J1.2 SOURCE TERM ESTIMATION OF A VOLCANIC ASH CLOUD USING A GENETIC ALGORITHM

Kerrie J. Schmehl and Sue Ellen Haupt*
Applied Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania
* National Center for Atmospheric Research, Research Applications Laboratory, Boulder, CO

1. INTRODUCTION

Volcanic ash clouds pose a serious threat to aircraft. Complete avoidance of these clouds remains the safest mitigation strategy for aircraft (Casadevall 1994, OFCM 2004, Fox 2009, Chivers 2010, Langston 2010). Thus, there is a need to accurately forecast the movement of such ash clouds. The atmospheric transport and dispersion models used for predicting ash cloud movement require accurate source term and meteorology variable input, particularly the emission rate and the transporting wind, in order to forecast the future state of the cloud. A method is presented that applies the Genetic Algorithm Variational (GA-Var) approach to retrieve the emission rate and representative wind speed and direction. With that information we can refine the forecast of the ash cloud movement and provide a more accurate forecast to warn and reroute aircraft in the region.

A case study is made of one event of the eruption of Mount Redoubt in 2009 (section 2). The GA-Var approach (section 3) is applied to estimate wind data and an emission rate by comparing the observed satellite data (section 4) to forecasts generated by a dispersion model (section 5) via a cost function (Fig. 1). The GA-Var approach is tested first with an identical twin experiment (section 6.1) and then with the observed satellite data (section 6.2). Section 7 discusses the results and prospects for the future.

2. CASE STUDY

Mount Redoubt is located along the Cook Inlet of Alaska. The 2009 eruption of Mount Redoubt consisted of 20 events: the first of which began on March 15th and the last that ended on April 5th. For this study, we focus on the 5th event which began at 1230 March 23, 2009 UTC and lasted approximately 20 minutes (Schaefer 2011). The maximum observed plume height during this event was recorded at 18.3 km (Schaefer 2011). The bulk of the ash was estimated to lie between 7.6 and 9.1 km above sea level (AVO/USGS 2010). Although the volcano did not emit a continuous rate of ash into the atmosphere, we model it as a uniform emission during that 20 minute period.

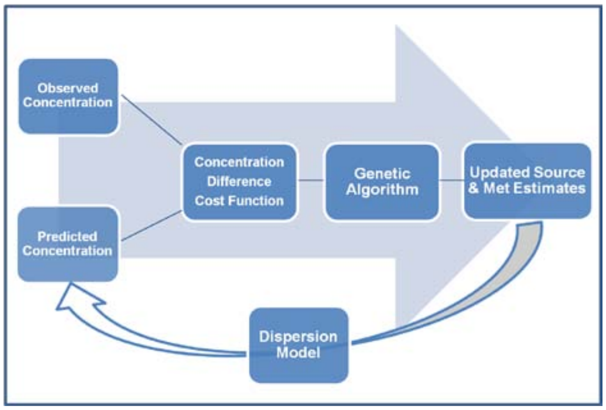

Figure 1. A schematic illustrating the GA-Var technique.

3. THE GENETIC ALGORITHM

The Genetic Algorithm is an artificial intelligence optimization method inspired the biological processs of genetic recombination and evolution. A schematic of the GA is presented in Fig. 2. It begins with an initial population of random values for emission rate, wind direction and wind speed. These values are then input into the dispersion model and a forecast is created. That forecast is then compared to the observed data via the cost function. The cost function takes the following:

$$\text{cost} = \frac{\sqrt{\sum_{s=1}^{TS}[\log(C_s+\varepsilon)-\log(O_s+\varepsilon)]^2}}{\sqrt{\sum_{s=1}^{TS}[\log(O_s+\varepsilon)]^2}}$$

where:

C_s is the forecast concentration at sensor, s,

Corresponding author address: Kerrie J. Schmehl, Applied Research Laboratory, P.O. Box 30, The Pennsylvania State University, State College, PA, 16804-0030; e-mail: kjl203@psu.edu

O_s is the observed concentration at sensor, *s*, and
TS is the total number of sensors and
ε is a small constant used to threshold the data.

Solutions with high costs are discarded while solutions with low costs are selected to participate in the mating and mutation operations. The cost functions are evaluated again and the potential solutions ranked. This process is repeated iteratively until convergence is reached and the final estimates attained. For further details regarding the particular GA used here, the reader is referred to Haupt and Haupt (1998, 2004).

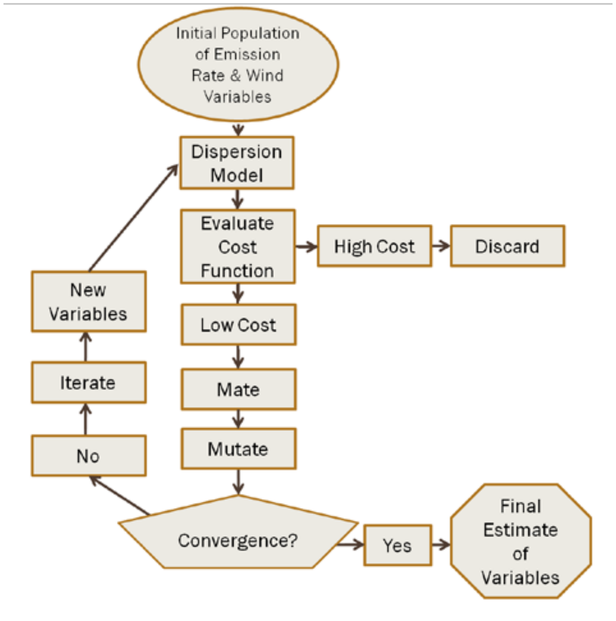

Fig. 2. Schematic illustrating the Genetic Algorithm.

There are innumerable ways to configure the GA's settings. Here we use a population of 64 chromosomes and a mutation rate of 20%. Half of the population is selected to participate in mating while the other half is discarded. The GA is run for 200 iterations. The transporting wind speed and direction as well as the emission rate, are the unknown variables we seek. The GA searches a range of potential values for each of these variables. The emission rate can vary from 1×10^3 to 1×10^7 kg s^{-1}, the wind direction can span the entire range of values, 0 through 360°, and the wind speed can vary from 0 to 50 m s^{-1}.

4. SATELLITE DATA

The satellite data was provided by the National Environmental Satellite, Data, and Information Service (NESDIS) of NOAA. The data is derived from the Advanced Very High Resolution Radiometer (AVHRR). Details of satellite retrieval method are available in Pavolonis (2010). The retrieval includes an estimate for mass loading (3a), the height of the cloud ash (3b), and the effective particle radius (3c). The location of Mt. Redoubt is indicated by the inverted triangle in the lower left of Figure 3. In order to convert the mass loading (given in T km^{-2}) into concentration values, we must assume a thickness for the ash cloud. We use an assumption from Prata and Grant (2001) that estimates vertical thickness, dz, as 0.4 times the cloud top. (The cloud top is estimated from the satellite data depicted in 3b.) For this study, we focus on concentration values derived at a height of 6 km, which is where the bulk of the plume lies as indicated by Fig. 3b.

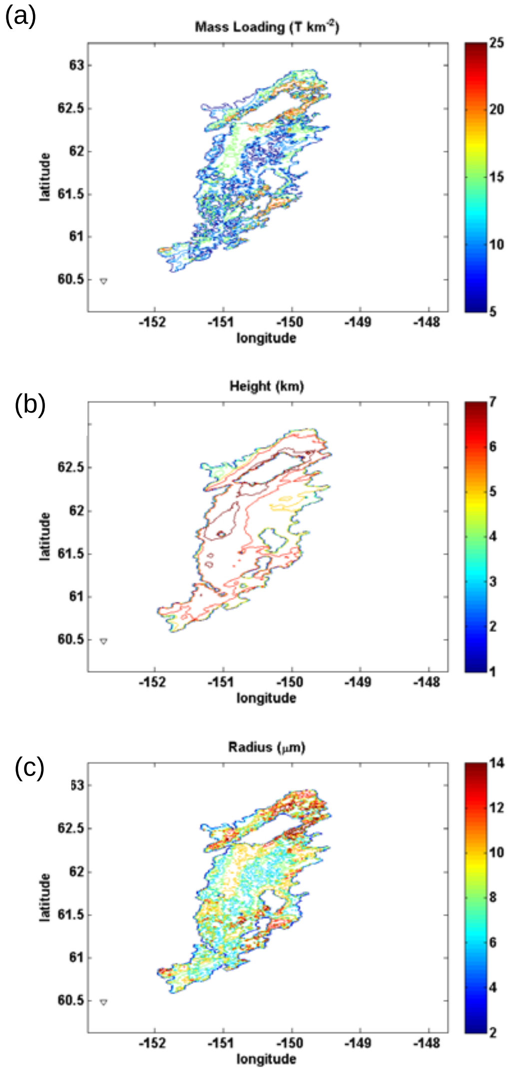

Figure 3. The mass loading in ton/km^2 (a), height of the ash cloud in km (b), and radius of the ash in microns (c) derived from the satellite retrieval.

5. DISPERSION MODEL

We use the Second-Order Closure Integrated PUFF (SCIPUFF) model as our atmospheric transport and dispersion model. SCIPUFF is a sophisticated puff-based transport and dispersion model that accounts for turbulence, terrain, and weather effects (Sykes 2004). SCIPUFF tracks individual puffs, evolves the dispersion coefficients, splits and merges the puffs, and incorporates advanced methods to assess turbulence levels.

For this case, we model the transport and dispersion of the ash particles ranging in size from 0.10 to 100 microns (commensurate with the values indicated by Fig. 3c). We assume the ash has a density of 2600 kg m^{-3} (Scott and McGimsey 1994). Note that we do not include effects resulting from chemical reactions. Because we are considering a single integrated level of concentration data, we consider only a single representative wind speed and direction for the purpose of the retrieval.

6. RESULTS

6.1 Identical Twin Results

To first test the GA-Var method, we conduct an identical twin experiment where the SCIPUFF model is used to create synthetic data for testing. We simulate observed concentrations by inputting known source term parameter values and running SCIPUFF. This approach allows us to analyze and refine the algorithm's application.

The values for the emission rate, wind speed and wind direction are chosen to mimic but not exactly match the true values associated with event 5. The emission rate is set to be 7.8x10^5 kg s^{-1}. The emission begins at 1230 UTC and lasts for 16 minutes. The wind speed and direction are set to be uniform throughout the domain at 16 m s^{-1} and 215° respectively. A SCIPUFF forecast is run with these values and the resulting concentration at our sensor network is computed at 1430 UTC (Fig. 4a). These computed concentrations become the concentration observations for the identical twin experiment.

GA-Var is then run with these synthetically created observations ten times. The best solution of the ten runs (the solution with the lowest cost function) corresponded to a wind direction of 214.9°, a wind speed of 15.9 m s^{-1}, and an emission rate of 7.9x10^5 kg s^{-1}. This translated into a percent error in wind direction of 0.04%, in wind speed of 0.2% and in emission rate of 1.6%. SCIPUFF is then initialized with this best GA-Var solution and a new forecast is created (Fig. 4b). As the percent errors likely indicate, the two forecasts are visibly indistinguishable which implies that GA-Var is suitable for this type of problem.

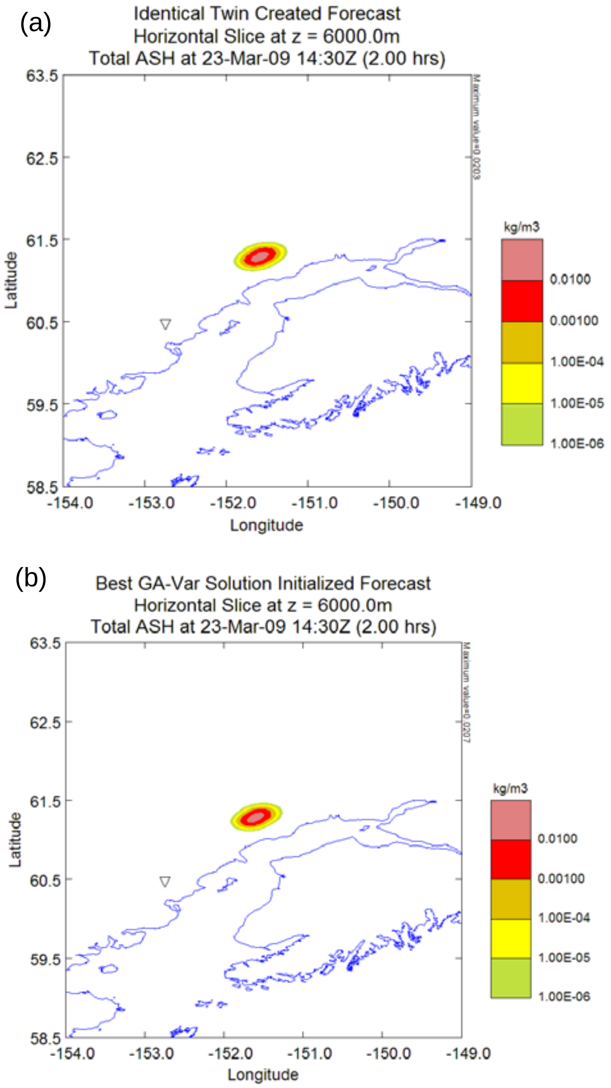

Figure 4. The forecast used to create the synthetic observation data (a) as compared to the forecast created with the best GA-Var determined solution (b).

6.2 Results from Satellite Data

After successfully retrieving the source term values in the identical twin experiment, GA-Var is next tested using the satellite derived observations (Fig. 5a). The population size, number of iterations, mutation rate and selection rate are the same values as used for the identical twin experiment. Again, GA-Var is run ten times. The best solution corresponded to a wind direction of 217.3°, a wind speed of 32.8 m s^{-1}, and an emission rate of $7.1x10^4$ kg s^{-1}. With this emission rate, the total mass of ash ejected into the atmosphere is $8.5x10^7$ kg. Little variability is noted among the solutions for the wind variables. The mean wind direction is estimated to be 216.1 ± 1.4° and the mean wind speed is 31.9 ± 1.9 m s^{-1}. The emission rate, however exhibits considerable more spread with a mean solution of $1.1x10^5 \pm 1.2\ x10^5$ kg s^{-1}. Note that the solutions for emission rate exhibited more variability than the solutions for the wind variable in the identical twin experiment also.

As before, SCIPUFF is initialized with the best GA-Var solution and a new forecast is created (Fig. 5b). The GA-Var solution captures the relevant trajectory of the cloud well but under-predicts the size of the cloud. The GA-Var estimated value for wind speed matches the top portion of the satellite data where relatively higher concentration values are located. Had a lower value been predicted, GA-Var likely would have matched the portion of the plume closer to Mount Redoubt.

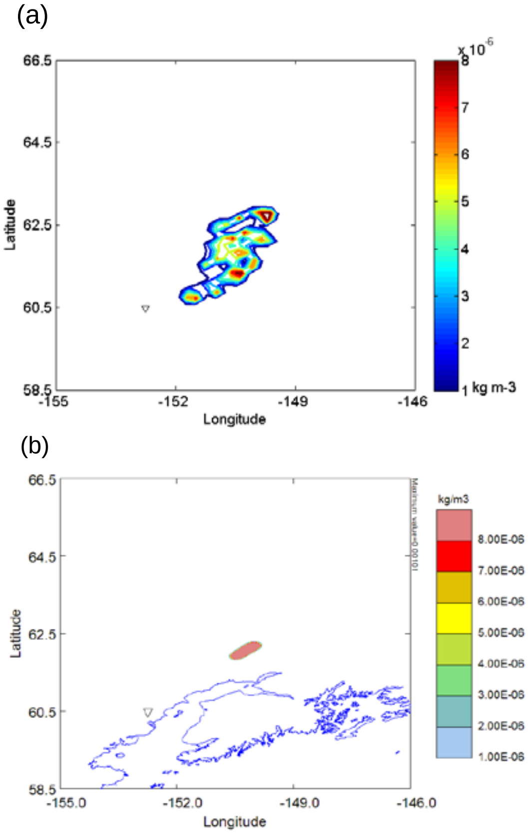

Figure 5. The satellite derived concentration data (a) as compared to the forecast created with best GA-Var determined solution (b).

Verifying the GA-Var estimated solutions for the wind variables is not as straightforward as with the identical twin experiment. Soundings were taken at Anchorage, Alaska, which is about 110 miles away from Mt. Redoubt at 1200 UTC (one half hour before the event begins). The recorded wind at a height of 6 km was ~16 m s^{-1} at 205° (University of Wyoming Atmospheric Soundings). In addition, NWP runs using WRFv3.1 were conducted over Alaska at 12 km resolution (Skamarock et al. 2008). The WRF data indicate that in the vicinity of Mount Redoubt at 1200 UTC (0400 AKDT) and 6 km, the wind speed was 22.7 m s^{-1} and the direction was 201°. Downwind of Mount Redoubt closer the edge of the plume pictured in Fig. 5b (62°N and -150°W) at 1500 UTC (0700 AKDT) and 6 km, the wind speed was 11.3 m s^{-1} and the wind direction was 218°. The best GA-Var estimated wind direction of 217.3° compares well with the observed values, however, the GA-Var estimated wind speed is much higher than the observed wind speed of 16 m s^{-1}. Note that the WRF runs were initialized with boundary conditions for the initialization time from the Global Forecast Model (GFS), but they did not incorporate data assimilation, and thus, are not necessarily tied to the ground truth.

We verify the GA-Var estimated value for emission rate by using equation (1) of Mastin et al. (2009). Based on that equation and the maximum observed plume height of 18.3 km (or 15.2 km above the vent), the total mass of ash from event 5 alone is estimated to be $1.4x10^{10}$ kg. In Schaefer (2011), the author estimates the amount of mass emitted from event 5 to be only $4.5x10^9$ kg. Both of these estimates are considerably higher than the estimate presented here of $8.5x10^7$ kg.

7. DISCUSSION

The large discrepancy between the estimate presented here and the value reported in Schaefer et al. (2011) is likely due to the fact that we do not take into account the fine ash fraction. The fine ash fraction is the fraction of the total emitted mass that is transported long distances from the volcano (Dacre 2011). While the larger ash particles tend to fall out near the volcano, these smaller fine ash particles can stay in the ash cloud for hours or days and fall out at rates that are not well understood (Mastin et al. 2009). It is common practice in volcanic ash modeling to apply this fine ash fraction to the modeled concentration that produce the best match with the observations. The appropriate fraction can vary widely given the type of eruption. Mastin et al. (2009) lists the mass fraction for particles smaller than 63 microns from 0.01 to 0.7. Dacre et al. (2011) study the 2010 Eyjafjallajökull eruption and find that using lidar observations only between 3 and 4% of the total emitted mass flux was transported by ash particles smaller than 100 microns in diameter. Here we have attempted to match the concentration values derived from the satellite data without estimating the fine ash fraction. If the mass of 4.5×10^9 kg (determined by Schaefer et al. (2011)) is taken to be the total emitted mass, then the GA-determined emission rate represents ~2% of that total emitted mass, which lies within the range listed in Mastin et al. (2009). Thus, we must recognize that the emission rate computed by GA-Var has essentially matched the fine ash fraction that is appropriate for producing a cloud that matches the satellite data concentration levels. The GA-Var derived value has the appropriate fine ash fraction built into it.

We have successfully demonstrated that a genetic algorithm can be applied to determine the emission rate and relevant wind data governing a volcanic event. Having derived the representative wind speed and direction as well as the relevant emission rate, one could forecast the movement of the ash cloud. Future directions include testing the technique on additional cases, including multiple data sets for the same eruption or new eruptions altogether.

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