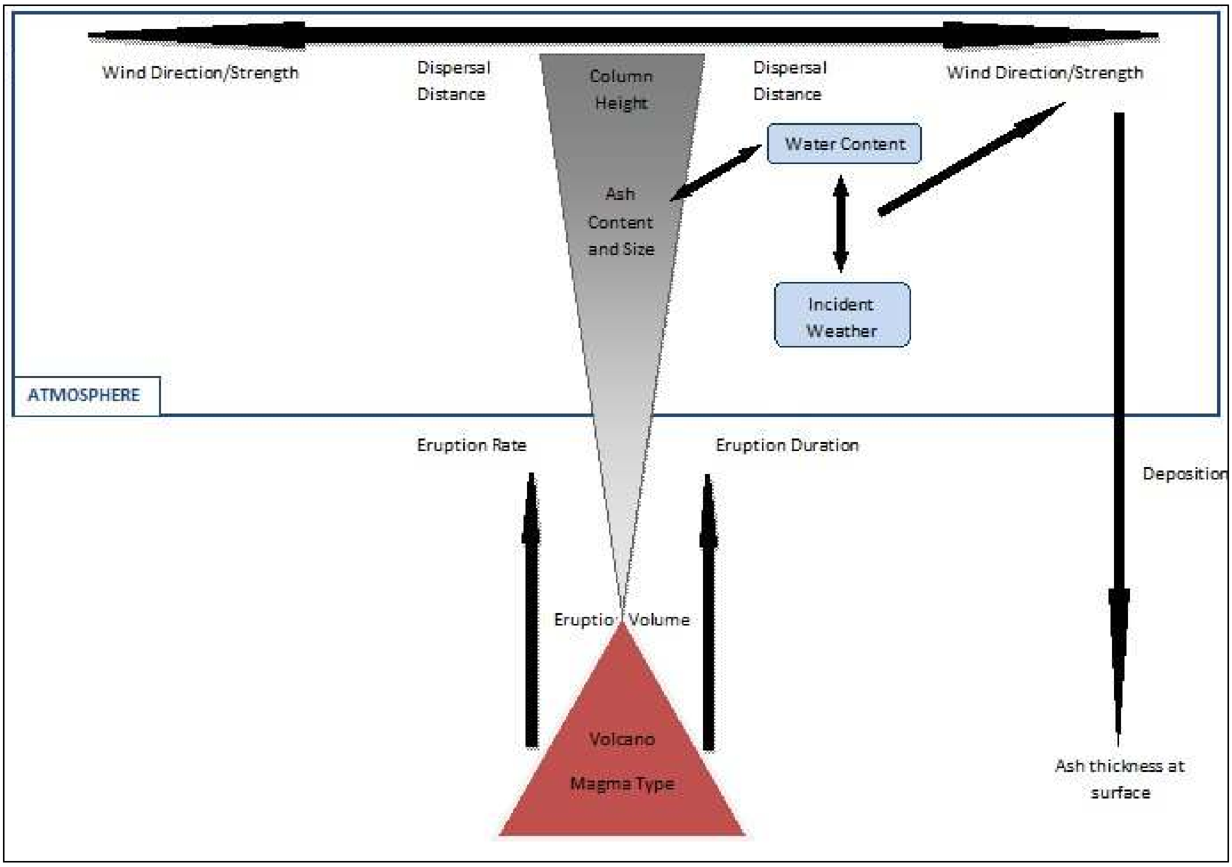

Fig 2: A Graphical Representation of the DDA model

Figure 2 is a graphical representation of the DDA model. There are seven categories/areas of data needed when concerning the eruption and ash itself. These are (as in Figure 2) magma type, eruption volume, eruption rate, eruption duration, column height (at umbrella height), ash content of eruption cloud and ash particle size. There are also five categories within the atmosphere, these are; wind direction, wind strength, water content of atmosphere, incident weather and deposition. The principal of parsimony has been used as much as possible to reduce the chance that any errors present within the model can propagate and create larger modelling errors (Seasholtz and Kowalski, 1993).

The reasons for the inclusion of these categories within the model will now be discussed. *Magma type* is included as a parameter as it is a set type dependant on the eruption. When considering Montserrat the magma type is a mixture of dacitic and andesitic magma (Hale *et al.* 2009; Mastin *et al.* 2009); however it can be changed when considering other volcanoes with differing magma types. *Eruption volume* is needed to determine both the amount of ash in the eruption column and the size of ash within the eruption column. *Eruption rate* is included as this determines the amount of ash released during the eruption. *Eruption duration* is needed to calculate the amount of ash released. *Column height* (at umbrella) is needed to determine height of horizontal dispersal of ash particles (Figure 3); however this is dependent on wind speed. If a column rises faster than the average wind speed in the area then an umbrella cloud will form on top of a vertical column, if a column rises slower than the average wind speed then a plume which is bent over and weak will form (slight bending of a strong eruption column can still occur) (Webley and Mastin, 2009).

Figure 3: Eruption Column topped by umbrella cloud during the eruption of Mt. Chaitén, Chile (Folch*et al.* 2008)

Ash content of eruption cloud is needed to determine how much ash will disperse at the umbrella top. *Ash particle size* (sometimes referred to as fraction of fine ash (Webley *et al.* 2009a)) is a parameter and is needed to calculate how far and how much ash will disperse at the column or umbrella top. *Wind direction* and *wind strength* are needed to determine in what direction and how far ash is carried before deposition requirements are met. *Water content* (humidity) and *incident weather* is included as a larger water content of the atmosphere causes conglomeration of ash particles which increases fall velocities, incident weather is included for similar reasons; if ash is released during a rainfall period water molecules pick up ash particles and are subsequently removed from the atmosphere (Textor *et al.* 2006a; Textor *et al.* 2006b), moist conditions can also increase the height of the eruption column by a number of kilometres (Webley and Mastin, 2009), large amounts of precipitation can also cause lahars.

Figure 4: Fallout of ash from Mt. Chaitén near Tecka, Argentina (Folch*et al.* 2008)

The final parameter is *deposition* (also known as fallout – shown in Figure 4) which is needed to determine when ash particles will be removed from the atmosphere and the *ash thickness* at the surface (Mastin *et al.* 2009).

Conceptual Model, Assumptions and Boundary Conditions

Figure 5 (appendix) shows the conceptual model created for DDA.

Listed below are the inputs of the model:

- Magma Type
- Eruption Rate
- Eruption Duration
- Eruption Volume
- Column Height (Can be calculated from eruption rate and volume if not known)
- Wind Speed
- Wind Direction
- Relative Humidity
- Precipitation Amount
- Mass fraction of fine ash

Of these inputs magma type, mass fraction of fine ash and relative humidity (if needed) will remain constant throughout a model run.

Listed below are the processes of the model:

- Dispersal of Ash
- Deposition of Ash

Listed below are the outputs of the model:

- Total fine ash in column
- Distance travelled by Ash
- Ash thickness at surface

At the end of a model run the results can be superimposed onto a map of the area to see areas most likely to be affected; this allows risk and hazard assessments and warnings to be made during or prior an eruption episode. The initial conditions of this model is stated as follows - prior to simulation there is no significant ash being released by the volcano; this can either mean that before simulation there is no eruption in progress or that there has been a revival of an eruption already in progress.

The following assumptions have been made when creating the conceptual model:

1. Eruption duration (T_H) is the amount of time when a significant amount of ash is released – i.e. enough to cause harm (Mastin *et al.* 2009)
2. Eruption rate (R) is linked to plume top height (H_T) and plume umbrella height (H_U).
3. Eruption volume (V) is related to plume top height (H_T) and plume umbrella height (H_U).
4. Eruption rate (R) and eruption volume (V) are linked, i.e. a larger eruption rate specifies a larger eruption volume.
5. Particles within the eruption cloud larger than 1mm fall at terminal velocity out of the eruption cloud within 30 minutes of release into the atmosphere (Rose, 1993)
6. Only ash particles <63 μm are considered to be the best indicator size and have the most noticeable effects on aviation and humans. (Bonadonna *et al.* 2002a).
7. Magma type (M) negates ash content (A_C) of the eruption column and ash particle size (A_S) (Mastin *et al.* 2009).
8. Column height at umbrella (H_U) is where the majority of ash disperses horizontally in the atmosphere (Mastin *et al.* 2009).
9. Stokes settling law is used for deposition (Mastin *et al.* 2009). This is illustrated in Figure 5 by the equation $pg/n = 1.08* 10^9 \ m^{-1} \ s^{-1}$. Applying this to Soufrière the equation becomes: ($950 \ kg \ m^3 * 9.8 \ ms^{-1}/n = 1.08* 10^9 \ m^{-1} \ s^{-1}$) this equation is taken from Searcy *et al.* (1998).
10. No turbulent flow will occur within dispersal of ash, it is assumed that particles will fall at terminal velocity once no longer suspended in the air due to insufficient wind velocity. Turbulent flow is not being included due to large issues of uncertainty involved with the basic processes (Webley and Mastin, 2009).

Equation Selection:

A short explanation of important equations selected and shown in Figure 5will now be given.

The relationship between eruption rate and plume umbrella height (H_U) (as in Figure 5.) is given as $H_U = 0.236 * R^{1/4}$, this was taken from Parfitt and Wilson (2008). If plume umbrella height is not known or only an estimated height is available, this can be used to give a more accurate result. Alternatively if eruption volume (V) is known (or an estimation made) then the equation $H_U = 25.9 + 6.64_{\log 10}$ (V) can be used to estimate plume umbrella height, this was taken from Mastin *et al.* (2009). This must be used carefully as this equation is based on a line of best fit from a comparison of only 34 eruptions, it is for this reason that if plume umbrella height is needed the equation from Parfitt and Wilson (2008) is preferred. One of the most important terms of the model is Stoke's Settling Law; this has been adopted from

Searcy *et al.* (1998), as shown in assumption number 9 above. It is included as a constant to remove the complications of highly varied settling times amongst differing ash sizes.

The following boundary conditions apply:

1. If the eruption column reaches into the stratosphere and varying amounts of ash are subject to high speed winds such as jet streams, results may be unpredictable as the deposition rules of the model would not simulate movement of ash in this way. However this is only relevant at latitudes where movement of ash into stratospheric high speed winds is applicable or for extremely large VEI 7 or 8 super eruptions. This is because turbulent flow is not included within the model.
2. The model is limited to dispersal over national scale areas (~250,000 km^2) and is not suitable for worldwide dispersal of ash.
3. Topographic information is not taken into account in the model; any eruption in areas with large differences in elevation could not be simulated accurately due to abnormal wind flow conditions which may occur, for example in the Andes.

Discussion

To apply and initialise the model retrieval of source eruption parameters would be needed, the minimum number of specific parameters needed to be able to apply the model to an eruption include, column height, eruption rate, eruption volume and duration (Webley *et al.* 2009a; Webley *et al.* 2009b), wind speed and direction can be estimated although actual wind conditions are preferable.

The data for column height, eruption rate and eruption volume can all be estimated/obtained from various sources – these are; visual observations which can suffer from large inaccuracies, satellite data using visual/infra-red/radar techniques which can also suffer inaccuracies due to differing data assimilation techniques (Mastin *et al.* 2009) and existing ash column models such as ATHAM (Textor *et al.* 2006a) which are based on the buoyant plume theory (Costa *et al.* 2006). Magma type and mass fraction of ash will be determined on analysis of previous eruptions and assigned as appropriate. It should be noted though that magma type can vary even within eruptions at Soufrière Hills with both andesitic and silicic magma types present during eruptions (Mastin *et al.* 2009). The mass fraction of ash (<63 µm) value shown in Figure 5 of 0.4-0.7 was taken from Bonadonna *et al.* (2002a) and is an average based on ash samples taken after the previous eruptive episode which started in 1995. Another valuable source for information on all aspects of the eruption of Soufrière Hills is Druitt and Kokelaar (2002). Meteorological information (wind speed, wind direction, humidity and precipitation) can be obtained with relative ease from weather organisations such as the MET Office who keep and analyse data on a worldwide scale. There is also a large amount of information available from NOAA (National Oceanic and Atmospheric

Administration) in the form of synoptic charts of which meteorological information can be estimated. When considering the application of the model to an eruption, the variables of humidity and precipitation can be deemed not necessary if there are negligible conditions present which would not affect deposition or transferral of ash (Textor *et al.* 2006a; Textor *et al.* 2006b). When conditions are present these variables should be used to improve the model simulation accuracy. Ensuing outputs and processes are computed using existing equations or using the previous categories.

The model would have the most effective results if it was run with all possible inputs including accurate source data and not estimated in anyway. If all or some of the inputs are unavailable, however, calibration should be used to remove problems in estimations and simulations to acquire the desired/expected results. In summary the model itself would be best run as a Lagrangian model as this has the ability to track particles (Costa *et al.* 2006), which would be best run as a Monte Carlo method of analysis giving multiple answers known as uncertainties, Monte Carlo analysis allows these uncertainties to be displayed explicitly so error ranges and ranges of results are known extremely clearly. Using this method means that less accurate grid-based models can be avoided (Hurst and Smith, 2004).

Overall the application of this model is not simple or easy, this is mainly due to the complexity of the processes that occur both within the eruption and the atmosphere and the difficulty of applying these. In many cases there are multiple theories for factors such as turbulent dispersion and column processes (Peterson and Dean, 2008).

There are several issues with VATD's in general, and these are also applicable to the DDA model. During an eruption event when source data are needed quickly, parameters are sometimes unavailable and estimations have to be made, in some circumstances these observations are visual however calculations from visual observations of characteristics such as plume height can differ by kilometres (Webley and Mastin, 2009). It could be argued that the lack of in-depth description of processes and the non-inclusion of some processes within the model make it less accurate and describe the system poorly; however equifinality tells us that there may be more than one way of producing the same output (Beven and Freer, 2001) and the principle of parsimony tells us that we should prefer the simplest explanation (Seasholtz and Kowalski, 1993). Whilst creating the DDA model the aim has been to describe the main processes which are occurring whilst retaining some of the principles of parsimony in creating a simple model.

Conclusions

In conclusion incorporating all processes which occur in the atmosphere and within the eruption cloud during volcanic eruptions into models is notoriously difficult (Dobran and Ramos, 2006). However it is extremely important in areas such as Montserrat to give the public and aviation industry forewarning of risks or hazards which may affect their lives in any way, and models such as this one can help and prepare organisations and the public to do this. Further applications of this model could be, as already stated, to other eruptions in similar circumstances. Another application of this model could be that of inverse modelling, where source volcano, ash thickness and dispersal area are known eruption volume, eruption rate and column height could potentially be calculated – this could be a useful application for studying past eruptions. A model such as this could also be useful to the London VAAC and NATS for predicting movements of ash clouds from Iceland, and is especially relevant following the chaos caused in European airspace after the eruption at Eyjafjallajökull, Iceland in 2010.

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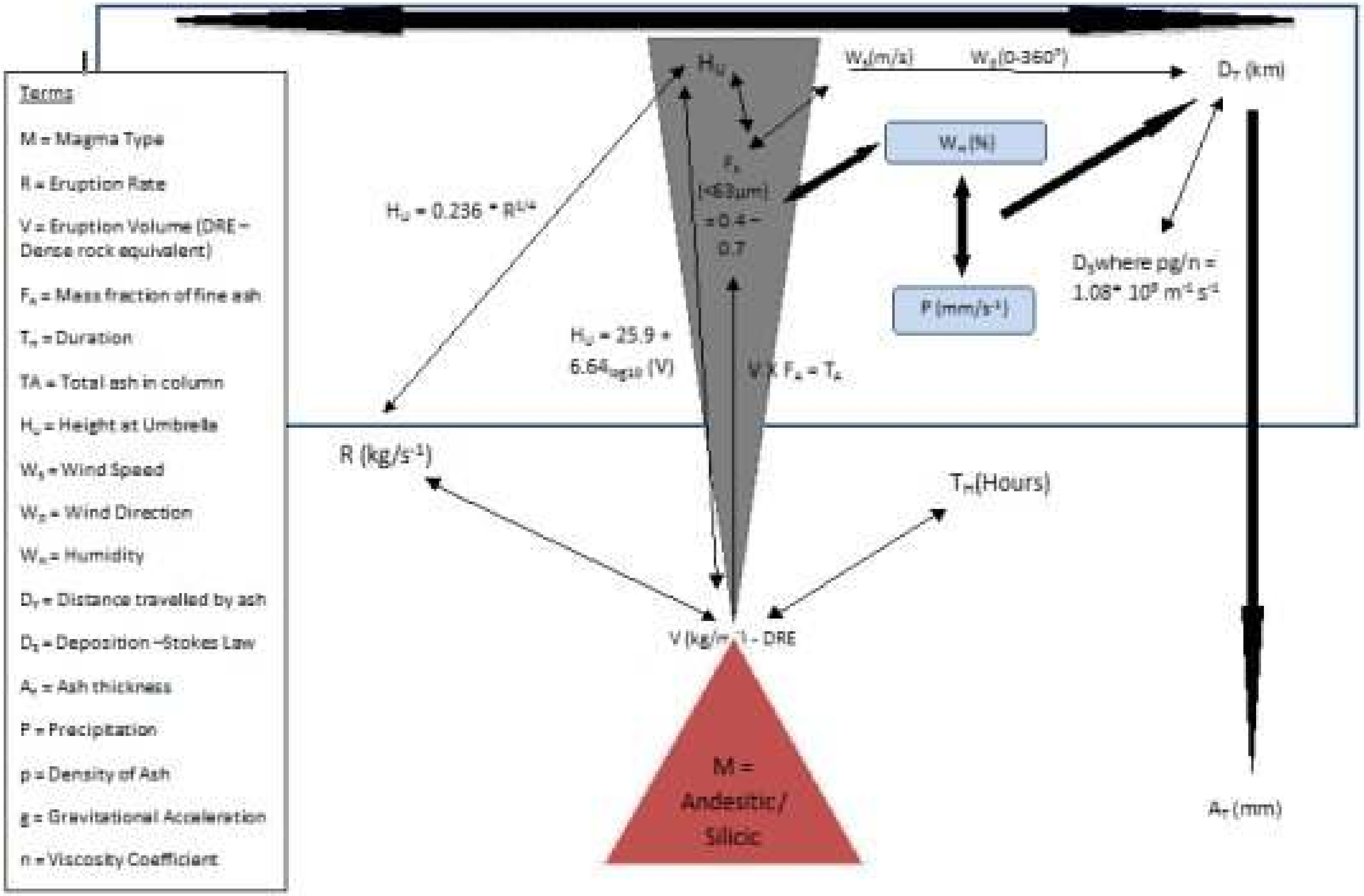
Appendix

Fig 5: Conceptual model for DDA



Terms

M = Magma Type

R = Eruption Rate

V = Eruption Volume (DRE – Dense rock equivalent)

F_A = Mass fraction of fine ash

T_H = Duration

TA = Total ash in column

H_U = Height at Umbrella

W_S = Wind Speed

W_D = Wind Direction

W_H = Humidity

D_T = Distance travelled by ash

D_S = Deposition –Stokes Law

A_T = Ash thickness

P = Precipitation

ρ = Density of Ash

g = Gravitational Acceleration

n = Viscosity Coefficient

Figure 5: Conceptual Model for DDA with terms and equations adapted from Searcy et al. (1998), Hurst and Smith (2004), Jaquet et al. (2006), Parfitt and Wilson (2008), Peterson and Dean (2008), Webley and Mastin (2009), Mastin et al. (2009) and Webley et al. (2009).

Fig 5: Conceptual model for DDA