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THE INJECTION OF VOLCANIC ASH INTO THE ATMOSPHERE

By Andrew W. Woods and Juergen Kienle

ABSTRACT

In this paper, we present some physical models that can describe the ascent of volcanic ash into the atmosphere during a volcanic eruption. We consider both sustained volcanic eruption columns and discrete volcanic thermal clouds. To test the modeling approach, we compare our predictions of the ascent rate of a model cloud with some observations of the ascent of the ash cloud during the April 15, 1990, eruption of Redoubt Volcano, Alaska. We also consider the radial spreading of ash as a gravity current following emplacement by the column and compare our theory with the observations from the April 21, 1990, eruption of Redoubt, Alaska. Both styles of eruption behavior are hazardous for aircraft.

INTRODUCTION

There is a range of styles of explosive volcanic eruption that can produce large convecting ash clouds and thereby inject ash high into the atmosphere. Ash can rise high into the atmosphere if the hot, erupted material can mix with and heat up a sufficient mass of air so that the bulk density of the mixture decreases below the ambient (Self and Walker, this volume). The typical ascent time of this ash to its maximum height is on the order of a few minutes; if this time is longer than the time over which the material is erupted and becomes buoyant, then the cloud will rise as a discrete volcanic thermal cloud (Wilson and others, 1978; Woods and Kienle, in press). Such volcanic thermal clouds formed, for example, during the April 15 and 21, 1990, eruptions of the Redoubt Volcano, Alaska. Figure 1 is a photograph of the April 21 eruption cloud, which ascended about 12 km into the atmosphere. The main eruption cloud has reached its maximum height and has begun to spread laterally into the atmosphere. A relatively small, vertical column may be seen below this main cloud. This column contains material rising from the ground after the ascent of the main cloud—this material is less energetic than that in the main thermal cloud. In the photograph, a small secondary lateral intrusion has begun to develop from this column.

In a more sustained eruption, lasting several hours, material is continually erupted from the vent. In this case, a maintained eruption column, injecting ash high into the atmosphere, will form if the hot ash can entrain and heat a sufficient quantity of air so that the bulk density of the mixture falls below that of the ambient. Two different mechanisms of buoyancy generation are possible, and, during the course of an eruption, the style of eruption may change from one to the other: (1) If the erupted material is ejected upward from the vent very rapidly, the dense jet may entrain sufficient air to become buoyant before its upward momentum is exhausted; in this case, the material continues rising upward, driven by its own buoyancy thereby forming a classical Plinian eruption column (Sparks, 1986; Woods, 1988) such as the A.D. 79 eruption of Mt. Vesuvius, Italy. (2) If the erupted material is ejected from the vent with smaller momentum, that material will collapse back and spread out along the ground as an ash flow in a similar manner to the motion of water in a fountain. However, the material in the spreading ash flow may become buoyant through entrainment and mixing with air and sedimentation of large particles as it propagates along the ground. It will then rise off the ground to form a maintained eruption column, in this case called a co-ignimbrite eruption column (Sparks and Walker, 1977; Woods and Wohletz, 1991). Historical examples of eruptions, which include phases in which co-ignimbrite eruption columns developed, include the massive 1815 eruption of Tambora, Indonesia, and the 1912 eruption of Katmai, Alaska. Co-ignimbrite eruption columns tend to form during massive eruptions (Woods and Wohletz, 1991).

Both discrete and maintained eruption clouds can inject vast quantities of ash into the atmosphere—they thereby pose a serious safety problem for aircraft. However, sustained eruption columns are perhaps more hazardous for aircraft because they may persist for hours and can therefore inject very large quantities of ash, which spreads over a very wide area in the atmosphere. In order to evaluate the dangers of an eruption for aircraft, it is important to know the extent of the region in which the mass loading of ash in the air is at hazardous concentrations. When ash has been carried upward to its maximum height by the eruption column, it

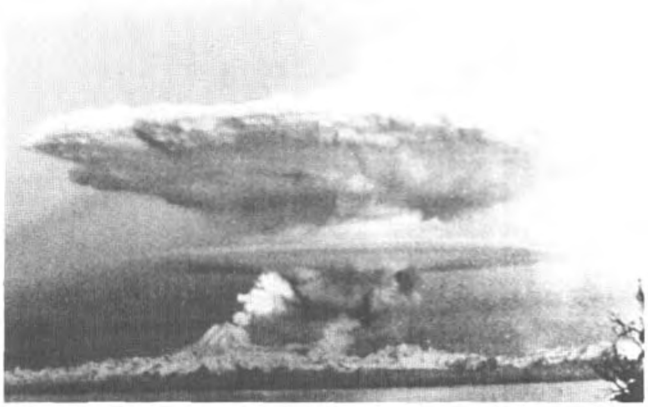

Figure 1. Photograph of the volcanic eruption cloud formed during the April 21, 1990, eruption of Redoubt Volcano, Alaska, seen from the Kenai Peninsula, east of the volcano. The main cloud ascended about 12 km, and the secondary intrusion ascended to an altitude of about 6 km. Photograph by Mark and Audrey Hodges.

spreads out laterally under gravity above its neutral buoyancy height and is carried by the wind to form a large, laterally spreading ash plume (fig. 2). The maximum ash concentration in this ash plume occurs at the top of the eruption column (before it is diluted through mixing with the ambient as it travels downwind).

In the following section, we describe the Plinian eruption-column model of Woods (1988) and the model of a volcanic thermal cloud of Woods and Kienle (in press). In order to test the modeling approach, we compare the predicted rate of ascent of a volcanic thermal, using the model of Woods and Kienle (in press), with the observed ascent of the thermal cloud during the April 15, 1990, eruption of the Redoubt Volcano, Alaska. We also investigate the radial spreading of the ash as a gravity current after it is emplaced into the atmosphere by the eruption; we compare a simple model with observations of the spreading umbrella cloud following the April 21, 1990, eruption of Redoubt Volcano. Details of the mass loading in eruption columns and the downwind dispersal of ash are given in other articles in this volume (Sparks and others, this volume; Bursik and others, this volume; Self and Walker, this volume).

MODELING THE DYNAMICS OF ERUPTION CLOUDS

Although the initial momentum of the material erupted from the vent accounts for the first few kilometers of the ascent, it is the generation of buoyancy that enables the material to ascend tens of kilometers (Woods, 1988). This buoyancy is generated through the entrainment of vast quantities of ambient air, which is heated and expands, ultimately lowering the density of the column below that of the surrounding air. Once buoyant, the material rises through the atmosphere until reaching the height at which its density equals the ambient again, called the neutral buoyancy height. At this point, the inertia of the material causes the material to continue rising some distance until the material comes to rest. It then collapses downward toward the neutral buoyancy height and spreads out laterally. In this overshoot region, the density of the cloud exceeds that of the surroundings, and the cloud may actually become tens of degrees colder than the environment (Woods and Self, 1992). This undercooling of the eruption cloud causes difficulties in the interpretation of thermal satellite images of the top of eruption columns; in particular, it is very difficult to estimate the height of the cloud top using the observed cloud-top temperature and radiosonde measurements of the environmental temperature as a function of altitude (Woods and Self, 1992).

In the past 10–15 years, a number of models have been developed to describe the motion of maintained volcanic eruption columns. These are summarized and reviewed in the paper by Woods (1988), in which a dynamically consistent model is presented. This steady-state model is based upon the conservation of mass, momentum, and enthalpy, assuming that the column entrains ambient air at a rate proportional to the vertical velocity of the column at any height, following Morton and others (1956). The model incorporates a number of simplifications, which are good approximations in many explosive volcanic eruptions. These include the assumptions that (1) the material in the eruption column behaves as a single-phase, perfect gas, (2) there is little interphase mass or momentum transfer, (3) the system is in thermodynamic equilibrium, and (4) all of the solid material is fine-grained ash and therefore ascends to the top of the column.

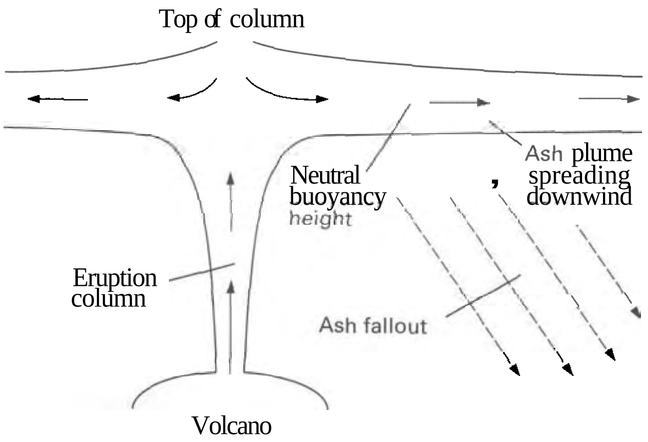

Figure 2. Schematic diagram of eruption column, spreading umbrella cloud, and downwind ash plume. Figure shows location of neutral buoyancy height.

In figure **3,** we present a graph, calculated using this model, showing how the total height of rise of the column and the neutral buoyancy height of the column vary with the mass eruption rate for three different initial temperatures. In this graph, it may be seen that the rate of increase of column height decreases once it passes through the tropopause. This is because the temperature begins to increase with height in the stratosphere, causing the atmosphere to become much more stratified. It may also be seen that, because hotter columns generate more buoyancy, they tend to rise higher. Further details of the model are described in Woods (1988).

Woods and Bursik (1991) have extended this model to include the effects of fallout of the larger solid clasts below the top of the column. They showed that, if many of the clasts do fall out (as occurs in eruptions of larger mean grain size), then the eruption column becomes progressively smaller. This is because more of the thermal energy is removed by these solids, and, ultimately, the material in the column has insufficient thermal energy to become buoyant and a collapsed fountain forms. Woods and Wohletz (1991) have shown that the ascent of a co-ignimbrite eruption column rising off a hot ash flow (Sparks and Walker, 1977) may also be described using this model. In this case, the material being supplied to the column originates from a large area; initially it has little upward momentum and is only just buoyant relative to the surrounding ambient atmosphere. However, after entraining more air, the material rapidly expands and becomes buoyant and, as a consequence, accelerates upward. Woods and Wohletz (1991) calculated that the ascent height of these co-ignimbrite columns was much less than that of Plinian columns because, typically, only about one-third of the erupted ash and solid material is elutriated from the ash flow into the rising cloud. This reduces the source of thermal energy, which results in ascent of the cloud.

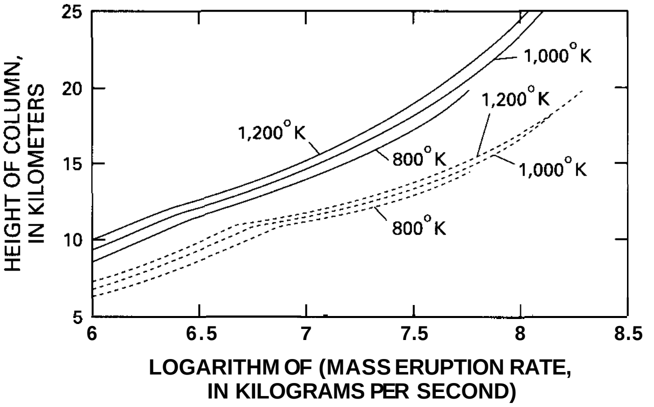

Figure 3. Calculations of neutral buoyancy height (dashed lines) and total column height (solid lines) as a function of erupted mass **flux.** Curves are given for three eruption temperatures **(800°K, 1,000°K, 1,200°K).** Calculations are based on the model of Woods (1988) using the standard atmosphere model described therein for which the tropopause is located at 11 km.

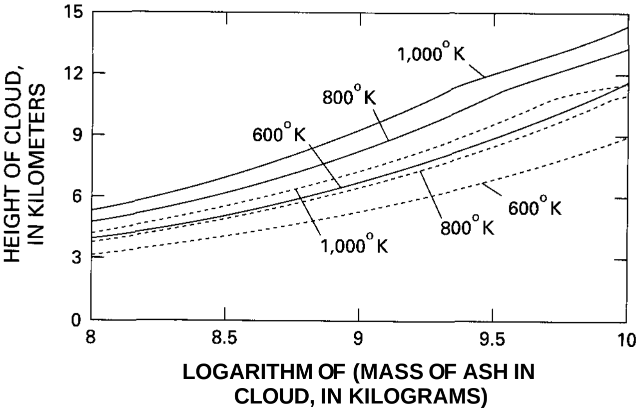

Figure 4. Calculations of neutral buoyancy height (dashed lines) and total cloud height (solid lines) as a function of erupted mass. Curves are given for three eruption temperatures **(600°K, 800°K, 1,000°K).** Calculations are based on the model of Woods and Kienle (in press) using the standard atmosphere as described in figure 3.

Using a similar approach, Woods and Kienle (in press) have presented a model of the ascent of discrete volcanic clouds. In this model, the discrete cloud is assumed to ascend as a sphere that entrains ambient air and therefore increases in radius as it ascends. The model calculates the altitude and radius of the cloud as well as the average density, temperature, and velocity in the cloud as functions of time. An important difference between the motion of a maintained, steady eruption column and a discrete volcanic thermal cloud is that, as a volcanic thermal rises, there is an additional drag exerted upon the cloud as a result of the air that must be displaced by the rising cloud. This is usually referred to as the virtual mass (Batchelor, 1967) and is incorporated in the model of Woods and Kienle (in press).

In figure 4, we present calculations using this model of the ascent height and neutral buoyancy height of a volcanic thermal cloud, such as that developed following the eruption Redoubt Volcano (fig. 1). We present calculations for three different initial temperatures as a function of the initial mass of the thermal cloud. The results are qualitatively similar to those in figure **3,** which describe maintained eruption columns.

TESTING ERUPTION-CLOUD MODELS

Relatively few detailed observations of volcanic eruptions, recording the ascent height of the cloud as a function of time or the velocity in a maintained eruption column as a

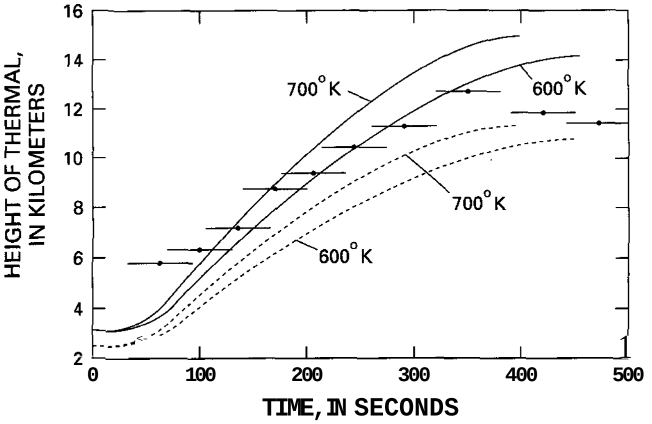

Figure 5. Comparison of observed ascent of the April **15, 1990,** Redoubt eruption cloud with the model predictions of the total cloud height (solid lines) and the height of the center of the cloud (dashed lines). Calculations are shown for two initial, model cloud temperatures **(600°K** and **700°K),** which represent bounds on the initial temperature of the cloud (Woods and Kienle, in press). The data were collected by analysis of video recordings of the cloud ascent. Horizontal lines through data points represent error bars.

function of height, have been published; such observations are necessary to test the accuracy of the modeling approach. Sparks and Wilson (1982) tracked several plume fronts rising from the crater of Soufriere St. Vincent and compared this with a model of a starting plume, and Sparks (1986) reported some satellite observations of the ascent of the lateral blast cloud of Mount St. Helens, May 18, 1980, and compared these with the theory of Morton and others (1956). More recently, Woods and Kienle (in press) have reported on some slow-scan video-camera recordings of the rise of the April 15, 1990, eruption cloud of Redoubt Volcano and compared this with a new model of a volcanic thermal.

During the April 15, 1990, eruption of Redoubt Volcano, a hot ash flow was produced from the explosion of a volcanic dome. This ash flow traveled along the ground for 3–4 km, following a natural ice canyon carved in a glacier. As the flow entrained and heated ambient air, the upper part of the flow became buoyant and rose into the atmosphere, forming a large, convecting volcanic thermal cloud. In figure 5, we present a graph showing the observed height of the cloud as a function of time as deduced from the slow-scan video recording. Post-eruption studies of the far-field air-fall (Scott and McGimsey, in press) and near-field flow deposits (C.A. Neal, oral commun., 1991) give estimates for the total mass of material erupted from the volcano during this eruption as approximately 2.5×10^9 kg. Using this data and the conservation of enthalpy in the flow (Sparks, 1986), we estimate that the temperature of the elutriated cloud was 600°K–700°K, assuming that it was just buoyant on ascent. This data provides the initial conditions for our model of the ascent of the thermal cloud and, in figure 5, we also present model ascent curves for clouds rising off the flow with temperatures of 600°K and 700°K. In these calculations, we have used meteorological radiosonde data from three stations near Redoubt Volcano taken at about the time of the eruption. It may be seen that the model is able to reproduce most of the features of the buoyant ascent very satisfactorily, especially the time scale of the ascent and the height of rise of the cloud. This gives us confidence in the accuracy, at least in terms of the order of magnitude, of the predictions of these models. Further details of this comparison and the field data are given in Woods and Kienle (in press).

In addition to field observations, some recent controlled laboratory experiments have been able to test aspects of these models (Woods and Caulfield, 1992). There are mixtures of methanol and ethylene glycol (MEG) with density less than that of water that, upon mixing with water, become more dense than water. Therefore, with sufficient initial momentum, a downward-propagating, but light, jet of MEG can entrain and mix with ambient water to become dense and thereby continue propagating downward (in an analogous fashion to a Plinian eruption column) (Woods and Caulfield, 1992). However, a relatively light jet of MEG, with sufficient initial downward momentum, comes to rest before it can mix with sufficient water to become dense; in this case, a collapsed fountain forms and the MEG mixture rises back up around the source. Woods and Caulfield (1992) developed a simple theoretical model of their laboratory experiments based on the same conservation laws as used in the eruption-column model of Woods (1988). The conditions under which experimental column collapse occurs were successfully compared with the model predictions; this further confirms the validity of the underlying physics in the models.

SPREADING UMBRELLA CLOUDS

We now describe the initial spreading of the umbrella cloud once it is emplaced into the atmosphere by the eruption column—the subsequent dispersal and fallout of ash has been described by Bursik and others (1992; this volume). Following injection into the atmosphere by the eruption column, the first stage of ash dispersal consists of the radial gravitational spreading of the cloud toward its neutral buoyancy height. This is the dominant mechanism causing lateral spreading of the ash cloud during the first few minutes after the ash is injected into the atmosphere. However, when the rate of spreading decreases below typical velocities associated with the ambient wind field and ambient turbulence, this gravitational spreading may become of secondary importance in comparison to the wind as an ash-dispersal mechanism. During the May 18, 1980, eruption of Mount St. Helens, the ash plume spread out under gravity from a radius of about 20 km to nearly 50 km in about 10 minutes (Sparks, 1986, fig. 5), whereas the April 21, 1990, eruption cloud at Redoubt Volcano spread out from a radius of about 6 km to over 15 km in about 10 minutes under gravity before being carried downwind. Woods and Kienle (in press) have described a simple model of the gravitational spreading of an ash cloud following Simpson (1987). In the model, the radial inertia of the cloud balances the gravitational force, which results from the vertical displacement of the air by the cloud. Woods and Kienle (in press) predict that an instantaneously emplaced cloud spreads radially at a rate proportional to $(\text{time})^{1/3}$, and an umbrella cloud continually supplied from below spreads at a rate proportional to $(\text{time})^{2/3}$ until the dispersal becomes dominated by wind. As can be seen in figure 6, this model compares favorably with direct observations from the spreading of the April 21, 1990, eruption cloud of Redoubt Volcano, which was emplaced nearly instantaneously.

CONCLUSIONS

We have described models of both instantaneous and maintained eruption columns. These models are based upon the conservation of mass, momentum, and enthalpy. We have compared our model of a thermal cloud with the observations of the Redoubt Volcano eruption of April 1990. We have also discussed simple models of the radial spreading of the umbrella cloud and have shown that the simple model compares favorably with observations from the April 21, 1990, eruption of Redoubt Volcano. The models have shown that even relatively small eruption clouds can ascend up to tens of kilometers into the atmosphere, causing a serious hazard for aircraft, which typically fly in the troposphere below about 11 km. Once the ash cloud has reached its neutral buoyancy height, the ash may then spread several hundred or even thousands of kilometers before settling from the atmosphere. A particularly important result of the modeling is that the upper surface of an eruption column may actually become tens of degrees colder than the surrounding environment, owing to the inertial overshoot of the erupted mixture above the neutral buoyancy height. This can lead to difficulties in interpreting the height of eruption clouds from thermal satellite images (Woods and Self, 1992). In a companion paper in this volume (Sparks and others, this volume), the models described herein have been used to calculate the ash loading at the top of eruption columns.

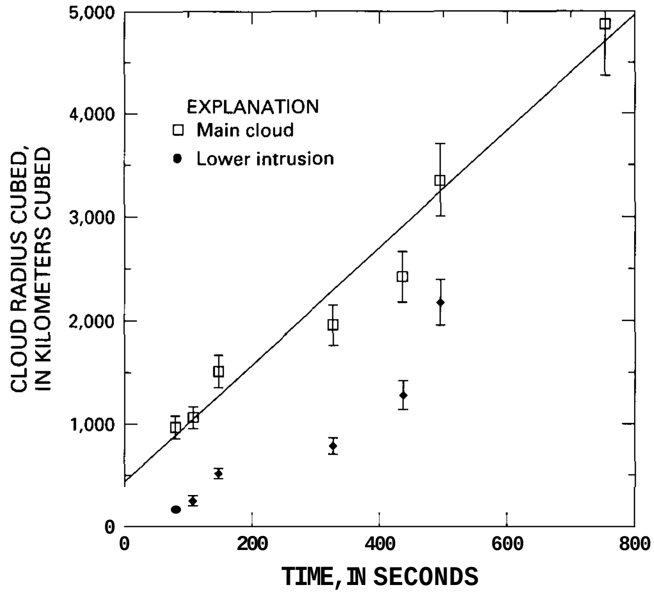

Figure 6. Comparison of observed spread of umbrella cloud that formed following the April 21, 1990, eruption of Redoubt Volcano and a simple model of a radially spreading gravity current, after Woods and Kienle (in press). The graph shows the rate of spread of the main cloud as well as the lower secondary intrusion, which can be seen in figure 1. The data were obtained from analysis of photographs by Mark and Audrey Hodges. Vertical lines through data points indicate error bars.

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