RESEARCH ARTICLE

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Long term exposure to respirable volcanic ash on Montserrat: a time series simulation

Abstract Frequent ash fallout from long-lived eruptions (with active phases greater than 5 years) may lead to local populations experiencing unacceptably high cumulative exposures to respirable particulate matter. Ash from Montserrat has been shown to contain significant levels of cristobalite and other reactive agents that are associated with an increased risk of developing pneumoconiosis (including silicosis) and other long-term health problems. There are a number of difficulties associated with estimating risks in populations due to uncertain and wide ranging individual exposures, change in behaviour with time and the natural variation in individual response. Present estimates of risk in workers and other population groups are simplifications based on a limited number of exposure measurements taken on Montserrat (1996–1999), and exposure−response curves from epidemiological studies of coal workers exposed to siliceous dust. In this paper we present a method for calculating the long-term cumulative exposure to cristobalite from volcanic ash by Monte Carlo simulation. Code has been written to generate synthetic time series for volcanic activity, rainfall, ash deposition and erosion to give daily ash deposit values and cristobalite fraction at a range of locations. The daily mean personal exposure for PM_{10} and cristobalite is obtained by sampling from a probability distribution, with distribution parameters dependent on occupation, ground deposit depth and daily weather conditions. Output from multiple runs is processed to calculate the exceedance probability for cumulative exposure over a range of occupation types, locations and exposure periods. Results are interpreted in terms of current occupational standards, and epidemiological exposure−response functions for silicosis are applied to quantify the long-term health risk. Assuming continuing volcanic activity, median risk of silicosis (profusion 1/0 or higher) for an average adult after 20 years continuous exposure is estimated to be approximately 0.5% in northern Montserrat to 1.6% in Cork Hill. The occupational group with the highest exposure to ash are gardeners, with a corresponding 2% to 4% risk of silicosis. In situations where opportunities for in-depth exposure studies are limited, computer simulations provide a good indication of risk based on current expert knowledge. By running the code for a range of input scenarios, the cost-benefit of mitigation measures (such as a programme of active ash clearance) can be estimated. Results also may be used to identify situations where full exposure studies or fieldwork would be beneficial.

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Keywords Monte Carlo · Montserrat · Respirable health · Risk · Silicosis · Volcanic ash · Cristobalite

Introduction

Scientists involved in volcanic crisis management increasingly are being asked for advice concerning the long-term

hazards and risks associated with volcanic activity. Such requests require prognosis of risk to human populations and development of assessments in cooperation with disciplines outside the natural sciences, such as social scientists, economists, psychologists, and in the case of health-related hazards with medical scientists. Environmental risk assessments typically involve incorporation of information that is highly uncertain or poorly constrained and consequently are best developed within a probabilistic framework. Risks need to be assessed taking account of uncertainties, yet presented in ways that enable public officials to make policy decisions. All these attributes of risk assessment are taking volcanologists to unfamiliar territory and concepts. Here we present the scientific component of work carried out to assess risk from long-term exposure to respirable volcanic ash on Montserrat. Although the study is specific, it illustrates generic principles for methods of making quantitative probabilistic assessments of volcanic hazards.

The Soufrière Hills volcano, Montserrat, has been erupting since July 1995 (Robertson et al. 2000; Druitt and Kokelaar 2002) and has produced frequent and heavy ash falls over the island (Bonadonna et al. 2002b). The ash is exceedingly fine-grained, with typically between 5–15 wt.% respirable (<10 μm) particles (Horwell et al. 2003b). The ash also contains abundant cristobalite, a crystalline silica polymorph associated with toxic effects in animals and humans (Baxter et al. 1999) and with generation of free radicals (Horwell et al. 2003a). These features have prompted concern that people living and working in the worst affected areas may be exposed to unacceptable levels of respirable ash. Uniquely, the close proximity of the island's population to the volcano has resulted in a new hazard of community exposure to elevated levels of crystalline silica. With a potential total duration of possibly decades, long-term exposures for certain groups may exceed occupational standards for cristobalite and respirable particulate matter (PM_{10}). PM_{10} is defined as particulate matter sampled through an inlet with 50% cutoff at 10 μm and roughly equivalent to the International Organization for Standardization (ISO) particle size fraction definition for health-related sampling (ISO 1995).

Since 1996, the UK Department for International Development (DFID) has been promoting work on the health risks of volcanic ash, following the finding of significant levels of cristobalite in ash from the Soufrière Hills volcano (Baxter et al. 1999). Work to date has included two laboratory studies looking at ash inhalation and instillation in the lungs of rats, and radiological and exposure studies conducted on the island (Cowie et al. 2002; Searl et al. 2002). The studies concluded that the ash was probably of low to moderate toxicity and that the majority of the present population (about 4500 people) had not been exposed to sufficiently high concentrations of ash for long enough to be at risk of developing silicosis. However, results of exposure surveys suggested that outdoor workers were at higher risk, with a small fraction possibly having had sufficient exposure to be at risk of developing a mild form of the disease. There has also been concern that children may be more susceptible to the adverse health effects of crystalline silica.

In assessing long-term exposure to dusts it is necessary to determine the concentration of airborne respirable particles. The UK Health and Safety Executive recommends a maximum occupational exposure limit for respirable crystalline silica of 0.3 mg m^{-3} (8 h time weighted average), although employers should aim to control exposures to below 0.1 mg m^{-3} (Health and Safety Executive 2003). The US National Institute for Occupational Safety and Health (NIOSH) recommends an exposure limit of 0.05 mg m^{-3} as a time-weighted average for up to a 10-hour workday during a 40-hour working week (NIOSH 2002). The UK air quality standard for PM_{10} in ambient air is 50 μgm^{-3}(Department for Environment, Food & Rural Affairs of the United Kingdom 2000).

A risk assessment needs to estimate the time-averaged and cumulative exposure to suspended respirable volcanic ash. Such estimates require knowledge of the processes that control dust suspension, including volcanic, meteorological, erosional and sedimentation phenomena, as well as human activities. Here we present a model of the physical processes that control suspended respirable dust levels as an input to the risk assessment. Because of the presence of epistemic and aleatory uncertainties in any representation of these processes (Woo 1999), the model is developed by simulating time series of exposure with large numbers of runs, sampling from the assessed uncertainties in relevant parameters by a Monte Carlo technique. Possible future exposures and the associated risk to health are thus evaluated in probabilistic terms.

Health hazards associated with volcanic ash

Epidemiological studies indicate that workers exposed to respirable silica have an increased risk of developing lung cancer, pulmonary tuberculosis and non-malignant respiratory disease (including silicosis) (NIOSH 2002). There are also possible links to autoimmune diseases. Airborne samples of Montserrat ash contain around 8 to 17 wt.% crystalline silica in the respirable (sub 4 μm) fraction (Horwell et al. 2003b). Baxter et al. (1999) found the crystalline silica content of the sub-10 μm (roughly equivalent to PM_{10}) fraction of ground deposits to be between 10 and 24 wt.% for dome collapse ash and between 3 and 6 wt.% for ash produced in Vulcanian explosions. About 97% (by particle number) of the crystalline silica is cristobalite (Horwell et al. 2003b). Critical factors governing biological reactivity of silica in the lung include particle size and surface chemistry. Both factors are subject to a high degree of natural variation and are not well understood, and thus introduce significant uncertainty into any risk assessment. The reactivity of other constituent particles is not fully understood and may be significant in terms of health risk. Concentrations of hydroxyl radicals in respirable ash from Montserrat are 2–3 times higher than the toxic quartz standard (Horwell et al. 2003a). In the lung, hydroxyl radicals

can cause damage to DNA and local inflammation. Reactivity of the ash particles declines with weathering, suggesting elevated risk shortly after an event. Results of animal experiments suggest that Montserrat ash is of moderate toxicity, similar to mixed coal mine dusts (Cullen et al. 2002). Fine dusts can also exacerbate pre-existing conditions such as asthma and bronchitis, especially in children and the elderly.

There are two main methods of assessing the potential long-term effects of inhalation of particulate matter: cumulative exposure and total dose. Cumulative exposure is a measure of the amount of contaminant to which an individual is exposed over a specified time period, and here is equal to the measured average concentration of the contaminant ($mg\ m^{-3}$) multiplied by exposure time (years). Total dose is the amount of contaminant actually absorbed by the body. Total dose is particularly difficult to estimate in the case of volcanic ash, as little is known about the biological reactivity of the constituent minerals. This risk assessment applies dose-response curves from two occupational epidemiological studies to estimate risk of silicosis based on cumulative exposure. It is not clear from existing studies whether or not it is reasonable to compare occupational exposure levels based on a 8-hour, 5-day working week exposure with potentially continuous exposure as experienced in some parts of the island. However, industrial standards provide the only guidelines currently available. An estimate for acceptable environmental exposure is one fifth of the recommended occupational exposure limit (Pilkington et al. 1996). More crucially, perhaps, there are no such standards for exposure levels for children and infants.

In this paper, cumulative exposure is quoted in $mg\ yr\ m^{-3}$, where 'year' denotes a complete year of exposure (24 h × 365 days). An 'occupational year' is taken as being 50 weeks × 40 h/week, therefore 1 occupational year ≈ 0.23 full years.

Definition of silicosis

Silicosis is diagnosed by chest x-ray. Radiographs are classified by profusion of small opacities on the lung and are typically read in accordance with the International Labour Organization (ILO) International Classification of Radiographs of Pneumoconioses (standard radiographs). There are four categories, with category 0 corresponding to no opacities and category 3 corresponding to the highest level of opacities. As it can be difficult to classify profusion precisely, the categories are subdivided to record uncertainty in classification. Category 1/0 corresponds to the case where a reader considered classification of category 0 before making a final assessment to classify as category 1 and represents only a minor radiographic abnormality. 1/1 represents a clear category 1 radiograph. Category 1 opacities are unlikely to give rise to discernable respiratory impairment. Category 2 opacities are a more specific cut-off, while category 2/1 + is regarded as the most reliable basis for identifying true cases of silicosis in large-scale epidemiological studies.

The model

Airborne ash levels are dependent on production of ash by the volcano, the remobilisation of ash deposits, weather conditions (e.g. wind, rain and dry conditions) and human activity (e.g. vehicle movements, grass-cutting or sweeping). The frequency and magnitude of ash deposition events and rate of erosion are major factors affecting long-term cumulative exposure. There is also natural variability in the cristobalite content of the ash. Cristobalite is formed by devitrification and vapour-phase crystallisation in the dome (Baxter et al. 1999). In the Montserrat eruption, at least, ash from Vulcanian explosions is significantly lower in Cristobalite than dome collapse ash. Airborne concentrations of re-suspended ash decreases exponentially with height above the ground, so small children will be exposed to higher ash concentrations than adults (Horwell et al. 2003b). An individual's exposure or 'dose' will therefore depend on rate of volcanic activity, deposit depth, origin and weather, and upon his or her occupation and activities.

Code has been written to simulate long-term volcanic activity, rainfall, ash deposition and erosion on Montserrat, with a time step of 1 day. Four sites are considered: Cork Hill, Salem, Woodlands and Fogarty (Fig. 1). Cork Hill was evacuated on 25 June 1997, remained within the exclusion zone until the end of April 2004, and was a comparatively high-risk area in the early phase of the eruption.

The model assumes volcanic activity with event magnitudes and frequencies similar to the 1995–2000 period for the duration of the simulation. To capture the variation in exposure across the population, 24 h mean PM_{10} and cristobalite exposures are calculated for six representative occupation groups ranging from highly exposed outdoor
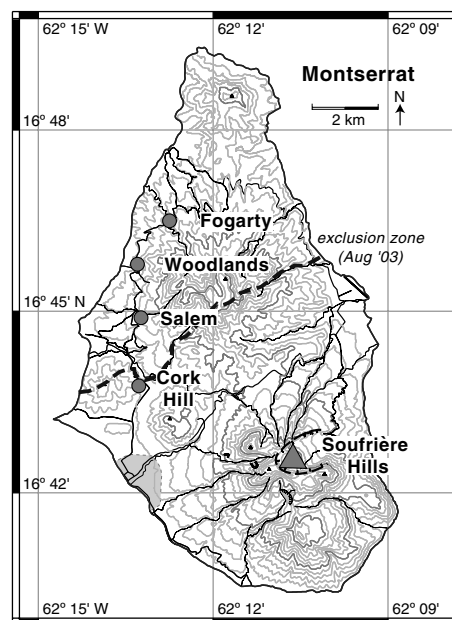
Fig. 1 Map of Montserrat showing sites for ash exposure risk assessment

Table 1 Personal exposure levels for the six population groups (dry day values) in milligrams per cubic metre. Categories cover both typical and high exposure groups. 'Average adult' represents typical exposure for an adult in an indoor occupation (e.g. office or shop work). 'Dusty indoor' represents adults in dusty indoor occupations (e.g. cleaning). Outdoor occupational categories include gardeners, police and Public Works Department workers (PWD). The child category represents the expected range in exposure for a child from birth to 10 years

Deposit state	Depth	Estimate	Average adult	Dusty indoor	Gardener	Police	PWD	Child
			PM_{10} exposure levels (mg m^{-3}) and beta distribution parameters $B(p,q)$					
Negligible	<1 mm	min	0.071	0.081	0.171	0.081	0.081	0.081
		mean	0.106 p=4.000	0.122 p=4.000	0.223 p=1.124	0.122 p=4.000	0.122 p=4.000	0.275 p=7.544
		max	0.142 q=4.000	0.163 q=4.000	0.408 q=4.000	0.163 q=4.000	0.163 q=4.000	0.378 q=4.000
Minor	<1 cm	min	0.213	0.244	0.379	0.244	0.244	0.244
		mean	0.283 p=2.000	0.325 p=2.000	0.483 p=0.296	0.325 p=2.000	0.325 p=2.000	0.706 p=5.940
		max	0.425 q=4.000	0.488 q=4.000	1.892 q=4.000	0.488 q=4.000	0.488 q=4.000	1.018 q=4.000
Moderate	1–3 cm	min	0.283	0.325	0.417	0.325	0.417	0.325
		mean	0.425 p=2.000	0.488 p=2.000	0.558 p=0.382	0.488 p=2.000	0.558 p=0.382	1.018 p=2.898
		max	0.708 q=4.000	0.813 q=4.000	2.042 q=4.000	0.813 q=4.000	2.042 q=4.000	1.974 q=4.000
Major	>3 cm	min	0.425	0.488	0.758	0.758	0.758	0.488
		mean	0.992 p=5.333	1.138 p=5.333	1.192 p=0.599	1.192 p=0.599	1.192 p=0.599	2.264 p=4.000
		max	1.417 q=4.000	1.625 q=4.000	4.083 q=4.000	4.083 q=4.000	4.083 q=4.000	3.531 q=5.604

workers and children to an average, moderately active adult (defined in Table 1). Individual daily exposure is a function of human activity (hence occupation), age, ash deposit thickness at a given site and rainfall, which dampens deposits, thus reducing airborne concentrations. Daily values are summed in a run to produce cumulative exposures for periods of 5, 10 and 20 years. Output is generated for $10000 \times n$ year simulations to produce exceedance probability plots of potential exposure for all occupation groups, locations and exposure periods. At each daily time step in a simulation, the code randomly samples from the probability distributions for all controlling variables, allowing for correlation between variables where appropriate (described below). Some input parameters have been determined by expert elicitation, informed by current knowledge and understanding of the processes; others are derived from empirical evidence and where appropriate or available, modelling studies. Figure 2 shows the components and processes of the model.

Methods

Monte Carlo simulation and uncertainty

Monte Carlo methods are well suited to analysis of complex systems and natural processes subject to a high degree of uncertainty. Controlling parameters are represented by probability density functions parameterised to capture aleatory uncertainties in the system. By repeated simulation, the range of expected behaviour of the system can be explored. Exceedance probability plots characterise the degree of uncertainty. A Monte Carlo scheme must account for correlation between variables in order to maintain physical accuracy. Variables may have different distributional forms, but the sampling has to be constrained in such a way as to avoid nonsensical outcomes.

A drawback of Monte Carlo simulation is model bias. In constructing any model, a large number of assumptions must be made. Although these may be based on the best available data and knowledge, they are open to error. This is a deterministic model and as such has a limited range of possible outcomes. In the hazard and risk arena it is essential to document the scope and limitations of the model, to draw attention to potentially significant states outside the model domain and any simplifications that impose limits on the degree of belief in the output (Burmaster and Anderson 1994). The output from a Monte Carlo simulation is not a forecast, rather a tool to enable risk-informed decision-making.

Number of trials

The optimum number of trials in Monte Carlo simulation can be decided by applying a 'stopping rule'. One standard stopping rule is to curtail the trials when the standard error

Fig. 2 Model flowchart for estimation of PM$_{10}$ and cristobalite exposure
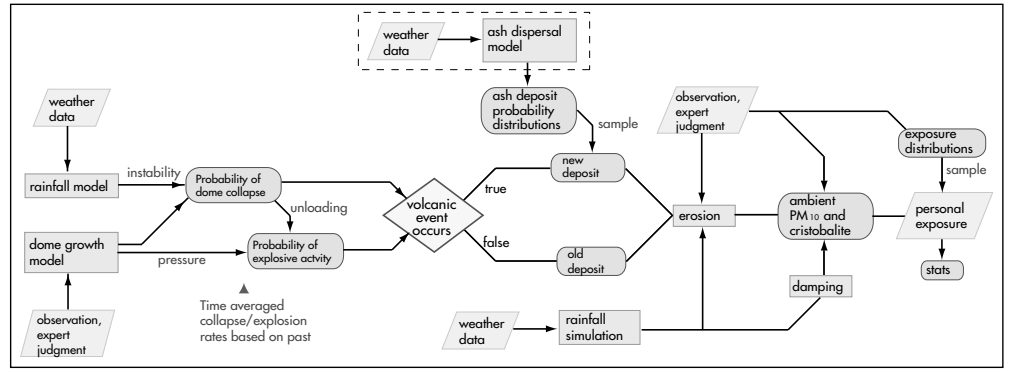
of the mean (S.E.M.) is <1% of the mean value.

$$S.E.M. = \frac{s}{\sqrt{N}} \tag{1}$$

where s = sample standard deviation and N = number of trials (Buslenko et al. 1966). For simulations presented here $N = 10000$ gives a S.E.M. in the range 0.14% to 0.37%.

Expert elicitation

Expert elicitation is a formal process of obtaining information and quantifying uncertainty where values cannot be obtained empirically or by physical models. The method involves a discussion of the model parameters by a group of experts. Each expert provides a best estimate value and upper and lower quantiles that can be used as tail markers for each parameter. The experts' estimates are pooled with some weighting according to the degree of informativeness and knowledge of the individual expert, calculated using formal mathematical scoring rules (Cooke 1991).

Statistical distributions

Certain statistical distributions are favoured in this kind of analysis. The beta distribution can be used to represent smooth variability over a fixed interval (cf. the triangular distribution). Two shape parameters (p and q) approximate a range of distribution shapes (Bruine de Bruin et al. 2002). Beta distribution parameters have been calculated using experts' best estimates for the minimum and maximum values (a and b) and sample mean ($\bar{x}$), and a fixed value for $p = 4$. Setting $p = 4$ gives a standard deviation of the order 13-18% of the distribution range.

For $a = 0$, $b = 1$ estimates for p and q are given by

$$p = \bar{x}\left(\frac{\bar{x}(1-\bar{x})}{s^2} - 1\right)$$
$$q = (1 - \bar{x})\left(\frac{\bar{x}(1-\bar{x})}{s^2} - 1\right) \tag{2}$$

Where s^2 is the sample variance.

When $a \neq 0$ or $b \neq 1$, we substitute

$$\bar{x}' = \frac{\bar{x}-a}{b-a} \quad \text{for the sample mean, } \bar{x}$$
$$s^{2'} = \frac{s^2}{(b-a)^2} \quad \text{for the sample variance, } s^2 \tag{3}$$

in (2) (NIST/SEMATECH 2003).

The lognormal distribution is continuous over the range x = 0 to $+\infty$. Lognormal distributions are typically used to represent multiplicative processes in nature, or where the law of proportionate effect applies (Aitchison and Brown 1957). Examples of lognormally-distributed variables include latency periods for infectious diseases, particle sizes (generated by natural processes in soils or rocks as well as mechanical grinding), human bodyweight, atmospheric turbulence and rainfall (Aitchison and Brown 1957; Crow and Shimizu 1988).

Simulations

The code has been run for periods of 5, 10 and 20 years, with 10000 runs per simulation. A number of modifications have been implemented to examine model sensitivity (Table 2), accounting for uncertainty in rates of volcanic activity and dome growth, PM$_{10}$ and cristobalite dose (exposure and environmental concentrations), atypical rainfall and the effect of a programme of active ash clearance.

Model inputs

Stochastic volcanic events

The eruption of the Soufrière Hills has been ongoing since July 1995 and we have based our model scenarios on this activity. We prescribe 6 event categories that can lead to significant production of volcanic ash:

$\geq 75 \times 10^6 \text{m}^3$ dome collapse
$50\text{–}74 \times 10^6 \text{m}^3$ dome collapse
$30\text{–}49 \times 10^6 \text{m}^3$ dome collapse
$10\text{–}29 \times 10^6 \text{m}^3$ dome collapse
$3\text{–}9 \times 10^6 \text{m}^3$ dome collapse

Table 2 Summary of simulations and sensitivity tests (tick denotes test carried out). Fixed personal exposure denotes exposure set at the beta distribution maxima (Table 1) for each population group. Typical exposure distributions are defined in Table 1. Fixed cristobalite content is 25% of PM_{10} for dome collapse (DC) ash and 5% of PM_{10} for ash from Vulcanian explosions (VE), otherwise cristobalite fraction is treated as a uniform random variable, 1 – 5% for VE ash 5 – 25% for DC ash.The rainfall model was modified by increasing or decreasing the mean rainfall by 20% (simulations 1e and 1f).

A correction was applied to airborne cristobalite concentration to account for the presence of non-volcanic dusts in simulations 2a–3b (see section 'Exposure to PM_{10} and Cristobalite'). Simulations 3a and 3b account for active ash clearance of moderate to major deposits. Deposit lifetimes are given in Table 4. Observed rates of extrusion and collapse activity were increased by a factor of 3 (4a and 4b) and a factor of 10 (4d) (see 'Dome Growth' section). Typical activity rates are given in Table 3. Simulations 4a and 4c were run with constant extrusion rates of 1 m^3s^{-1} and 3 m^3s^{-1} respectively

Simulation	Duration (years)	1. Fixed personal exposure	2. Fixed cristobalite content	3. Change to rainfall model	4. Correction for non-volcanic dusts	5. Active ash clearance	6. Growth & activity rate	7. Constant dome growth function
1a	20, 10, 5							
1b	20, 10, 5	✓						
1c	20, 10, 5		✓					
1d	20, 10, 5		✓					
1e	20			+20%				
1f	20			20%				
2a	20, 10, 5				✓			
2b	20, 10, 5	✓			✓			
2c	20, 10, 5		✓		✓			
2d	20, 10, 5	✓	✓		✓			
3a	20, 10, 5				✓	✓		
3b	20, 10, 5	✓			✓	✓		
4a	5, 20							✓
4b	5, 20						×3	
4c	5, 20						×3	✓
4d	5, 20						×10	

$0.4 \times 10^6 m^3$ Vulcanian explosions (a phase of 50 to 100 explosions, each $0.4 \times 10^6 m^3$ in volume, occurring at intervals of 24 h)

Smaller events are neglected as they generate trivial amounts of volcanic ash (Bonadonna et al. 2002b).

The simplest model approximates volcanic activity by a marked Poisson process, with a fixed daily probability of occurrence for each event category. The prior daily probability is modified to account for factors that may change the likelihood of event occurrence. The probability of initiating Vulcanian explosions is increased in periods of high dome growth rate and in the aftermath of a large dome collapse event ($\geq 30 \times 10^6$ m^3) (Druitt et al. 2002). The probability of dome collapse is increased in periods of heavy rainfall (Matthews et al. 2002). The probability of large collapse events decreases or even becomes zero after a major collapse until the dome has re-grown to a threshold size. Time averaged rates of activity (Table 3) are consistent with the last 8 years of the eruption.

Initial daily probabilities are modified to account for the time-averaged effect of rain (in the case of dome collapse events), eruptive history and dome growth rate (for Vulcanian explosions) so that for any given run:

$$E(event) \approx \sum_{t=1}^{t=T} P_t(event \mid r_t, h_t, g_t) \qquad (4)$$

where $E(event)$ is the expected number of events in T days ($T = 7300$ days), $P_t(event)$ is the daily (time varying)

Table 3 Expected number of events as a function of event magnitude, used to estimate base-rate daily probability of occurrence. DC = Dome collapse; VE = Vulcanian explosion

Magnitude	Expected number in 20 years E(event)
$\geq 75 \times 10^6$ m^3 DC	2.50
$50–74 \times 10^6$ m^3 DC	3.75
$30–49 \times 10^6$ m^3 DC	5.00
$10–29 \times 10^6$ m^3 DC	12.50
$3–9 \times 10^6$ m^3 DC	19.46
0.4×10^6 m^3 VE	2.00

probability of an event given rainfall (r_t), event history (h_t) and dome growth rate (g_t) at time t. $P(event) = 0$ when the dome volume is less than a threshold for the event. There are no long-term trends governing event frequency.

Variation of probability of dome collapse P(DC) with rainfall

Most of the major dome collapses of the Soufrière Hills (20 March 2000 and 29 July 2001) were preceded by prolonged and intense rainfall, with peak instantaneous rates in excess of 80 mm/hour (Matthews et al. 2002). Intense rainfall also occurred in the hours prior to dome collapse on 3 July 1998 and 14 October 2001(Matthews and Barclay 2004). The model therefore assumes an increased probability of collapse on days with extreme rainfall. This realisation has no memory; previous days rainfall do not contribute

to the new daily probability. Kerle et al. (2003) discuss the possible triggering effects of strong, continuous antecedent rainfall and intense episodic rainfall on flank collapse of a volcanic edifice, which would suggest modelling collapse probability as a higher order Markov process. However, data are not sufficient to formulate a statistical model in the present case, and it is problematic to quantify the effect of rainfall (particularly over time) on dome stability. Two simple rules were derived by expert judgement:

Daily rainfall ≥ 70 mm and < 200 mm: P(DC) = base probability $\times$ 18.25
Daily rainfall ≥ 200 mm: P(DC) = base probability $\times$ 73

The multipliers in these two rules (18.25, 73) are, respectively, estimates of Bayes likelihood ratios which would be consistent with the observed association of dome collapses with heavy rainfall and with the number of times per year that such heavy rainfall days occur without dome collapse.

Probability of Vulcanian explosions $P(VE)$

Several episodes of Vulcanian explosions on Montserrat (Robertson et al. 1998; Druitt et al. 2002) with substantial ash production have started within several hours of a major dome collapse. Conditions for explosive activity thus appear to be promoted by unloading due to dome collapse. The most substantial explosive activity occurred in 1997 when extrusion rates were high, a relationship interpreted as a consequence of higher overpressures in faster magma ascent rates. To capture this behaviour we assume an increased probability of entering a period of Vulcanian explosions $P(VE)$ following a large dome collapse ($\geq 30 \times 10^6 \mathrm{m}^3$) and when extrusion rates are high. $P(VE)$ is deemed to increase by an arbitrary factor of 10 (i.e. one order of magnitude) immediately after any collapse event $30 \times 10^6 \mathrm{m}^3$ or greater, but is otherwise independent of the magnitude of the collapse (Eq. 5). The effect is taken to decrease linearly with time, reducing to the base rate after 90 days. As there have only been 2 prolonged periods of Vulcanian explosions, there is no statistical justification for a more complicated relationship. Probability $P(VE)$ increases linearly with daily mean extrusion rate (Exq. 6). At the highest extrusion rate (10 m $^3\mathrm{s}^{-1}$), $P(VE)$ is a factor of 10 greater than at the minimum rate (0.5 m$^3\mathrm{s}^{-1}$).

Simple linear functions represent the variation in probability with growth rate and collapse activity. A basic model for the daily probability of entering a period of Vulcanian explosions was obtained by expert elicitation of the following parameters:

1. The range of $P(VE)$ for maximum and minimum growth rates
2. The time-averaged probability determined by the expected number of events in 20 years (independent of growth rate and other activity)
3. An estimate of the effect of a major dome collapse on $P(VE)$.

With less than 90 days since the last major dome collapse ($30 \times 10^6 \mathrm{m}^3$ or greater), we set:

$$P_t(VE \mid g_t, n_t) = \frac{0.0012}{19} (1.8g_t + 1) \left(10 - \frac{n_t}{10}\right) \qquad (5)$$

Where $P_t(VE \mid g_t, n_t)$ equals the probability of entering phase of Vulcanian explosions at time t (days) given the current extrusion rate g_t (m$^3\mathrm{s}^{-1}$) and time since the last major collapse n_t (days) for $0.5 \leq g_t \leq 10.0$ m$^3\mathrm{s}^{-1}$ and $0 \leq n_t \leq 90$ days.

When more than 90 days have elapsed since the last major dome collapse (i.e. $30 \times 10^6 \mathrm{m}^3$ or greater), we set:

$$P_t(VE \mid g_t) = \frac{0.0012}{19} (1.8g_t + 1) \qquad (6)$$

Where $P_t(VE \mid g_t)$ equals the probability of entering a phase of Vulcanian explosions at time t (days) given the current extrusion rate g_t (m$^3\mathrm{s}^{-1}$) for $0.5 \leq g_t \leq 10$ m$^3\mathrm{s}^{-1}$. Constants in Eqs. (5) and (6) have been calculated using upper and lower estimates for $P(VE)$, assuming a linear relationship between extrusion rate and probability of explosion.

The code tests for event occurrence at each time step (day) by sampling from a Bernoulli distribution given the current daily event probability (outcome is either true or false). The test is performed for each category of event and more than one event can occur within a period if there is sufficient dome material. Following an event, ash deposits at each site are obtained by correlated sampling (discussed in the following section), accounting for wind conditions, distance from the vent and source conditions.

Ash deposit distributions

The depth of ash deposited is dependent on the scale of the event (column height and total volume), site location with respect to the source, and wind speed and direction. To capture the variation in tephra deposit depth, the HAZMAP code (Bonadonna et al. 2002a) was run with three years of daily wind data for Montserrat to generate a series of tephra deposits for each location, event type and magnitude. The resulting output (1095 points per event/location) was used to calculate the best-fit distribution for deposit depth. HAZMAP has previously been calibrated to give an optimum fit to observed tephra distributions on Montserrat (Bonadonna et al. 2002b). HAZMAP models pyroclastic flows down 5 main valleys, and the outputs are weighted according to past behaviour. Vulcanian explosions are treated as single source events. Figure 3 illustrates the output as an exceedance probability plot generated from HAZMAP output for the four sites following a 75×10^6 m^3 dome collapse event. Truncated lognormal probability distribution functions are used to represent the range of possible outcomes, with distribution parameters for each combination of site and event type. The maximum deposit generated by the tephra dispersal model (based on the maximum available material) determines the point of truncation.
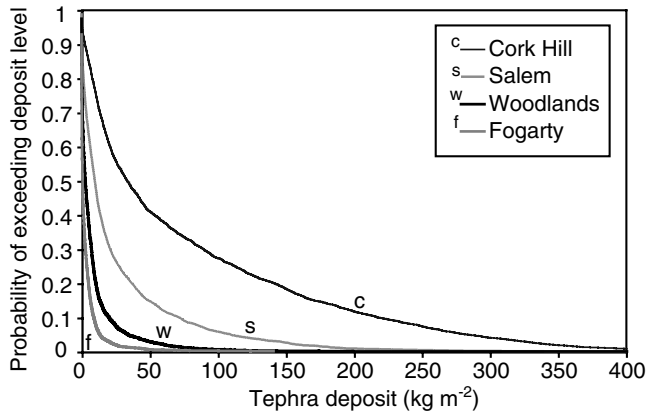
Fig. 3 Probability of exceedance plot for tephra deposits at 4 sites, following a 75 million cubic meter (or greater) dome collapse event. Deposit depths calculated using HAZMAP tephra dispersal code, run with 3 years of daily wind data and allowing for pyroclastic flows down 5 major valleys. c= Cork Hill, s= Salem, w= Woodlands and f= Fogarty (see Fig. 1 for locations)

Tephra fall deposits at fixed positions are highly correlated with respect to the source because they experience the same weather conditions. Correlated sampling applies Choleski decomposition, which involves constructing a matrix of the variances and covariances of the $\log_e$ of the HAZMAP output data, and calculating the Choleski factor (Press et al. 1996). For a real solution to exist the matrix must be symmetric (automatically satisfied) and positive-definite. Slight adjustment of the matrix elements, typically less than 1%, was required to meet the latter condition. Accuracy was tested by comparing the distribution of 10000 correlated sample values, for all event types and locations, with the HAZMAP data (Fig. 4), and by computing the sample mean, variance and skewness for both sampled and HAZMAP data.
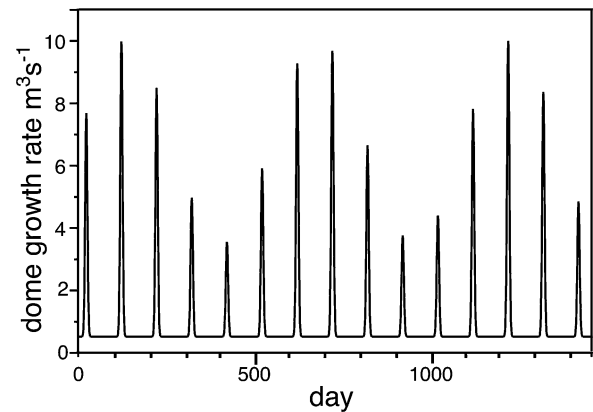
Dome growth

The dome growth function governs re-growth following a major collapse or period of explosive activity. As a collapse can only occur if there is sufficient dome material available, the replacement rate affects the frequency of large collapse events.

Dome growth during the Soufrière Hills eruption has been documented (Sparks et al. 1998; Voight et al. 1999; Watts et al. 2002). Extrusion rate has varied from almost zero to over 10 m^3s^{-1}, with long term averaged rates of 2–3 m^3s^{-1}. Fluctuations occur on timescales from hours to years, and there is evidence of periodic behaviour with characteristic periods of 2 to 4 months (Sparks and Young 2002). Two periods of continuous dome growth were separated by a 20-month period of no dome growth (Norton et al. 2002). A second period of no dome growth began in July 2003, and to date (March 2005) growth has not resumed. Our aim here is to develop a representative model with broadly similar temporal patterns.
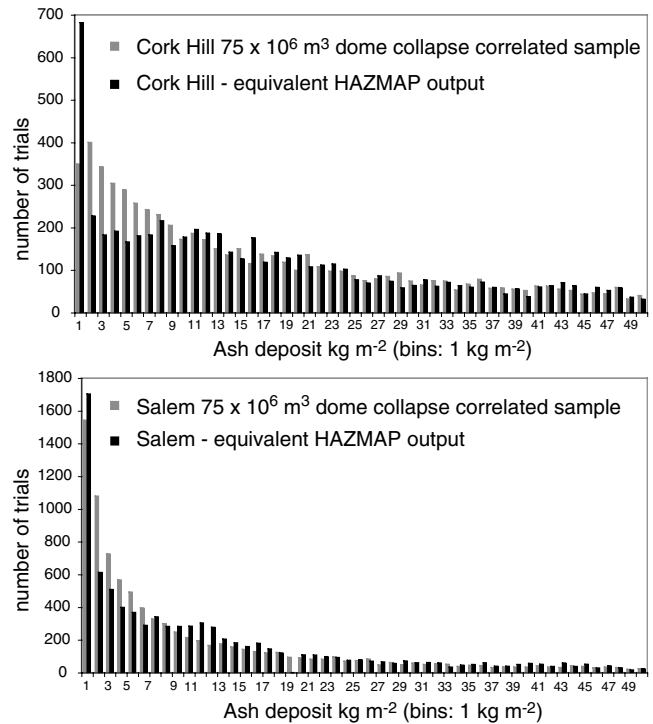

Fig. 4 Testing correlated sampling procedure for lognormal ash deposit distributions. Histogram of 10000 correlated samples and equivalent HAZMAP output (only Cork Hill and Salem data shown)

Fig. 5 Dome growth function. Periods of high growth rate occur approximately every 100 days, with a peak every 18 months

Dome growth is treated as regular and periodic (Fig. 5) with a long-term time averaged production rate of approximately 1 m^3s^{-1}, a maximum of 10 m^3s^{-1} and minimum of 0.5 m^3s^{-1}. Periods of high growth rate are short, of the order of days (Sparks et al. 1998; Watts et al. 2002), and in this model occur approximately every 100 days. A modulating component with a period of 18 months simulates long-term variations. Each run starts with a random phase shift, so that the growth rate cycle is not tied to season. We do not attempt to model extended periods of no growth. Fig. 6 shows a simulated 20-year time series for dome volume.
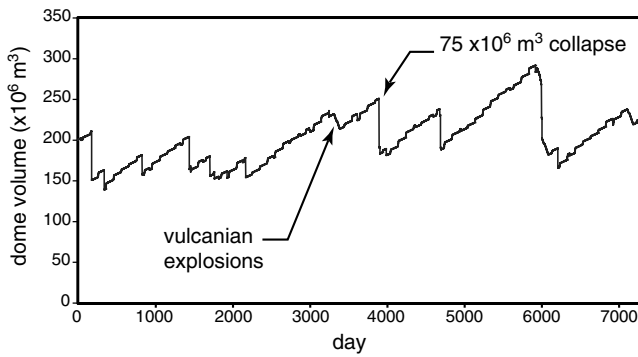
Fig. 6 Test time series for dome volume. Checks were made to ensure extrusion and collapse rates were consistent with observations, and that the total dome volume does not get unreasonably large

The dome growth function compounds the two modulating processes:

$$R = 0.5 + 2^{-48} \left[\sin\left(\frac{2\pi t}{100} + \theta\right) + 1 \right]^{48}$$
$$\times \left[3.25 \sin\left(\frac{2\pi t}{548} + \theta\right) + 6.25 \right] \quad (7)$$

where R is growth rate (m³ s⁻¹), t is time (days) and θ is a random phase shift (radians).

Constants have been set to give a time averaged extrusion rate of 1 m³s⁻¹. To test model sensitivity, simulations were run with constant extrusion rates of 1 m³s⁻¹ and 3 m³s⁻¹ (Table 2) and by using periodic growth functions with time−averaged rates of 3 m³s⁻¹ and 10 m³s⁻¹.

Erosion based on ash thickness

Erosion timescales were based on expert judgment because there are no established physical models for ash erosion. The lifetime of a deposit is defined for four categories of

ash thickness (Table 4), based on the experience of co-authors who have been on Montserrat for extended periods (Aspinall, Sparks, Searl, Baxter). The erosion function assumes removal by two mechanisms, wind and rain. Wind is active only in dry conditions, and insignificant in wet weather. Wind erosion is only dependent on deposit state and uses a beta distribution to represent the variation in deposit lifetime. Distribution parameters were calculated from estimates for the minimum, maximum and mean lifetimes determined by agreement of the experts, modified to account for the fraction of ash removed by rain. There is no seasonal component to wind removal in this model.

Effectiveness of active ash clearance

The code was run with reduced deposit lifetimes (Table 4) to simulate a programme of active intervention to clear dust following heavy ash fall. To represent the effect of such clean-ups, the mean lifetime for the 'major' deposit state was reduced from 2 years to 3 months, and the mean lifetime for the 'moderate' deposit state reduced from 6 months to 3 weeks.

Rainfall

Due to rapid evaporation rates and the typically short duration of rain showers outside the rainy season, low levels of rain have little, if any, erosive effect. Under light rain conditions (<3 mm in 24 hours), wind is assumed to be the dominant removal mechanism. For more intense rain a simple linear relationship between daily ash removal (kgm⁻²day) and rain depth (mm) is assumed:

$$A_{\mathrm{removed}} = \left(0.01 + \frac{r}{700} \right) A_{\mathrm{ground}} \quad (8)$$

where A_{removed}= ash removed (kg m⁻²); A_{ground}= ash deposit (kg m⁻²) and r = 24 hour rainfall (mm). Constants are

Table 4 Deposit lifetimes and beta distribution parameters for ash deposits for normal and active ash clearance. It is assumed that active ash clearance will only take place after heavy ash fall, and not affect 'minor' deposit lifetimes

Ash deposit state	Depth on ground	Estimate	Time to drop to lower deposit state	Beta distribution parameters $B(p,q)$	Time to drop to lower deposit state	Beta distribution parameters $B(p,q)$
			NORMAL ASH CLEARANCE		ACTIVE ASH CLEARANCE	
Negligible	<1 mm	min	No lower state: ash remains until removed by rain		No lower state: ash remains until removed by rain	
		mean				
		max				
Minor	<1 cm	min	1 day		1 day	
		mean	2 weeks	p=0.667	2 weeks	p=1.400
		max	3 months	q=4.000	4 weeks	q=4.000
Moderate	1−3cm	min	1 month		2 weeks	
		mean	6 months	p=3.341	3 weeks	p=0.800
		max	12 months	q=4.000	8 weeks	q=4.000
Major	>3 cm	min	1 year		2 months	
		mean	2 years	p=4.000	3 months	p=1.326
		max	3 years	q=4.000	6 months	q=4.000

Fig. 7 Time series output from a single run showing 10 years daily data for (**a**) rainfall, (**b**) dome volume, (**c**) daily probability of volcanic activity for a $\geq 75 \times 10^6$ m^3 dome collapse $P(75 \times 10^6 DC)$ and phase of Vulcanian explosions $P(VE)$, (**d**) ash deposit depth for Cork Hill and Salem, (**e**) airborne PM$_{10}$ and cristobalite levels (Salem only)
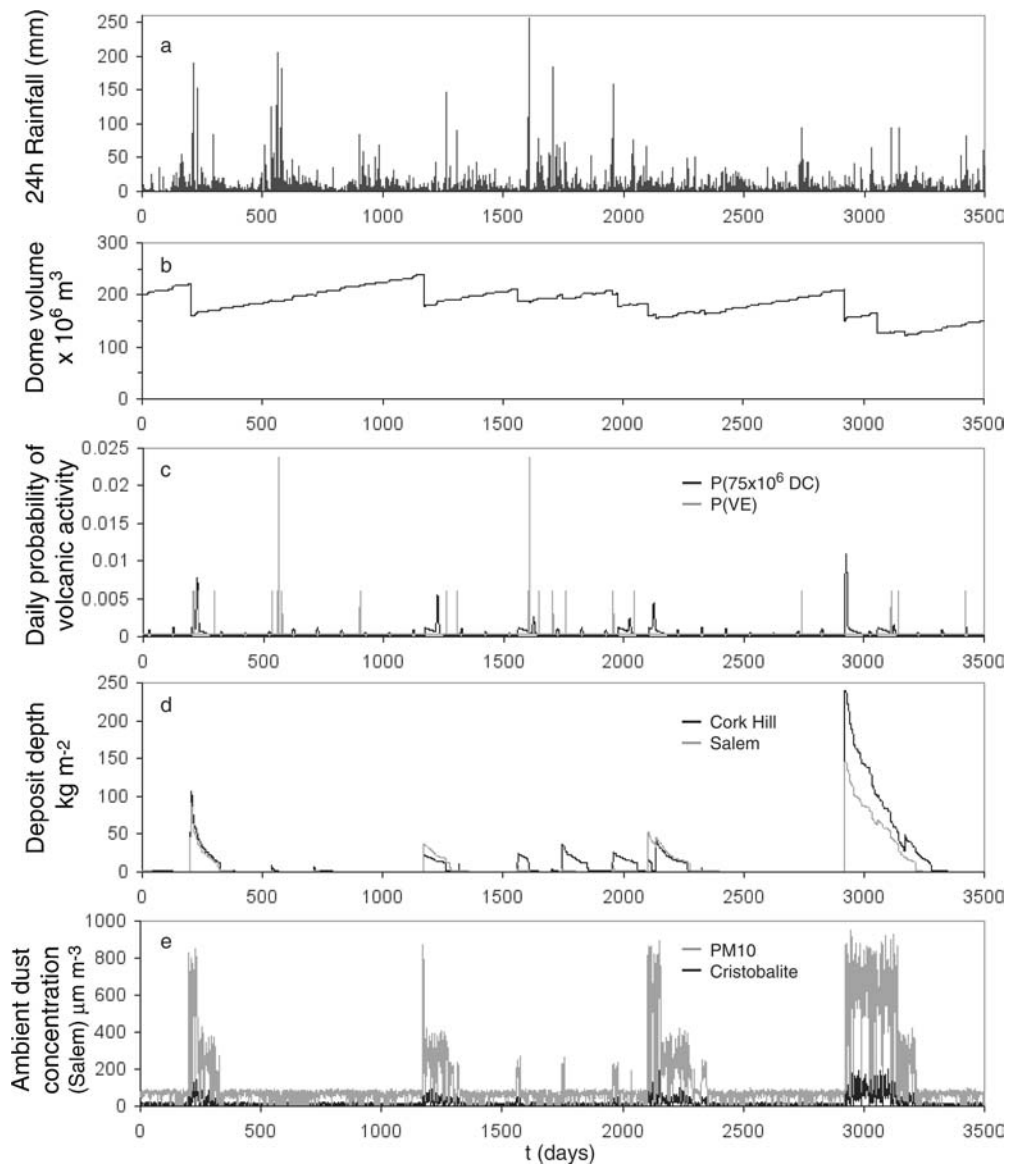

set to allow removal of 1.4% to 51% of the total ash deposit at a site in any 24–hour period, corresponding to daily rainfall in the range 3 mm to 350 mm. This is in keeping with observations that extreme rainfall will rework ash deposits, but not completely remove them. Typical hurricane rainfall rates in the Caribbean are of the order 150–350 mm/day. MVO rain gauges recorded 152 mm overnight on the 20 September 1998 during hurricane Georges, and 174 mm in 24 h on 19 November 1999 during hurricane Lenny (data: MVO/UEA). Figure 7d shows a typical time series for the depths of ash at two sites in a simulation, illustrating spatio-temporal correlations.

Rainfall time series

Rainfall is typically modelled as a two-part process. The first part generates a condition of 'rain' or 'no rain' and the second part determines the total rainfall (mm) on a wet

day. Rainfall affects the incidence of dome collapse events, ash erosion rates and airborne concentrations of PM$_{10}$ and cristobalite (Fig. 7). Our model aims to capture the key patterns and trends of rainfall in the region and is based on a time dependent daily probability of rain incidence (Fig. 8), mean and variance. For any day, when rain occurs, the total rainfall is obtained by sampling from a truncated lognormal distribution with a seasonally varying mean and standard deviation (Fig. 9) with an imposed upper limit of 350 mm for any 24–hour period.

For simulations of up to 20 years, correlation with long-term monthly and yearly meteorological averages is essential. Due to the limited rainfall data available for Montserrat, the time varying mean has been calibrated with 30 year averaged monthly means for Guadeloupe, a 15-month (partially complete) daily rainfall dataset for Montserrat (Jan 1999–Mar 2000) and 5 years of daily data for Antigua 1995–2000. The time varying standard deviation is based on a least squares best fit with
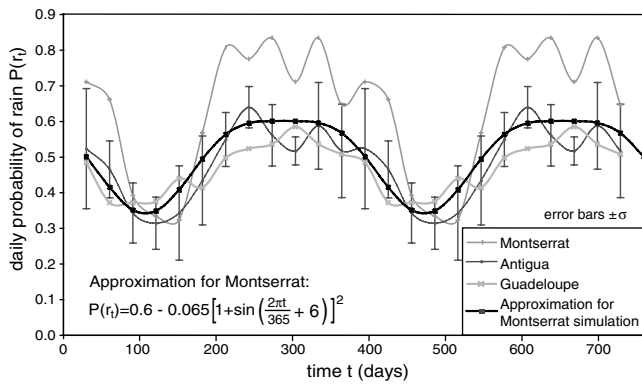
Fig. 8 Plot showing seasonal variation in incidence of rain. Data for Montserrat (12 months) Antigua (5 years) and Guadeloupe (30 year monthly averages for number of rain days/month) were used to estimate a time varying daily probability of rain for this simulation. The model for daily probability of rain, $P(r_t)$, at time t (days) is shown as a thick black line. Rainfall data for Montserrat were provided by the MVO, Antigua data by the University of the West Indies and Guadeloupe monthly averages are from the climatological information pages of the Hong Kong Observatory website
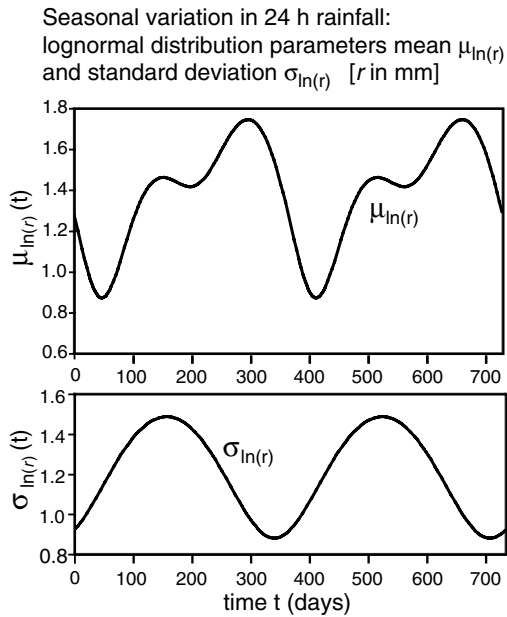
Fig. 9 Model for seasonal variation in 24 h rainfall (for days with rain). The amount of rain falling in a 24 h period was obtained by sampling from a lognormal distribution, with mean $\mu_{\ln(r)}$ and standard deviation $\sigma_{\ln(r)}$ that fluctuate through the year (two years are plotted for clarity). Derived from rainfall data for Montserrat provided by the MVO; Antigua data from the University of the West Indies and Guadeloupe monthly averages from the climatological information pages of the Hong Kong Observatory website

monthly standard deviations calculated from daily data for Montserrat and Antigua. Monthly standard deviations are calculated for ln*(rainfall)* for rain days only. This method ensures that the long-term behaviour of the simulated rainfall is in keeping with the available regional data. Rainfall statistics critical to the exposure model (number of days with rainfall >3 mm, >10 mm, >70 mm,

>200 mm, rainfall mean and variance) were calculated for all simulations to test the reliability of the rainfall model.

The first part of the rainfall simulation tests for the occurrence of rain, using a time varying probability of rain $P(r_t)$ at time t (Fig. 8):

$$P(r_t) = 0.6 - 0.065 \left[1 + \sin\left(\frac{2\pi t}{365} + 6\right)\right]^2 \qquad (9)$$

When a rain event occurs, the amount of rain (in mm) falling within 24 h is obtained by sampling from a truncated lognormal distribution with seasonally varying mean and variance (Fig. 9). The distribution parameters are estimated from the mean and variance of the natural logarithm of the rainfall data (for rain days only).

Mean μ of ln (rainfall) at time t (days):

$$\mu_{\ln(r)}(t) = 4.1 + 1.16 \sin\left(\frac{2\pi t}{365} + 3.37\right)$$
$$+ 0.75 \sin\left(\frac{2\pi t}{182.5} + 3.41\right) \qquad (10)$$

Standard deviation σ_t of ln(rainfall) at time t (days):

$$\sigma_{\ln(r)}(t) = 3.4 + \sin\left(\frac{2\pi t}{365} + 5.14\right) \qquad (11)$$

To test exposure sensitivity to the rainfall model simulations were run with a 20% increase in mean rainfall and a 20% reduction in mean rainfall (discussed in results section). There is no attempt to incorporate persistence (in terms of the one-day autocorrelation) in the current model, as this would only affect the short-term fluctuations in exposure intensity and duration but not cumulative exposure.

Exposure to PM_{10} and Cristobalite

Individual exposure to PM_{10}

Personal exposure is dependent on ash deposit state, occupation group and weather conditions. Table 1 reports the range of potential dry day exposure levels. Exposure ranges are represented by beta distributions; with distribution parameters calculated from minimum, maximum and mean PM_{10} exposure values supplied by the Institute of Occupational Medicine database. During the eruption, PM_{10} concentrations have been monitored at intervals and in one campaign using up to six Dust Trak instruments deployed in a network across the island, giving estimates for exposure levels as a function of occupation, deposit depth and weather conditions. Data on suspended PM_{10} are provided in Baxter et al. (1999), Searl et al. (2002) and Moore et al. (2002). Individual daily mean exposures are obtained by sampling from the appropriate distribution (given daily deposit state and occupation group), with a final adjustment for the effect of rainfall on airborne ash (see following

section). The cumulative exposure is the sum of the daily exposures over the time period of interest (in this case 5,10 or 20 years).

There is considerable uncertainty associated with children's exposure levels and any subsequent risk of disease. This is largely due to lack of measurement data and appropriate epidemiological case studies in a disease that is almost only seen in occupational settings. The ash concentration in the atmosphere is strongly dependent on height above the ground, exposing a small child to higher concentrations of ash than an adult under the same deposit and weather conditions. Horwell et al. (2003b) provide data on PM_{10} concentrations with height, suggesting suspended PM_{10} concentrations are about twice as large for a 10 year-old child as for an adult (other factors being equal). Due to a lack of field data and the high degree of natural variation in exposure we cannot fully account for the effect of age on childhood exposure. In this model, exposure distribution parameters for a child (Table 1) are assumed to apply from birth to 10 years of age, and over this period remain constant in time. To err on the side of caution, this is a conservatively high estimate. The 'average adult' exposure profile is assumed to apply from age 10 years onwards. Thus for someone born at or just before the eruption starts, this represents an entire lifetime of continuous exposure for a young person and is therefore the most extreme case.

To determine the upper exposure limit for each population group, the code was run with individual 24-hour mean exposures fixed at the upper limits of the elicited range (i.e. the beta distribution maxima).

Effect of rainfall on airborne PM_{10} and cristobalite levels

For daily total rainfall, r (mm):

3 mm < r < 10 mm: the exposure is reduced to 70% of dry day value

r ≥ 10 mm: the exposure is reduced to 10% of dry day value

to reflect the 'damping down' effects of rain. Due to rapid evaporation rates, it is assumed that less than 3 mm rainfall in 24 h will not significantly affect the daily exposure. These correction factors were determined by expert judgment and are based on Dust Trak measurements (Searl et al. 2002). Background exposure to both PM_{10} and cristobalite is assumed to exist even at the lowest deposit thickness (negligible ash, Table 1).

Fraction of cristobalite

Dome collapse ash is significantly richer in respirable silica compared to explosion ash (Horwell et al. 2003b). To account for this variation, quantities of ash due to dome collapse and due to explosion are each logged separately for each site. In this model, airborne cristobalite fraction is treated as a uniform random variable, 1 – 5%

by weight for ash from Vulcanian explosions (VE); 5 – 25% by weight for dome collapse ash (DC). These ranges represent the expected natural variation in cristobalite content and are based on measurements of environmental concentrations of respirable dust and cristobalite in Searl et al. (2002) and Horwell et al. (2003b). Individual cristobalite exposure is calculated from the daily personal PM_{10} exposure, the fraction of ash at the site from each event type (DC or VE) and random samples from the cristobalite fraction distribution for each source. In this model, airborne cristobalite fraction is not a function of the age of the dome. No robust model exists to describe rates of cristobalite formation, and field measurements of airborne cristobalite levels are limited in number and scope. Cristobalite forms within the dome on timescales of the order days to weeks (Baxter et al. 1999), but its not known how much more cristobalite will be present in dome material a few years old compared to a few months old, and all collapse events involve material of varying age and cristobalite content. Searl et al.(2002) document 172 airborne samples from the period September 1996 – June 1997 with a large variation in cristobalite fraction. Horwell et al.(2003b) present analyses of 12 samples (from 1997 – 2000) including 4 airborne samples from February 2000.

Horwell et al. (2003b) showed that non-volcanic particles (typically clay and salt) constitute 11 to 28 number percent of the airborne ash on Montserrat. Simulation 1 (see Table 2) assumes all airborne particulate matter is of volcanic origin, and calculates cristobalite concentration from the total PM_{10}. In simulations 2 and 3 we account for non-volcanic dusts by subtracting 10 μgm^{-3} from the daily mean PM_{10} concentration, and use this reduced value to calculate cristobalite concentration (as there is no cristobalite contribution from the non-volcanic fraction).

The surface chemistry of the silica particles is a significant factor affecting reactivity in the lungs. Freshly fractured silica is much more toxic than aged and weathered material, suggesting that there should be some correction made to account for the age of the deposit. However, due to long exposure periods and high variation in exposure conditions, existing epidemiological studies cannot provide a quantitative relationship between the age or surface properties of the particles and toxicity. A study on respirable quartz exposure in Scottish coal workers (Buchanan et al. 2003) showed that following a period of unusually high exposure to freshly fractured respirable quartz (due to machine cutting of sandstone), some workers exhibited radiological changes within several years. Buchanan et al. (2003) proposed a regression model for risk of silicosis based on cumulative exposures to crystalline silica at intensities above and below a threshold concentration of 2 mg m^{-3}, giving a higher weighting (by a factor of 3) to concentrations above the threshold. The data show no differentiation at lower exposure concentrations. However this could be due to the workers' high mean exposures (Table 5) limiting the resolution at low exposure concentrations. The study also comprised a relatively small sample (547 men). If exposure intensity and weathering are critical to biological reactivity in the lung, this will have a significant

Table 5 Comparison of occupational exposure from two cohort studies (Hughes et al. 1998 ; Buchanan et al. 2003) with estimated exposure on Montserrat. The cristobalite content of PM$_{10}$, however Horwell et al. (2003b) show that cristobalite is preferentially fractionated in the respirable (PM$_4$) fraction of the Montserrat ash has been measured as fraction of PM$_{10}$.

Study	Silica content of respirable dust PM$_4$ (sub 4 μm)	Typical duration of employment & years since first exposure	Mean respirable dust and silica (*occupational exposure is average over working hours only*)	Occupational cumulative exposure range (*mg yr m^{-3} occupational years*)	Equivalent full year cumulative exposure	Comments
Hughes et al. (1998) Retrospective cohort study of Diatomaceous earth workers	Natural diatomite: 3% calcined: 20% flux-calcined: 60% Checkoway et al. (1999):10% calcined 20% flux calcined Cristobalite forms during heating processes, so composition of silica dust is similar to volcanic ash	5.54 years median duration of employment Mean 11.5 years from first employment to date of last x-ray(range: 1 month - 46 years)	Dust: 0.93 mg m^{-3} Silica:0.30 mg m^{-3} Mean crystalline silica exposure:0.76 g.m^{-3} (hired before (1940) 0.12 mg m^{-3} (hired 1960 or later)	<1 mg yr m^{-3} to 12 mg yr m^{-3} (at low concentrations), or 18 mg yr m^{-3} (high concentration) 357 workers with cumulative exposure >3 mg yr m^{-3} were exposed to a mean concentration of 0.5 mg m^{-3}	~0.2 mg yr m^{-3} to 2.7 mg yr m^{-3} (low conc.) 4.1 mg yr m^{-3} (high conc.) *NB: distribution is highly skewed towards the low exposure end of the scale*	Most analogous to exposure on Montserrat Age (which is highly correlated with exposure intensity) is more statistically significant than cumulative exposure in estimates of risk of silicosis at low exposures Risk is calculated for category 1/1 opacities for two exposure categories: ≤0.5 mg m^{-3} and >0.5 mg m^{-3}
Buchanan et al. (2003) Scottish coalminers	Typical UK coalmine dust: up to 10% quartz (unpublished IOM report for the HSE, 1998) Very mixed composition dust, including a period of very high quartz concentration (>2 mg m^{-3})	A minimum of 12 years from first employment to last x-ray	Median exposure 0.01–0.1 mg m^{-3}. Small number of workers exposed to >3 mg m^{-3} Typical exposure ~8000 hours at quartz concentrations >0.1 mg m^{-3}	Risks are given for cumulative exposures in the range 0 – 4 mg yr m^{-3}	0 - 0.9 mg yr m^{-3}	Exposure to high quartz concentrations resulted in rapid radiological changes within several years. Risk function gives a higher weighting to exposures at concentrations ≥2 mg m^{-3} At follow-up 29% (158 of 547) showed profusion 1/0 or higher and 8.6% profusion 2/1+ (Miller et al, 1998)

Table 5 Continued.

Study	Cristobalite as fraction of PM$_{10}$	Typical duration of employment & years since first exposure	Mean respirable dust and silica (*occupational exposure is average over working hours only*)	Occupational cumulative exposure range (*mg yr m^{-3} occupational years**)	Equivalent full year cumulative exposure	Comments
Estimated exposure on Montserrat	Cristobalite fraction (model) 1–5 wt.% (ash from Vulcanian explosions) 5–25 wt.% (dome collapse ash)	Up to 8 years exposure to date (outside exclusion zone)	24 h mean:~0.02–0.06 mg m^{-3} in exclusion zone, ~0.01–0.04 mg m^{-3} outside zone. Range ~0.005–1.02 mg m^{-3}	10 years exposure ~1.0–2.7 mg yr m^{-3} in exclusion zone, ~0.5–1.9 mg yr m^{-3} outside zone (exposure varies with occupation)	10 years exposure ~0.2–0.6 mg yr m^{-3} in exclusion zone, ~0.1–0.4 mg yr m^{-3} outside zone	X-rays of 421 subjects taken in 2000 (after 5 years exposure) showed no evidence of chest abnormalities (Cowie et al. 2001)

* For conversion purposes an 'occupational year' is equivalent to 2000 h (Hughes et al. 1998)
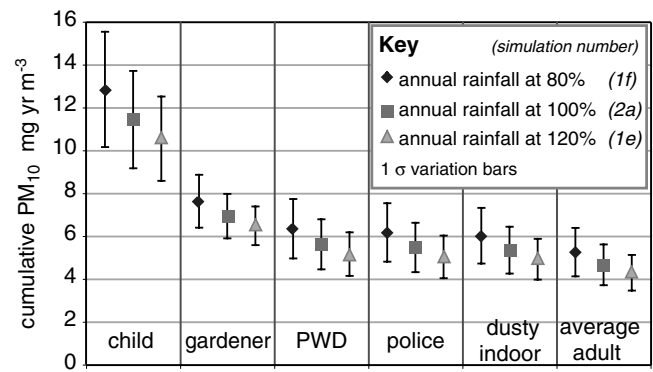
Fig. 10 Sensitivity test results for a 20-year simulation (Cork Hill only), showing cumulative PM$_{10}$ exposure for all occupation groups. See Table 2 for details of simulations

effect on estimates of risk. At present this model makes no distinction between recently deposited ash and old ash.

In simulations 1c, 1d, 2c and 2d (Table 2) the cristobalite fraction of the ash was set at the upper limit for each source (25 wt% of PM$_{10}$ for dome collapse ash and 5 wt% of PM$_{10}$ for ash produced in Vulcanian explosions) to simulate extreme-case exposure.

Results and implications

Figure 10 compares cumulative PM$_{10}$ exposure (20 years at Cork Hill) under 'typical' rainfall conditions with exposures generated for both low and high rainfall conditions (annual mean rainfall ± 20%). In this model, exposure sensitivity to variation in the rainfall model is small compared to the uncertainty in the exposure rules (airborne PM$_{10}$ levels and cristobalite content). Figure 11 shows cumulative cristobalite exposure (20 years at Cork Hill), comparing the effects of active ash clearance, high cristobalite content (fixed at 5% for VE ash and 25% for DC ash) and variation in rate of volcanic activity. Figure 11b shows that a constant extrusion rate has a minor effect on cumulative exposure (a slight increase in exposure mean and variance) due to the effect of growth rate on the temporal distribution of volcanic events. A 3-fold increase in time-averaged extrusion rate and frequency of collapse events results in a significant increase in cristobalite exposure (a factor of approximately 1.8 for a child and 1.4 for a gardener). Cumulative exposure increases asymptotically with increasing extrusion rate, limited by the 24 h exposure set for the upper deposit level.

Deliberate ash removal has a negligible effect on cumulative exposure under normal simulation rules (Fig. 11a) because it is assumed that such clearance will only take place on rare occasions following deposition of extremely large quantities of ash. For the majority of the time, deposit levels at the sites (particularly those furthest away from the volcano) fall in the 'negligible' and 'minor' categories, for which deposit lifetimes are unchanged.

Probability of exceedance curves for 20 years cumulative cristobalite exposure under the standard simulation rules
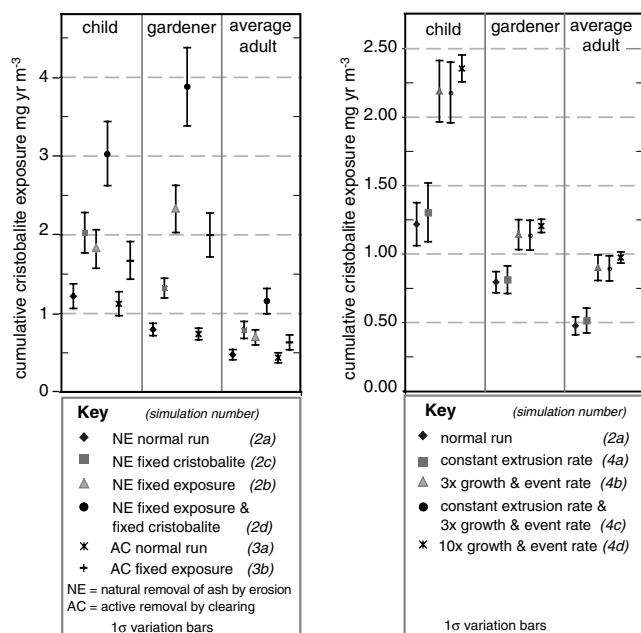
Fig. 11 (**a**) and (**b**). Sensitivity test results for a 20-year simulation (Cork Hill only), showing cumulative cristobalite exposure for a child, gardener and average adult. See Table 2 for details of simulations

(simulation 2a) are presented in Fig. 12. Estimated cumulative exposures for an average adult range from 0.20–0.25 mg yr m^{-3} (90th and 10th percentiles) for Fogarty (i)(f), to 0.39–0.56 mg yr m^{-3} in Cork Hill (i)(c). Exposure for a child at Cork Hill (iii)(c) under the same conditions is approximately 2.5 times higher: median cumulative exposure is 1.2 mg yr m^{-3} and the 90th and 10th percentiles are 1.0 and 1.4 mg yr m^{-3}. In the north of the island a child's estimated 20 year exposure is in the range 0.55-0.70 mg yr m^{-3} (iii)(w) and (f). Typical cumulative exposures for a gardener working on island for 20 years are 0.70-0.89 mg yr m^{-3} in Cork Hill (ii)(c), and 0.43-0.55 mg yr m^{-3} in Fogarty (ii)(c).

Comparison with occupational standards

Occupational exposure standards exist for PM$_4$ (sub 4μm) respirable dusts. The US National Institute for Occupational Safety and Health (NIOSH) recommend a time averaged upper limit for exposure to crystalline silica (including cristobalite) of 0.05 mg m^{-3} (airborne concentration, per m^3 of air). This is a time weighted average, based on an eight-hour working day, five-day week and a 40-year working life. It is difficult to apply such standards to 24-hour domestic exposure as industrial workers are typically subjected to more short duration, high intensity exposures and potentially fresher, more reactive material. Such occupational standards are made stringent to ensure a high degree of protection as is reasonably practicable under highly variable conditions. In the absence of a good understanding of the relationship between risk of disease and exposure intensity (especially at low exposures) we cannot determine
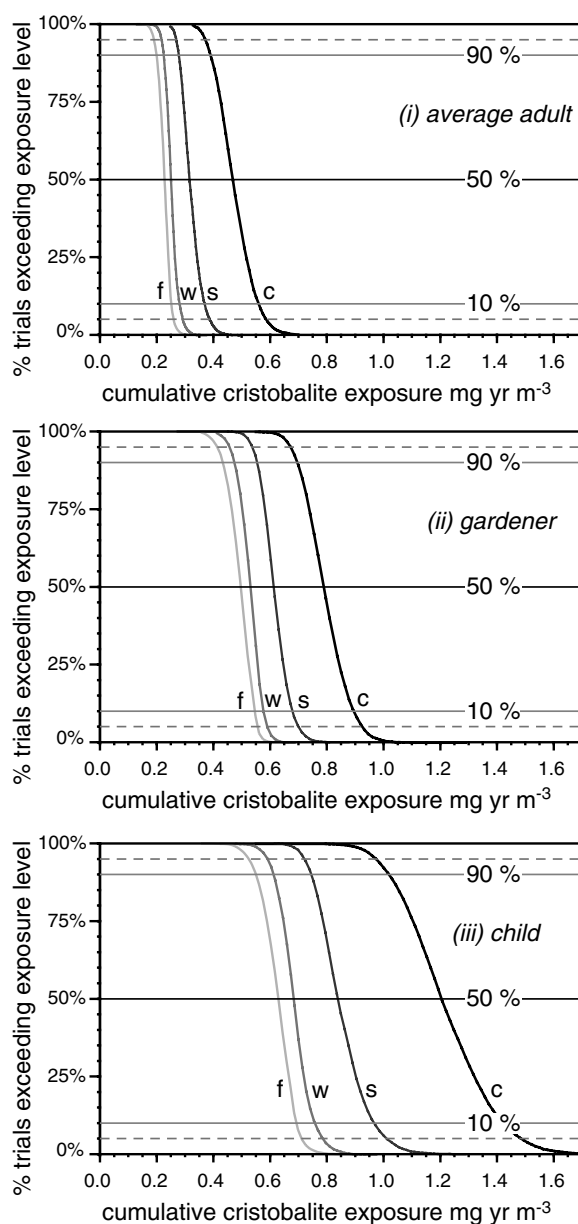
Fig. 12 Probability of exceedance curves for 20 years cumulative cristobalite exposure, under normal simulation rules (simulation 2a in Table 2). Results shown for an average adult (i), gardener (ii) and child (iii). Sites are labelled as follows: c= Cork Hill, s= Salem, w= Woodlands and f= Fogarty

a reliable 'domestic' or 24-hour standard for application to exposure on Montserrat. Assuming a working year of 2000 h, a naive equivalent limit might be of the order 0.01 mg yr m^{-3} (PM$_4$) for a single year of 24-hour environmental exposure (an occupational-year is taken as being 50 weeks × 40 hours/week, therefore 1 occupational-year ≈ 0.23 full years). Early crude risk assessments made by us (Baxter, Searl) based on Muir et al (1989) recommended that radiological silicosis signs develop at cumulative silica exposure levels >1 mg occupational-year m^{-3} (or 0.23 mg yr m^{-3} in units of full years) for total exposure periods of more than 5 years, with risk of even earlier onset in children.
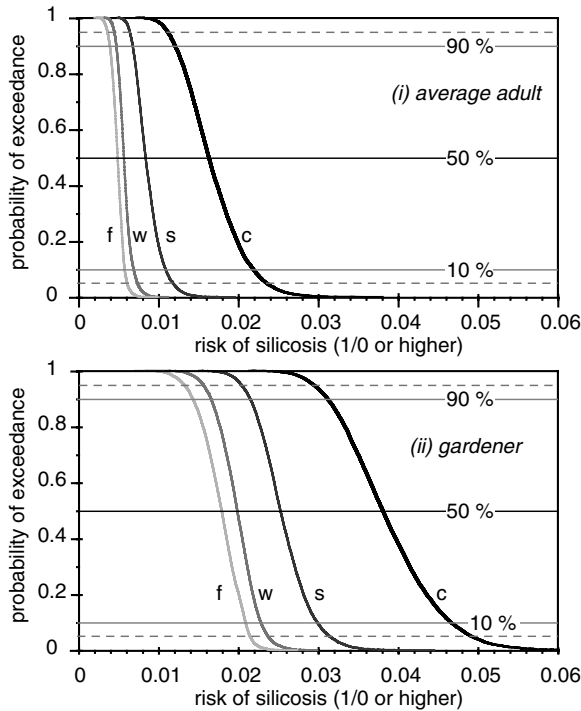
Estimated risk of silicosis

Two risk functions were selected to calculate the probability of developing silicosis (classification 1/0 or 2/1) given cumulative exposure (compared in Table 5). The Hughes et al. (1998) retrospective cohort study of diatomaceous earth workers was considered to be most analogous to exposure on Montserrat, due to the comparable percentage of cristobalite in the crystalline silica fraction of the dust, and equivalent exposure pattern and toxicity. Percentage crystalline silica in the respirable dusts ranged from 3% to 60%, depending on stage in the calcination process.

The model of Hughes et al. (1998) for cumulative risk of silicosis suggests:

$$R(c) = 1 - \frac{1}{1 + e^{\frac{(-3.250 + 0.731\phi)}{0.597}} c^{\frac{1}{0.597}}} \quad (12)$$

$R(c)$ is the probability of having a positive radiograph (classification 1/0 or higher), given a cumulative exposure to crystalline silica, c (in mg occupational-year m^{-3}). Exposure intensity is accounted for by the parameter φ, where $\varphi = 0$ for average exposure concentrations ≤ 0.5 mg m^{-3} and $\varphi = 1$ for average exposure concentrations > 0.5 mg m^{-3}.

The Hughes model has been applied to estimate the risk of silicosis (1/0 or higher) given 20 years projected cumulative exposure. Figure 13 shows probability of exceedance

Fig. 13 Probability of exceedance curve for risk of silicosis (classification 1/0 or greater) calculated from simulated cumulative exposures, using the Hughes et al. (1998) equation. Results are shown for 20 years exposure (simulation 2a in Table 2) for an average adult (i) and gardener (ii). This represents the best estimate of risk of silicosis in the Montserrat population (given continuous exposure on island). c= Cork Hill, s= Salem, w= Woodlands and f= Fogarty

for $R(c)$ calculated for an average adult and gardener, given 20 years exposure under normal simulation conditions (simulation 2a). The median risk for a gardener (working for the full 20 years) is approximately 2% in the north of the island, increasing to 4% in Cork Hill. Risk to an average adult under the same conditions is approximately 0.5% in the north, and 1.6% in Cork Hill. However, some caution is required in applying the Hughes model to populations in the north as this involves extrapolating to low exposures where the empirical Eq. (12) may not be valid. Estimated cumulative exposures for residents in northern Montserrat (Fogarty) are outside the calibrated range of the Hughes et al. (1998) equation, and a factor of 2 to 40 times lower than the miners' cumulative exposure. Cumulative exposures for populations south of Fogarty are generally within the bounds of the Hughes cohort, although at the low end and roughly within the bottom 20%. Exposure intensity is also significantly higher for the Hughes cohort; workers mean exposures are typically 2–76 times higher than estimated exposures on Montserrat (Table 5).

A cohort study of Scottish coalminers was chosen to represent the upper limit of silicosis risk (Buchanan et al. 2003). Risk of silicosis (given cumulative exposure) is significantly higher than for the Hughes et al. (1998) cohort, due to the high toxicity of freshly fractured sandstone. Although cumulative exposures are comparable to Montserrat, miners in the study typically spent ~8000 h at quartz concentrations >0.1 mg m^{-3}. Under normal simulation conditions with an average respirable cristobalite concentration of ~14% of PM$_{10}$, cristobalite exposures only exceed 0.1 mg m^{-3} after heavy ash fall. For a 10-year exposure period, we estimate that permanent residents of Cork Hill could receive in excess of 9000 h exposure at the maximum deposit state, with average concentrations >0.1 mg m^{-3}. This falls to around 2000 h in Salem, 340 h in Woodlands and 40 h in Fogarty.

Assuming no long term changes in rates of volcanic activity, the projected number of hours at exposures >0.1 mg m^{-3} for a 10 year exposure period outside the exclusion zone on Montserrat is approximately 0.5–5% of that received by the Buchanan et al. (2003) cohort. This model is therefore less appropriate for assessing the long-term health risks.

Probability of exceedance curves for risk of silicosis (classification 2/1 or greater) have been calculated using the model proposed by Buchanan (Fig. 14):

$$\log\left(\frac{p_2}{(1 - p_2)}\right) = -4.83 + \frac{443}{8760}c_{<2} + \frac{1323}{8760}c_{>2} \quad (13)$$

Where p_2 is the probability of silicosis (classification 2/1 or higher at follow-up) given cumulative exposure, c (measured in mg yr m^{-3}). $c_{<2}$ and $c_{>2}$ denote cumulative exposure for periods where exposure concentrations were below and above 2 mg m^{-3} respectively. The 'worst case' cristobalite exposure conditions (assuming the maximum ash deposit and a 25% of PM$_{10}$ cristobalite content) give
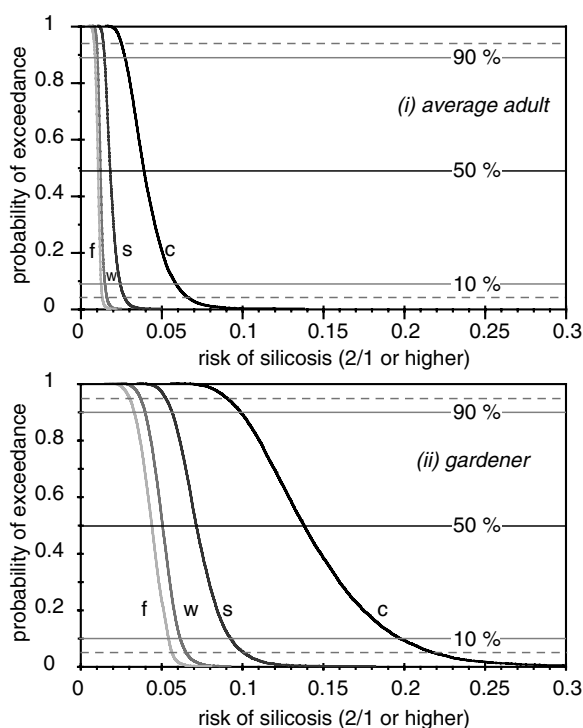
Fig. 14 Probability of exceedance curve for risk of silicosis (classification 2/1 or greater) calculated from simulated cumulative exposures, using the Buchanan et al. (2003) equation. Results are shown for 20 years exposure (simulation 2a in Table 2) for an average adult (i) and gardener (ii). The Buchanan equation represents the extreme upper limit of estimated risk. c= Cork Hill, s= Salem, w= Woodlands and f= Fogarty

an estimated upper exposure limit of approximately 1 mg m^{-3} in 1 day (see Table 1 for 24 h mean exposure levels for PM$_{10}$). In the risk estimates presented here we assume $c_{>2}$=0.

Figure 14 shows the variation in projected risk of silicosis (2/1) for the average adult and for a gardener, based on 20 years exposure and using normal simulation conditions (simulation 2a). The median value for risk using the Buchanan equation is ∼5% for a gardener in the north of the island, working for the full 20 years, increasing to 14% in Cork Hill. Risk to an average adult under the same conditions is approximately 1.2% in the north, and 4% in Cork Hill.

Improvements to model and follow-up

A critical and limiting assumption of this model is that volcanic activity will continue at rates similar to the past 8 years. A second major source of uncertainty lies in the estimation of a suitable dose-response relationship for exposure to volcanic ash, as there are few studies of exposure in volcanic settings. Existing occupational studies have limited application as workplace exposure may include more short duration exposures to high concentration and high toxicity dust, and the surface chemistry and composition of workplace dusts are typically quite different to volcanic ash. Widely variable dose-response relationships have been found in different occupational studies, suggesting that risk

of silicosis is not simply related to the silica content of dusts. It is also unreliable to assume that a child will have the same dose-response as an adult.

In 2000, a survey was conducted on 421 Montserratians in occupations associated with potentially high volcanic ash exposures (Cowie et al. 2002). There was no evidence of chest abnormalities on x-rays, however, at that stage, the individuals in the study had only been exposed to respirable ash for 4 years. This is probably too early to expect visible symptoms, as a number of occupational studies account for a latency of around 5 years from first exposure to manifestation of disease (Muir et al. 1989). Short timescale follow-up studies may therefore not provide the best indication of long-term health risks. An x-ray survey should thus be carried out on the most exposed residents 10 years after first exposure to volcanic ash in order to calibrate the risk assessment results.

Elements of the model could be improved by gathering more data. The collection of more full shift personal samples that can be analysed for cristobalite for workers in dusty occupations combined with better measurements of the proportion of cristobalite in ambient air on days of differing dustiness would lead to an improvement in our estimation of exposures to cristobalite. A specific study of children's activity patterns would allow a better estimate to be made of their potential exposures to the ash. Recommencement of continuous monitoring of PM$_{10}$ in combination with collection of rainfall data would allow a refinement of the relationship between rainfall and airborne ash concentrations. Ash erosion rates are currently based on limited observations and expert judgement, and could be improved by additional field data and a better understanding of the mechanisms of transport and erosion.

This study of health implications related to ash exposure develops a generic approach to volcanic risk estimation that can be applied in many different contexts. The essence of the methodology is to quantify and enumerate all the processes and effects from a volcanic hazard that influence risk. The uncertainties in all the controlling parameters can be evaluated on the basis of observations, models and expert judgement. These uncertainties are sampled by Monte Carlo simulation to generate a range of outcomes that can be presented statistically. The outputs of such simulations can then be used to identify the most significant sources of uncertainty and to provide a basis for decision−making.

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