OPERATIONAL VOLCANIC ASH PLUME PREDICTION MODEL PUFF AT THE JAPAN AIRLINES

H. L. Tanaka (Geoenvironmental Sciences, University of Tsukuba, Tsukuba 305-8572 Japan),
Saburo Onodera (Japan Airlines, Tokyo Japan), and DAISUKE NOHARA (Meteorological Research Institute, Tsukuba Japan)

1. Introduction

Volcanic ash cloud floating and traveling in the air is a great concern to airline pilots. If a commercial jet aircraft encounters ash cloud, the damage could be serious enough to cause an engine failure (Hobbs et al., 1991; Casadevall, 1994; Onodera, 1997). In order to avoid serious accidents of commercial aircrafts, real-time volcanic plume prediction models have been developed by some agencies.

A 3-D turbulent diffusion model was developed by Armienti and Macedonio (1988) using an observed upper air wind data and applied to stronboli eruption of Mt. St. Helens in 1980. Glaze and Self (1991) constructed a turbulent diffusion model considering the vertical wind shear and applied to Usu volcano in 1977 to see distributions of ash fall. Hurst and Turner (1999) developed a 3-D turbulent diffusion model called ASHFALL to predict volcanic ash fall for operational use. In this model, the regional distribution of upper air wind is prepared by RAMS (Regional Atmospheric Modeling System). Turner and Hurst (2001) further combined HYPACT (Hybrid Particle and Concentration Transport Model) with RAMS to improve the model. Heffter and Stunder (1993) developed a transport dispersion model called VAFTAD (Volcanic Ash Forecast Transport and Dispersion) to predict ash plume floating in the air.

A group of worldwide volcanic ash advisory services was organized to form volcanic ash advisory centers (VAACs) by nine organizations under the auspice of the International Civil Aviation Treaty (ICAO). The Tokyo VAAC is one of the nine VAACs, which was established in April 1997 at the Tokyo Aviation Weather Service Center. The Tokyo VAAC operates the Lagrangian and Eulerian models to forecast the position of the volcanic ash clouds (Tokyo Aviation Weather Service Center, 2001).

In parallel with those activities, a real-time volcanic ash plume tracking model called PUFF was developed for the purpose of real-time aviation safety in northeastern Pacific rim including Alaska volcanoes (Tanaka, 1991; Kienle et al., 1991; Dean et al., 1993; Tanaka, 1994; Searcy et al. 1998). It is noted that the PUFF model is the earliest ash tracking model applied for the aviation safety purpose in a real-time operation (Tanaka et al., 1993; Akasofu and Tanaka, 1993). The model is operational under the Alaska Volcano Observatory (AVO) at the Geophysical Institute of the University of Alaska Fairbanks (GI/UAF) since the eruption of Redoubt volcano in 1990. The PUFF model at the University of Tsukuba was applied to the actual eruption of Usu volcano on 31 March 2000 in Hokkaido (Endoh et al., 2001; Tanaka and Yamamoto, 2002) and Miyake-jima Volcano on August 18 2000.

The research product of the *PUFF* prediction system, including the model simulation and animation graphics of the simulation results, was transplanted to Japan Airlines with the assistance by the Japan Weather Association (JWA). This report describes the latest improvements installed in the PUFF model operational at the Japan Airlines.

2. Description of the model

The volcanic plume prediction model PUFF was constructed in 1991 and reported in detail by Tanaka (1994) and Searcy et al. (1998) as an application of pollutant dispersion models. The model is based on the three-dimensional (3-D) Lagrangian form of the transport-diffusion equation. In the Lagrangian framework, a realization of the stochastic process of plume particles may be described by a random walk process (e.g., Chatfield, 1975). Here, the diffusion is simulated by a sufficiently large number of random variables $r_i(t)$, $i=1 \sim M$, representing position vectors of M particles from the source S of the volcanic crater. The diffusion is superimposed on convective transport and gravitational fallout.

With a discrete time increment, (t=5 minutes), the Lagrangian form of the governing equation may be written as

$$\begin{cases} r_i(0) = S, & i = 1 \sim M,\ for\ t = 0, \\ r_i(t+\Delta t) = r_i(t) + V\Delta t + D\Delta t + G\Delta t, & i = 1 \sim M,\ for\ t > 0, \end{cases} \tag{1}$$

where $r_i(t)$ is a position vector of an i-th particle at time t, V is the local wind velocity to transport the particle, D is a vector containing three Gaussian random numbers for diffusion, and G is the gravitational fallout speed approximated by Stokes Law.

For the computation of convective transport, the wind velocity $V=(u,v,w)$ is obtained from the global Grid Point Values (GPV) provided by Japan Meteorological Agency (JMA). The gridded data are first interpolated in time onto the model's time steps of every 5 minute. A cubic spline method (see Burden et al., 1981) is used to interpolate the wind data from 6 hour interval to the model's time step. Then, the wind velocity at an arbitrary spatial point is evaluated using the 3-D cubic-splines from the nearby gridded data.

The diffusion of the ash particles $D=(c_h, c_h, c_v)$ is parameterized by the random walk process, where the horizontal and vertical diffusion speeds c_h, c_v may be related to the horizontal and vertical diffusion coefficients K_h, K_v. We have repeated diffusion tests with various values of diffusion coefficients, and the resulting dispersals are compared with satellite images of actual dispersals for several volcanic eruptions in the past (Yamagata, 1993; Yamamoto 2000; 2002). With these diffusion tests, we find that the appropriate horizontal and vertical diffusion coefficients are K_h=150 and K_v=1.5 ($m^2\ s^{-1}$), respectively. Note that the values may be different for different volcanoes and for different weather conditions.

The gravitational settling is based on Stokes Law as a function of the particle size r. The fallout velocity $G=(0,0,-v_t)$ is approximated by the terminal speed v_t of plume particles below:

$$\frac{v_t}{v_o} = \frac{r_o}{r}\left[\left\{\left(\frac{r}{r_o}\right)^2 + \frac{1}{4}\right\}^{\frac{1}{2}} - \frac{1}{2}\right]^{\frac{3}{2}} \tag{2}$$

where v_0 (=1.0 m/s) is a reference velocity, and r_0 (=150 μ m) is the particle size that separates the inertial range and viscosity range. In the viscosity range, the frictional force of the particle is proportional to v_t, so the terminal velocity becomes a function of r^2. Whereas, in the inertial range, the frictional force is proportional to v_t^2, so the terminal velocity becomes a function of $r^{1/2}$. In the present formulation, the terminal velocity v_t shifts smoothly from the former to the latter separated by r_0.

The actual eruption contains large fragments up to few meters in size as well as fine ash over a continuous particle size to less than 1 μ m. Large particles settle out within a short time, so the particle size spectrum shifts toward the smaller particles as time proceeds. Because we are interested in the particles which can travel for several hours, we have assumed that the initial particle size distribution obeys a logarithmic Gaussian distribution centered at 100 μ m with its standard deviation 1.0. Thus, about 95% of particles are supposed to have their size between 1 μ m and 1 cm. In practice, the particles larger than 1 cm drop quickly within a few time steps of the simulation. The particles less than 100 μ m can travel far from the source providing important information of the plume dispersion.

Sufficiently large numbers of particles are contained within the initial vertical column above the crater of the erupting volcano. During the 5 min of a time step, the particles are released constantly in time from the crater in the model.
A simple buoyancy model is considered with initial upward motion w_0 and a constant damping rate λ (=1/60s). When the equilibrium plume height z_2 is given, the initial speed w_0 may be evaluated from z_2, and the vertical plume distribution z may be calculated from the following form:

$$Z = Z_2 - \frac{\omega_o}{\lambda} e^{-\lambda t} \tag{3}$$

Random numbers are generated uniformly in time t for the time step of 5 min, which produces dense plume particles near the top of the plume. The gravitational fallout and convective transport during the 5 min are calculated for a given time t superimposed on the vertical distribution to generate the plume source $S=(x,y,z)$.

In a case of a short-time explosive eruption puff, the ash particles are generated only for the initial time of the time integration. When the eruption continues for certain period of time, the model generates new particles over the same vertical column for every time step during the specified eruption period. For a steady eruption, the particle number tends to increase in the model atmosphere before the plume particles have dropped or crossed the vertical wall of the model domain. Therefore, the number of particles released at every time step is adjusted in order to draw optimal statistical information from the model products. For this reason, we set the number of the particles released for a time step as 100 in this study. Although it is possible to increase the number toward the limit of the computer capability, the time integration will then be considerably slower, which is a disadvantage for the urgent case. An excessive complication and sophistication are not recommended in the application to the real-time operational prediction.

3. Results

Figure 1 illustrates an example of the ash plume distribution simulated for a hypothetical eruption of Etna Volcano. The simulation started from 21:00 UTC, 28 July 2004, and the ash distribution is for 9 hours after the beginning of the eruption. Plume height in feet is designated by different colors. The model simulation takes about 2 min and the graphics takes about 3 min using the SUN Workstation Ultra 60. After the 5 min of the computation time, we can observe the 3-D animation of the ash plume dispersal during the first 10 hours of the volcanic eruption.

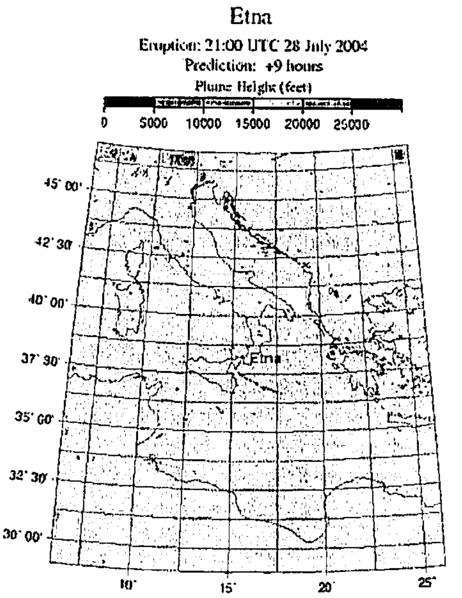

Figure 1. An example of the ash plume distribution simulated for a hypothetical eruption of Etna Volcano. The simulation started from 21:00 UTC, 28 July 2004, and the plot is for 9 hours after the eruption.

The 5 min is the critical time for the aviation safety purpose. The model simulation can be repeated many times whenever a new information, such as the accurate plume height, is reported. The model is applicable to any volcano in the world, and is routinely running for hypothetical eruptions of Sakura-jima, Usu Volcano, Miyake-jima, Mt. Asama, Mt. Fuji in Japan, Redoubt volcano, Augustine volcano in Alaska, and Etna volcano in Italy. Those PUFF model simulations may be seen at the following web site.
(http://air.geo.tsukuba.ac.jp/puff/index.html)

4. Concluding Summary

Volcanic ash cloud floating and traveling in the air is a dangerous object for commercial and non-commercial aircrafts. In order to avoid encounters with ash cloud, a real-time volcanic plume prediction model, called PUFF, has been developed in 1991 and reported by Tanaka (1994) and Searcy et al. (1998) for Alaska volcanoes. The performance of the ash tracking accuracy has been checked whenever actual eruptions occur in the world. The demonstration to real eruptions of Usu volcano and Miyake-jima are reported to assess the performance of the model for tracking the airborne ash clouds for the aviation safety purpose (Tanaka and Yamamoto, 2002). The PUFF model has been updated, and the latest version as described in this report is installed at the flight operation system in the Japan Airlines.

Since the establishment of ICAO's VAACs, volcanic plume tracking becomes operational in the world, providing useful information to aviation industry. Along with the VAACs, we need further to improve the accuracy of the PUFF model by accumulating experience in the flight operations and by establishing timely notification system to pilots with much user-friendly graphic interface.

Acknowledgments

The authors are grateful to the support rendered by Drs. S. Akasofu, K. Dean, J. Dehn of the University of Alaska. Thanks are extended to Mr. S. Shimoda and Ms. S. Yamagata of JWA for their technical support. The authors appreciate Ms. K. Honda for her technical assistance. This research was supported by the IARC/NASDA research project: Modeling the dynamics of volcanic eruption cloud, and by Asahi Breweries Foundation.

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