Modeling Volcanic Ash Plumes Using Puff and AVHRR

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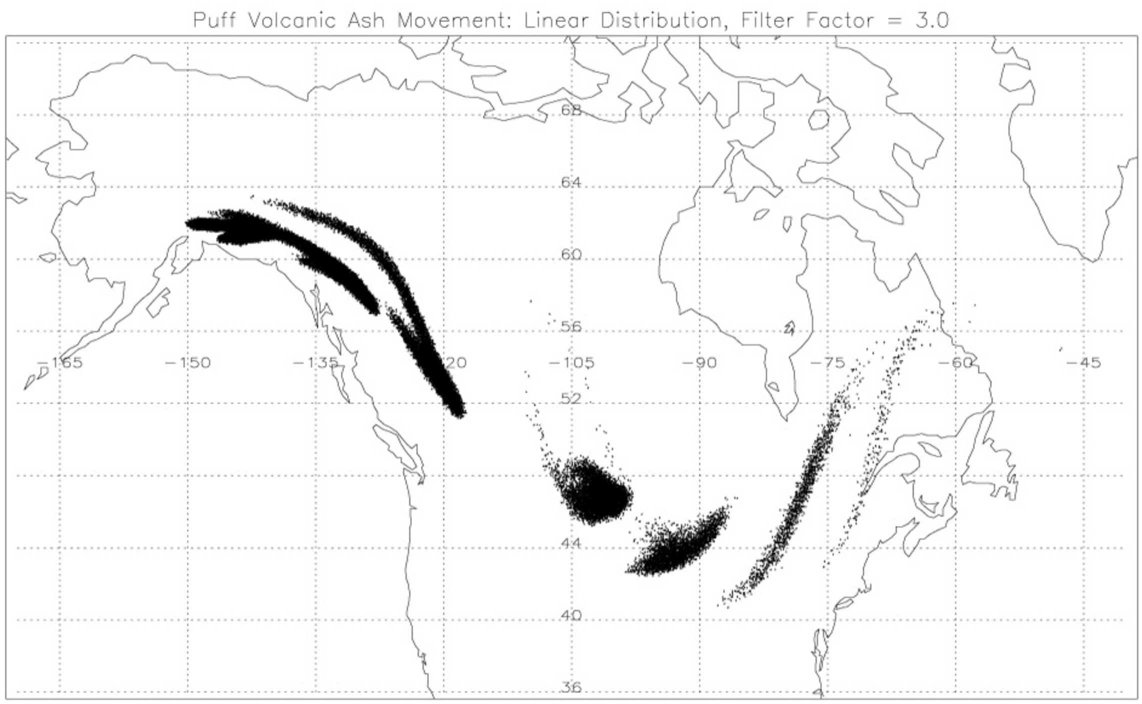

1 Background

At the University of Alaska, Fairbanks – Geophysical Institute, scientists have been using satellite remote sensing and ash dispersion modeling to observe and predict the movement of volcanic ash plumes after eruptions. Information about the location, size, and shape of the plume in the hours following an eruption is crucial to public safety. Young ash clouds are particularly hazardous because they contain the greatest concentrations and largest particles of ash. Cities close to the volcanoes experience devastating effects from the ash fallout.[1] Volcanic ash is also a major hazard to aircraft, having caused serious damage to plane engines in several cases when an aircraft flew through the ash plume.[2]

1.1 AVHRR

Scientists at the Geophysical Institute are able to monitor volcanic activity as it occurs using satellite images acquired from Advanced Very High Resolution Radiometer (AVHRR), which is onboard NOAA satellites. AVHRR satellites are polar orbiting and have a relatively high temporal resolution at the polar regions, so they are particularly useful for monitoring volcanoes in Alaska and the Northern Pacific region. The satellites make about 8 - 10 passes above the region per day, acquiring a new set of data each time. For each pass, AVHRR satellites record data from 5 spectral bands ranging from visible (Bands 1 and 2, 0.5 - 1.1 μm) to long-wave infrared (Band 5, 11.5 - 12.5 μm) wavelengths. The spectral signatures of eruption clouds vary as a function of wavelength,[3] allowing remote sensing specialists to infer certain information about the ash plume. For example, images from the visible range (Band 1) can be useful to calculate plume height using the location of the plume shadow and the time of day.[3] Plume information from Band 1 is limited, however, because images from the visible spectrum require solar illumination and an unobstructed view of the plume. Weather clouds and night-time darkness pose common constraints on the usefulness of data acquired from AVHRR Bands 1 and 2.

A more reliable technique for detecting plumes is the split-window technique (Figure 1). Using this method, the data from AVHRR Band 5 (11.5 - 12.5 μm) is subtracted from the Band 4 (10.3 - 11.3 μm) data. Since there is very little difference between the spectral signatures of weather clouds in B4 and B5, but there *is* a difference in the signature of *volcanic* ash clouds, the resulting image (B4 - B5) shows the signature of the volcanic ash plume where the brightness temperature difference is less than zero. While this technique is useful, it does not always show an ash signature for very dense or opaque clouds and can also mistake storm fronts for ash clouds.[4]

[1] C. Searcy et al., 1998
[2] M. Aloissi et al., 2002
[3] K. Dean et al., 2002
[4] Simpson et al., 2000

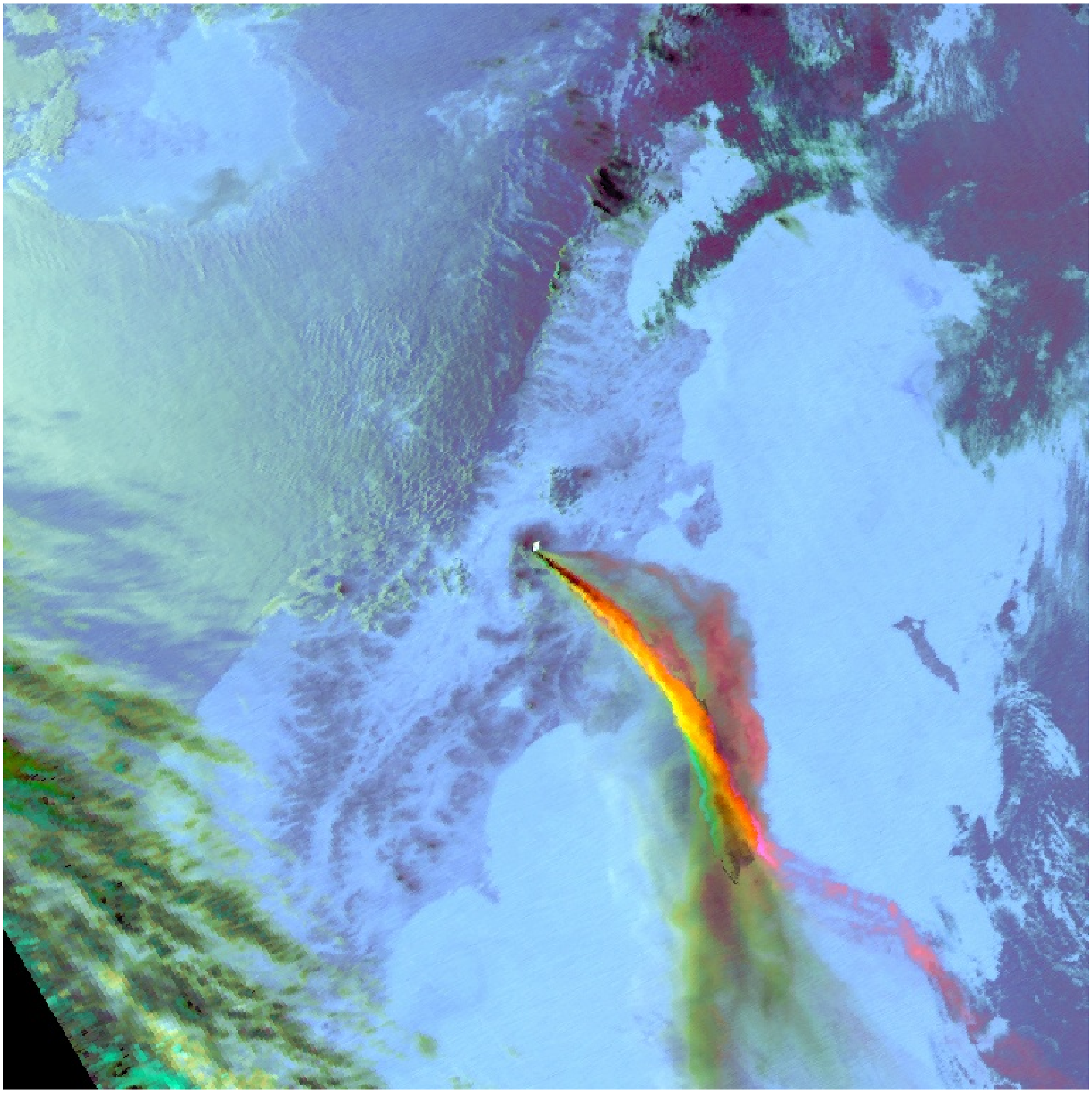

Figure 1: AVHRR split-window (B4 - B5) image of eruption cloud from September/October 1994 eruption of Klyuchevskoy Volcano, Kamchatka Peninsula, Russia. Source: http://puff.images.alaska.edu/

1.2 Puff

Puff is a numerical volcanic ash dispersion model. Using Puff, a user can *predict* the movement of an ash plume with minimal knowledge about the details of the eruption. Puff is based on the three-dimensional Lagrangian formulation of pollutant dispersion developed to simulate the behavior of young ash clouds.[1] The model requires a gridded wind data forecast in near real-time to predict the movement of the ash cloud.[1] The current model has been developed into software with a graphical user interface (Figure 2) and default input parameters so that it can be used quickly in an operational setting. To obtain a first approximation of the movement of an ash plume, the user need only know the time of the eruption, the volcano name (or latitude, longitude coordinates), and have access to the appropriate wind field data for the duration of the eruption. As more details about the eruption are received, the user can specify additional input parameters to make the prediction more accurate. The mathematics used by the model predict the position of each ash particle using the Lagrangian formulation[5]

$$\mathbf{R}_i(t + \Delta t) = \mathbf{R}_i(t) + W(t)\Delta t + Z(t)\Delta t + S_i(t)\Delta t \tag{1}$$

where $\mathbf{R}_i(t)$ is the location of the ith particle at some time t after the eruption, W is the local wind velocity, Z is a vector representing turbulent dispersion, and S_i is the terminal gravitational fallout vector.[5]

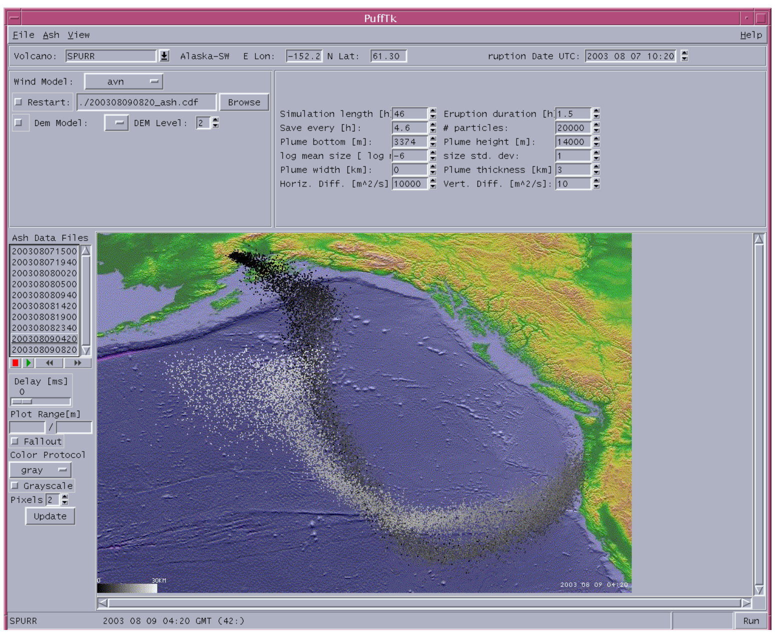

Figure 2: PuffTk: Puff graphic user interface program shown here for a hypothetical eruption of Mount Spurr Volcano on August 07, 2003 at 10:20 UTC. Important input parameters include the horizontal diffusion, eruption duration, and plume shape, which are all adjustable within PuffTk.

[5] C. Searcy et al., 1998

Some of the most important input parameters, which affect the shape and movement of the ash cloud, include the horizontal diffusion, eruption duration, plume height, and plume shape. For this study, linear and poisson plume shapes were compared. For a choice of *linear* distribution in the puff model, a column of evenly distributed ash particles is initialized in a vertical column above the appropriate volcano, then released and carried by the wind. For a *poisson* plume shape, the ash particles are arranged so that there is a Poisson distribution of ash particles released from above the volcano, with a greater concentration of particles in the middle-upper portion of the release column.

Currently, unlike other dispersion models such as HYSPLIT and CANERM,[6] Puff contains *no* explicit information about the ash concentration through time. Other models allow the user to display the concentration of an ash plume. Puff displays all the ash particles regardless of how dense, or how diffuse the cloud is.

2 Project

From June 15 to August 15, 2003, as part of the UAF/GI Solid Earth Geophysics REU Program sponsored by the National Science Foundation, I have been working on a project with Dr. Rorik Peterson, Laura Bickmeier, and Professor Ken Dean to learn about, test, analyze, and improve the Puff distribution model. I performed a single case study: the September 17, 1992 eruption of Mount Spurr Volcano in southern Alaska. The September eruption was well documented and well known because of its close proximity to Anchorage. AVHRR data also provided a series of well-defined images that track the cloud signature across North America on the days following the eruption as shown in Figure 3. Thus, the event served as a nice test of the Puff dispersion model.

2.1 Basis/Hypothesis

The current Puff model works well for young ash clouds. In previous analyses, Puff has shown to perform sufficiently well for the first 24 hours of simulation when satellite image observations are not available.[7] For older ash plumes, however, it has been noted that "often the simulated cloud is slightly larger than the observed (AVHRR) cloud..." (example: Figure 4) "...By modifying input parameters such as plume height or diffusivity, model results can be 'tuned' to more precisely match the observed cloud."[7] Surprisingly, sometimes the diffusivity would need to be set to zero to produce Puff simulation results which looked like the AVHRR images.

In an attempt to eliminate the need for fine-tuning of input parameters, which sometimes results in unrealistic values for the parameters, an alternative method was proposed. This project is based on the hypothesis that at some lower limit of ash density, AVHRR will no longer detect the ash cloud.

By developing a concentration model for Puff, the user would be able to display only the ash particles

[6] K. Dean, *Cities on Volcanoes.*, 2003
[7] C. Searcy et al., 1998

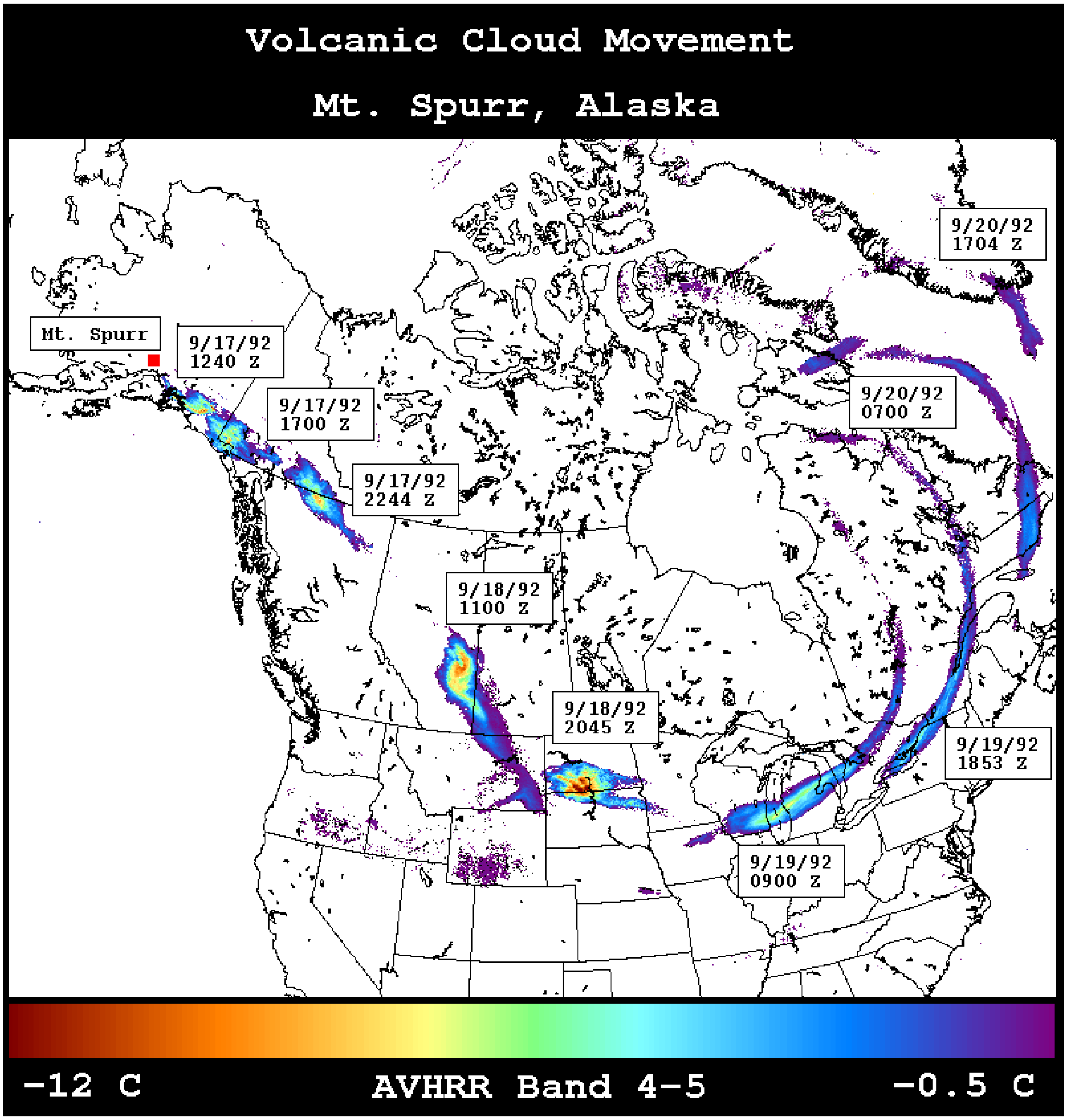

Figure 3: AVHRR B4-B5 composite image showing the ash cloud signature for the September 17 eruption of Spurr Volcano in southern Alaska as it moves across the United States on the days following the eruption. Image source: http://puff.images.alaska.edu/

above some threshold density. This technique would eliminate many of the outlying (diffuse) ash clusters from the display and make the Puff cloud size smaller, and more *comparable* to the AVHRR (B4-B5) image, without needing to set input parameters to unrealistic values. If the cloud looks more similar after filtering, it will be easier to analyze what (realistic) input parameters work best for the Puff model.

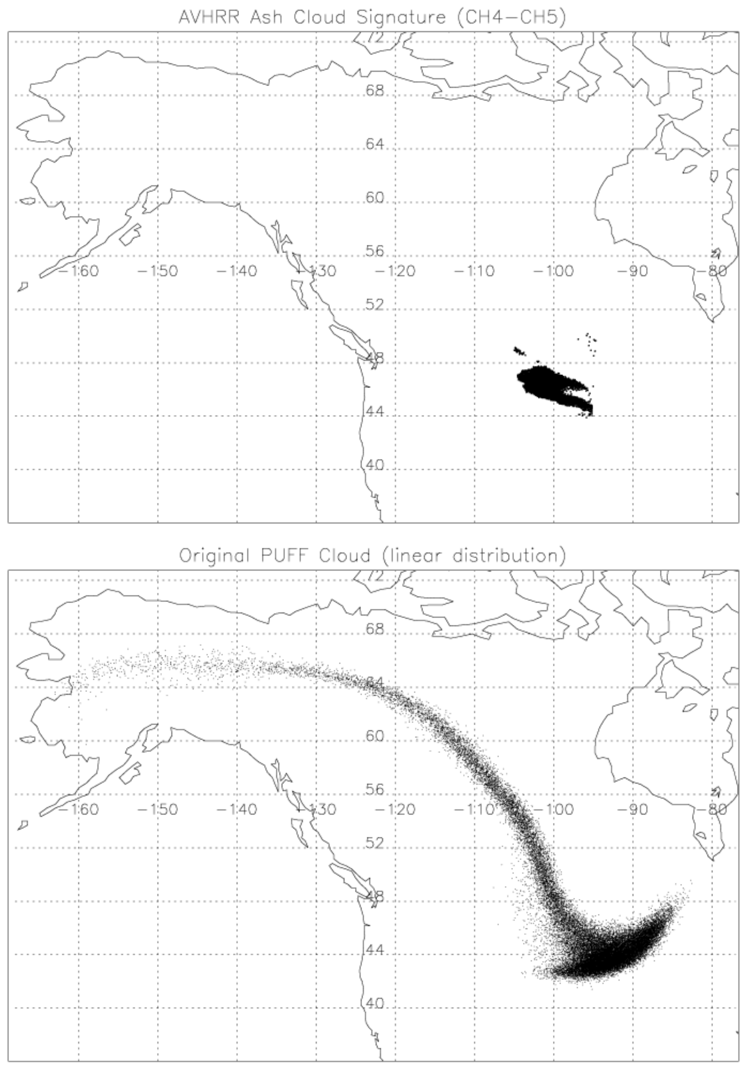

Figure 4: Comparison of AVHRR ash cloud signature and (unfiltered) simulated ash cloud produced by current Puff model. The Puff model displays a long trail of ash, whereas the AVHRR ash cloud signature is shown as a much smaller figure. It appears that the area where the Puff ash concentration is the highest corresponds closely with the location of the AVHRR (B4-B5) image.

2.2 Approach

To explore the usefulness of low-density ash filtering and determine if it would be worthwhile to incorporate something similar into Puff, it was decided that I should develop a test program (`filter.pro`) written in Interactive Data Language (IDL), which filters out low-density ash from the Puff model output. In addition, an IDL program named `puff_avhrr.pro` was written by Laura Bickmeier to calculate the percent overlap between the AVHRR and Puff ash clouds and provide a method to quantify how well the two clouds match.

The program, `filter.pro`, which incorporates `puff_avhrr.pro`, does the following: defines the density of the puff ash cloud, filters out ash particles below and adjustable threshold density, creates a filtered ash cloud, quantifies how well the filtered cloud matches the AVHRR ash cloud signature, and gives the user the choice to save several useful plots of ash density and comparison plots of AVHRR, puff, and filtered puff clouds as PostScript files. For each run, the program will also automatically save key results in a text file. Several components of the program are designed specifically for research purposes, but the basic 'filtering' algorithm could be extracted from `filter.pro` and eventually incorporated into the source code for Puff.

The current version of `filter.pro` requires the AVHRR Band 4-5 data recorded as a text (ascii) file, the Puff generated output of the latitudes and longitudes for each Puff particle recorded in a text file, and a value for the `filter_factor` (λ), which controls the amount of ash which is filtered from the original puff cloud.

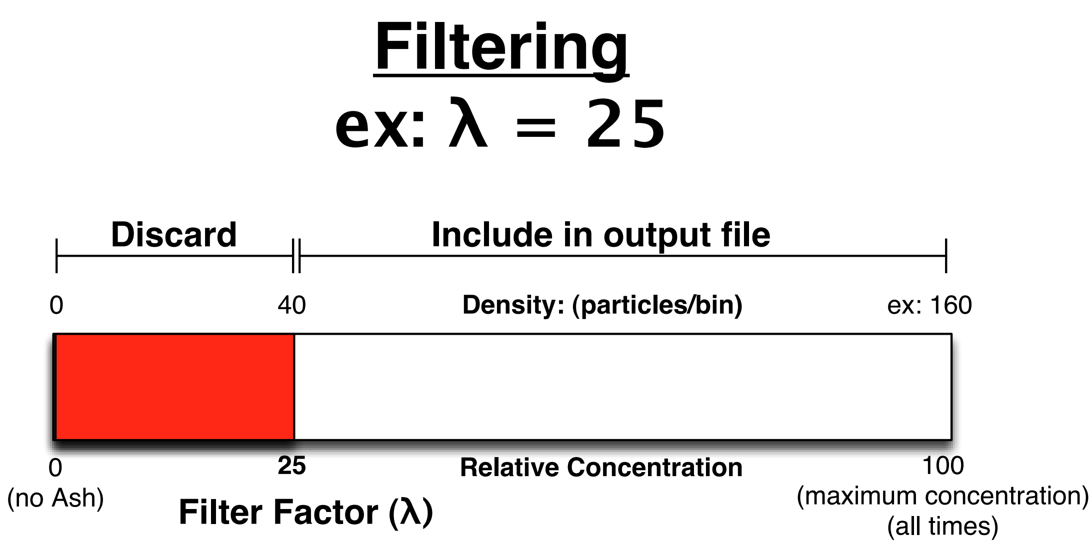

Figure 5: Diagram showing which ash bins are discarded from filtered ash cloud, given some value for `filter_factor` (λ). Notice that for $\lambda = 0$, no ash is filtered, whereas when $\lambda = 100$, all of the ash is filtered from the most dense cloud. For this case ($\lambda = 25$), each 0.1 by 0.1 degree grid space with fewer than 40 particles ($\frac{25}{100}(160) = 40$) will not be displayed in the output ash cloud.

Since the puff output includes no explicit information about the concentration of ash particles, the first step for `filter.pro` is to define the density of the puff cloud given only the latitude and longitude of each particle. Rhe area covered by the puff cloud is split into 0.1 by 0.1 degree grid spaces, and the number of ash particles which fall within each grid-space are stored in an array which represents the concentration of the cloud at different locations.[8] Using `filter.pro`, the user can specify which concentrations of ash should be included in the output file by choosing an appropriate value for (λ) as illustrated in Figure 5.

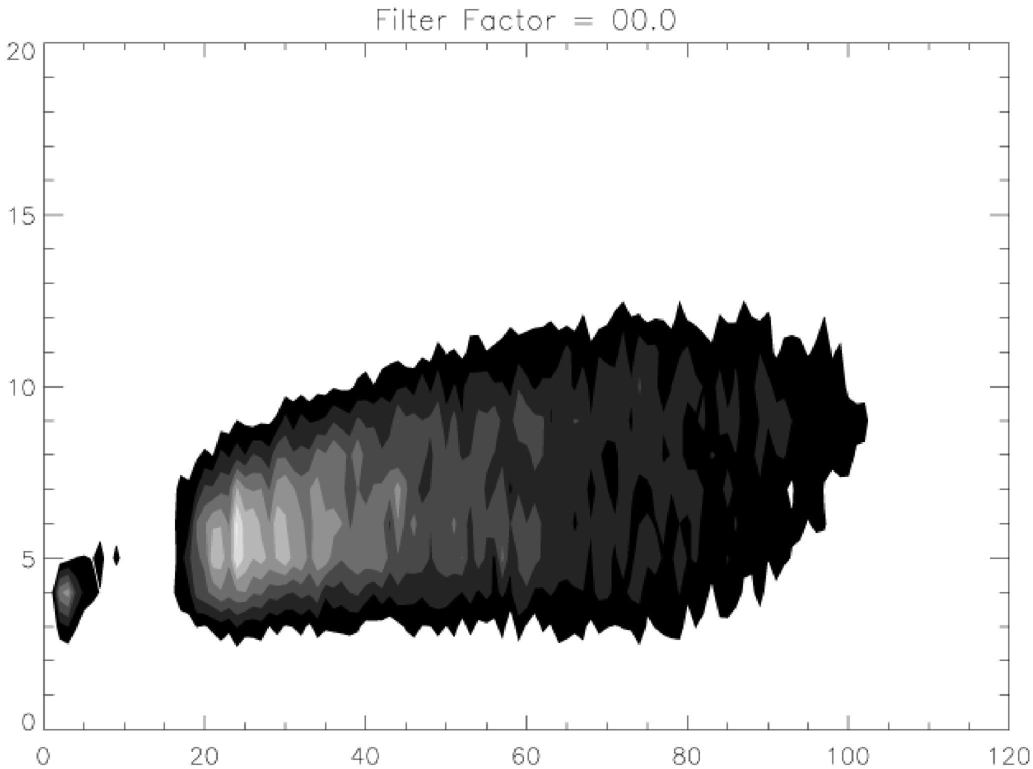

Figure 6: Example of contour concentration plot produced by `filter.pro`, showing the density of the ash plume about 4.5 hours after the eruption of Spurr Volcano (1244 UTC). The x and y axes correspond to the relative longitude and latitude, respectively. Lighter areas indicate areas where there more *counts/bin* (higher density) and lower density regions of the cloud are represented by the dark region. Spurr Volcano would be located just to the left of the plot, with the wind carrying the plume east. The most dense bin here contains 171 particles.

[8]While 0.1 by 0.1 degree grid spaces are simple to use, the area of each grid-space is not necessarily equal. Density for `filter.pro` is defined here in terms of *counts/bin* instead of *counts/area*. At high latitudes, the area of each grid space varies significantly from the area of low-latitude grid-spaces so the density array generated by `filter.pro` may be misleading. For the Spurr 1992 case study, the areas of the grid spaces are approximately equal since the latitude values do not approach extreme limits, so the *counts/bin* concentration definition works reasonably well. If `filter.pro` is eventually incorporated into Puff, the definition of density should be changed so that depends on *counts/area* instead of *counts/bin*.

To process data using `filter.pro`, the user must know a bit about IDL to efficiently use the program. Several components of the program require the user to modify the source code (as noted in the comments sections of the program) so that IDL will be able to find the necessary input files and save output files with appropriate names. The user must specify the directory containing the AVHRR text files, the puff-generated text files, and the location where the filtered puff cloud will be saved. The user must also re-execute several IDL statements after each non-initial run (as explained in the comments of the `filter.pro` source code) to allow for more efficient data processing.

Before performing Puff simulations, information from previous studies[9] was acquired about the details of the 17 September Spurr eruption in order to determine realistic input parameters. Table 1 shows the input parameters were used for the eruption simulation[10]:

Table 1: Input parameters used for Puff simulation of 17 September, 1992 eruption of Spurr Volcano.

Volcano Name	Spurr
Eruption Date[9]	1992 09 17 08:04 (UTC)
Horizontal Diffusion	10,000 m^2/s
Plume Shape	linear (run no.1), poisson (run no.2)
Eruption Duration	1.5 hours
Number of Particles	50,000
Plume Height[9]	14,000 m
Size Standard Deviation	1
Vertical Diffusion	10 m^2/s
Plume Width	2 km
Plume Thickness	3 km
Display Range	(airborne particles only)

2.3 Results

The results of filtering were assessed both quantitatively and qualitatively, as described below. One technique to quantify how well the puff cloud matched the AVHRR cloud was by calculating the 'percent overlap' using the algorithm developed by Laura Bickmeier in `puff_avhrr.pro`. The value for percent overlap (P) is given by the equation $P = m/a$ where m is the number of puff particles (coordinates) which **m**atch AVHRR ash coordinates and a is the the number of AVHRR **a**sh coordinates).[11] A plot of percent overlap versus time, for varying amounts of filtering, is shown in Figure (7).

[9] *Mt. Spurr's 1992 Eruptions*, Eos, Transactions, American Geophysical Union, 74:19, pp 217 and 221-222

[10] In an article about the details of the eruption[9], the eruption duration was reported at 3 h 36 min., but a shorter eruption time was necessary for the puff cloud to match the shape of the AVHRR cloud. Presumably, most of the ash from the eruption was ejected from the volcano early in the eruption, thus making a shorter Eruption Duration value more appropriate for the simulation. The quoted eruption time from the article was used for the simulation.

[11] See the source code for Bickmeier's `puff_avhrr.pro` for a more thorough definition of 'percent overlap'.

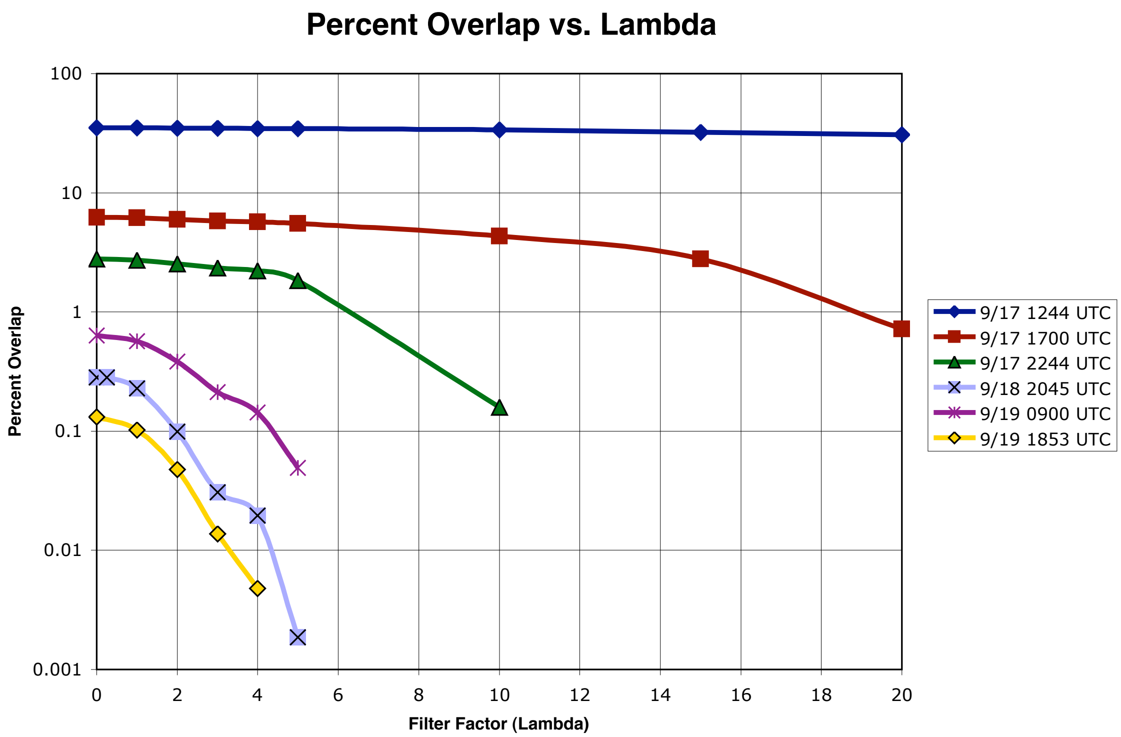

Figure 7: Percent overlap at different times for varying amounts of filtering. The program `filter.pro` was used to filter out Puff ash particles with $\lambda = 0, 1, 2, 3, 4, 5, 10, 15,$ and 20 for each time after the eruption when AVHRR data was captured. The percent overlap decreases at later times and with larger values of λ.

After running `filter.pro` at each time and for various values of λ, the plots of AVHRR, original Puff, and filtered Puff were compared to determine the best value for λ. An appropriate level of filtering was determined by noting when the filtered cloud looked most like the AVHRR cloud. The original puff cloud, such as the one shown in Figure (4), produced a tail-like string of ash ash at times approximately 1.5 days after the eruption. In these cases, the value of λ was recorded as a 'best' value when the (diffuse) tail of the ash cloud was no longer displayed on the filtered cloud. A value of $\lambda = 3.0$ was chosen as the best value for this eruption.

While the *absolute* value for percent overlap is difficult to interpret, the *relative* value can be useful for comparing percent overlap between slightly different Puff simulations. For the September 1992 Spurr case study, we were interested in determining what distribution of Puff ash particles (linear or Poisson) best matched the AVHRR data for a filtered cloud. After choosing an appropriate amount filtering ($\lambda = 3.0$), the percent overlap for linear and Poisson distributions were plotted at different times after the eruption(Figure 8).

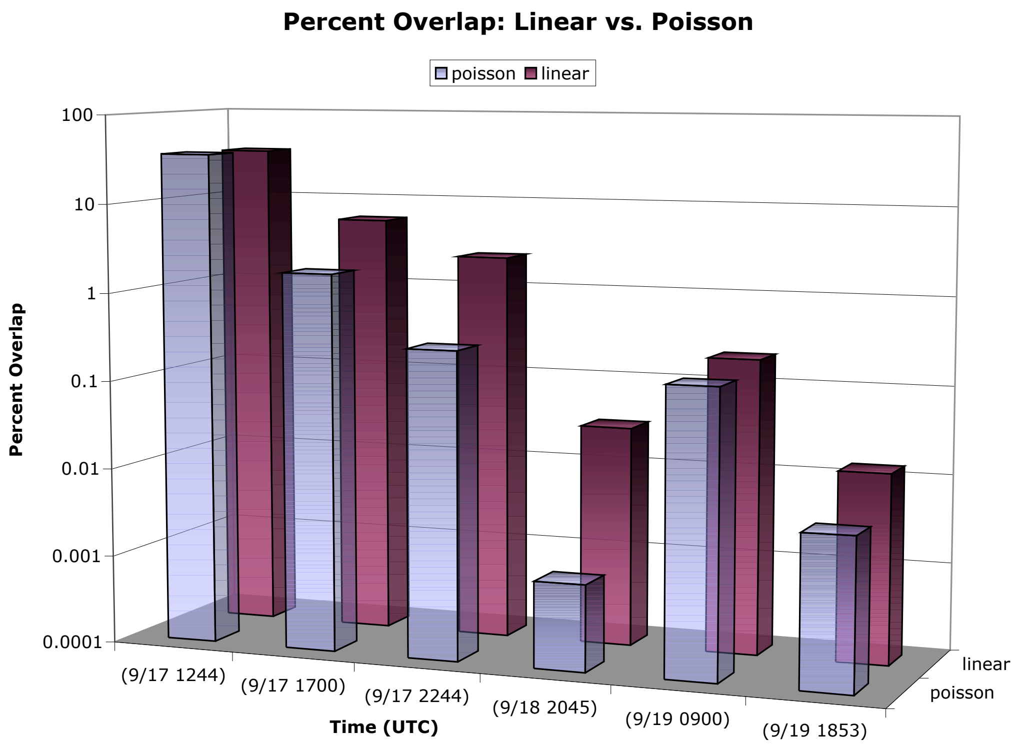

Figure 8: Percent overlap at different times for linear and Poisson distributions of ash and filtering with $\lambda = 3.0$. For this case study, the linear distribution yielded a higher percent overlap at most times.

To better illustrate the effects of filtering, comparison plots of the unfiltered (original Puff results) and filtered `filter.pro` results) ash clouds were also plotted next to each other. The following figures illustrate the dramatic effect of filtering. In Figures (9) and (10), the output from unfiltered and filtered results were plotted as composite images in the same way that the AVHRR composite image of volcanic cloud movement was plotted in Figure (3).

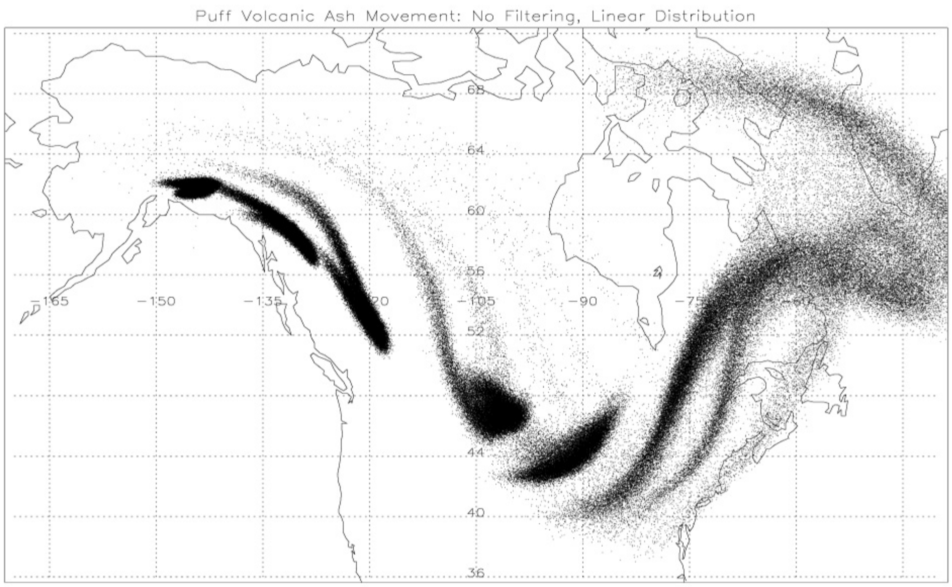

Figure 9: Unfiltered composite image of original puff ash cloud at times corresponding to when AVHRR data was captured. The AVHRR composite showing the observed Volcanic Cloud Movement is shown in Figure (3). The unfiltered puff clouds become very diffuse at later times, whereas the AVHRR ash cloud stays more compact, as noted in previous studies.

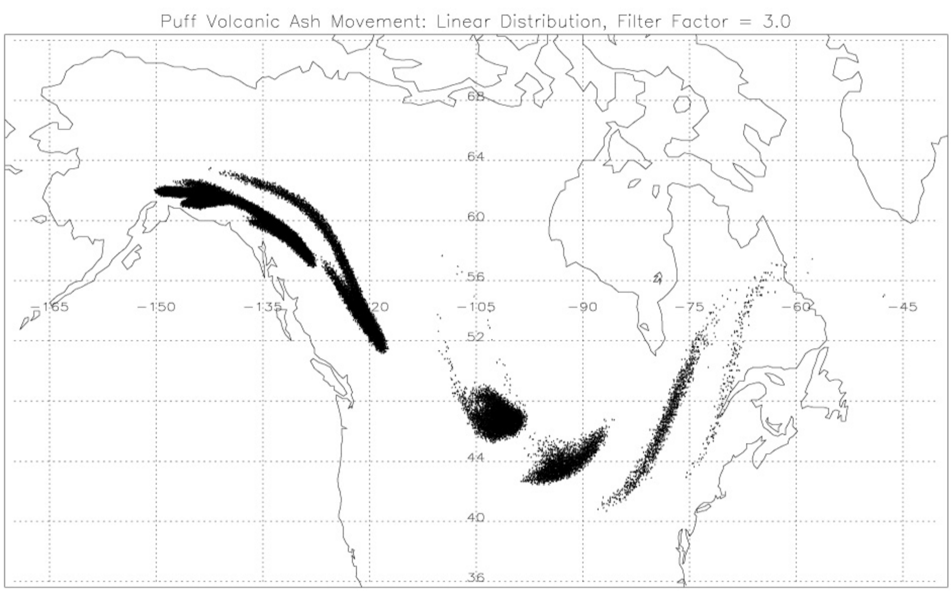

Figure 10: Composite image of *filtered* puff ash cloud at times corresponding to when AVHRR data was captured. The filtered data yields a dense ash cloud which more closely resembles the AVHRR ash cloud shown in Figure (3). The diffusivity of the initial Puff run may have been set too high for this run (10,000 m^2s^{-1}), as indicated by the cloud 'dissolving' faster than the AVHRR cloud. The simulated ash cloud also seems to 'get ahead' of the observed AVHRR cloud in Figure (3).

After filtering the ash cloud, a revised image of the cloud movement (Figure 10) could be compared to the AVHRR cloud movement to determine how well the simulation matches the observed (satellite) cloud. The approximate location of the center of the AVHRR and Puff ash clouds was recorded at each time, and the separation distance between the two are plotted in Figure 11.

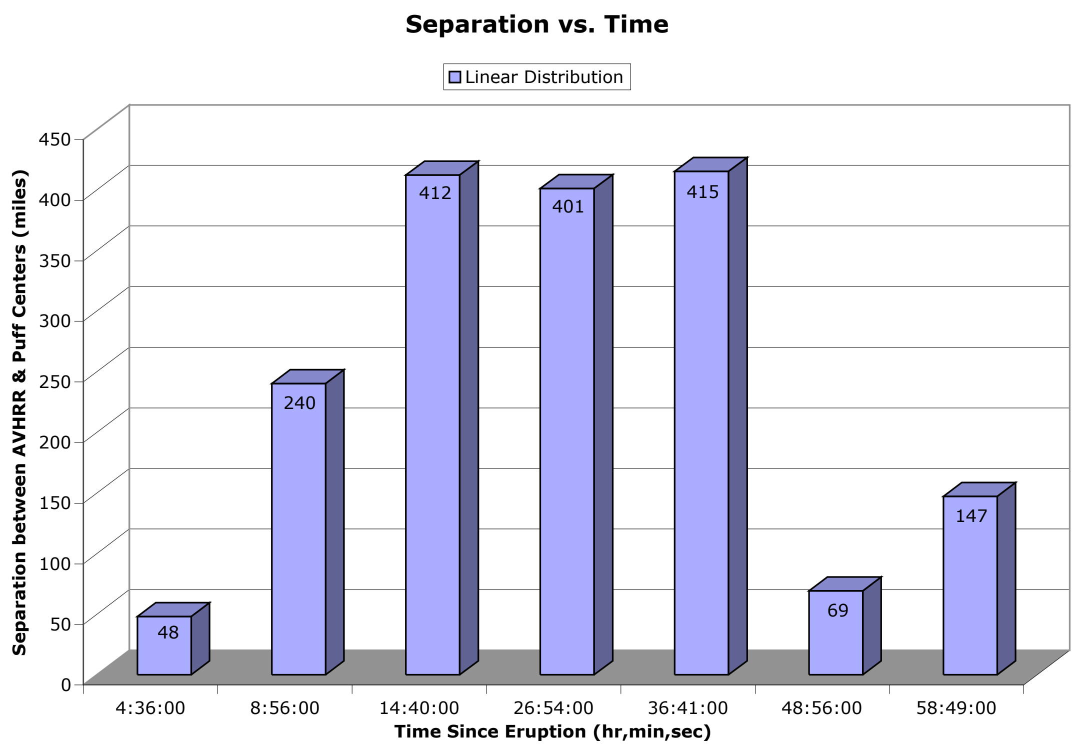

Figure 11: A plot of the separation distance between the centers of the simulated (puff) and observed (AVHRR) ash clouds through time. Curiously, the simulated cloud seems to match better at later times than at middle times.

2.4 Discussion and Conclusions

Based on on the comparison of original and filtered puff clouds to AVHRR images, it appears that the filtering of Puff ash particle produces simulated ash clouds which better resemble AVHRR ash cloud signatures. Simulated ash particles are displayed only if they are above a threshold density. As a result, the simulated ash cloud 'dissolves away' through time as the ash concentrations become less dense and as ash particles fall to the ground. Currently, the Puff model displays *all* airborne ash particles, making the cloud look very large and diffuse at later times – making the model hard to compare to AVHRR images to check its accuracy. Filtering, using the algorithm developed in `filter.pro`, is an effective way to reduce the size of the puff cloud at later times so that it is easier to compare to observed AVHRR data. As a result, input parameters need not be set to unrealistic values.

For this case study, the filtering of ash particles from Puff output was indeed effective and useful. A filter factor of $\lambda = 3.0$ worked best to filter out low-density ash particles that do not appear in the AVHRR B4-B5 images. Also, a choice of a linear (versus Poisson) distribution of ash particles yielded a higher percent overlap at most times. Re-assessing the Puff input parameters chosen for this case study (shown in Table (1)), a choice of diffusivity =10,000 m^2/s (the default puff value) may have been too high. With a smaller value for diffusivity *and* filtering, the original puff cloud would have diffused more slowly and probably would have remained above threshold densities for longer, enabling the cloud to remain for as long as the AVHRR B4-B5 cloud shown in Figure (3).

The data seems to suggest that the ash detected by AVHRR satellites indeed *does* depend on the density of the ash cloud, although it may also depend on the elevation. This aspect was not explored in this project. Also, the Puff ash cloud seems to move faster than the observed cloud. An additional improvement may be the introduction of a drag coefficient as another variable for the puff model. Future work might also include investigation of the *upper* density limit at which AVHRR can detect ash. These suggestions would need to be explored more rigorously before any conclusions could be made.

3 Acknowledgments

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