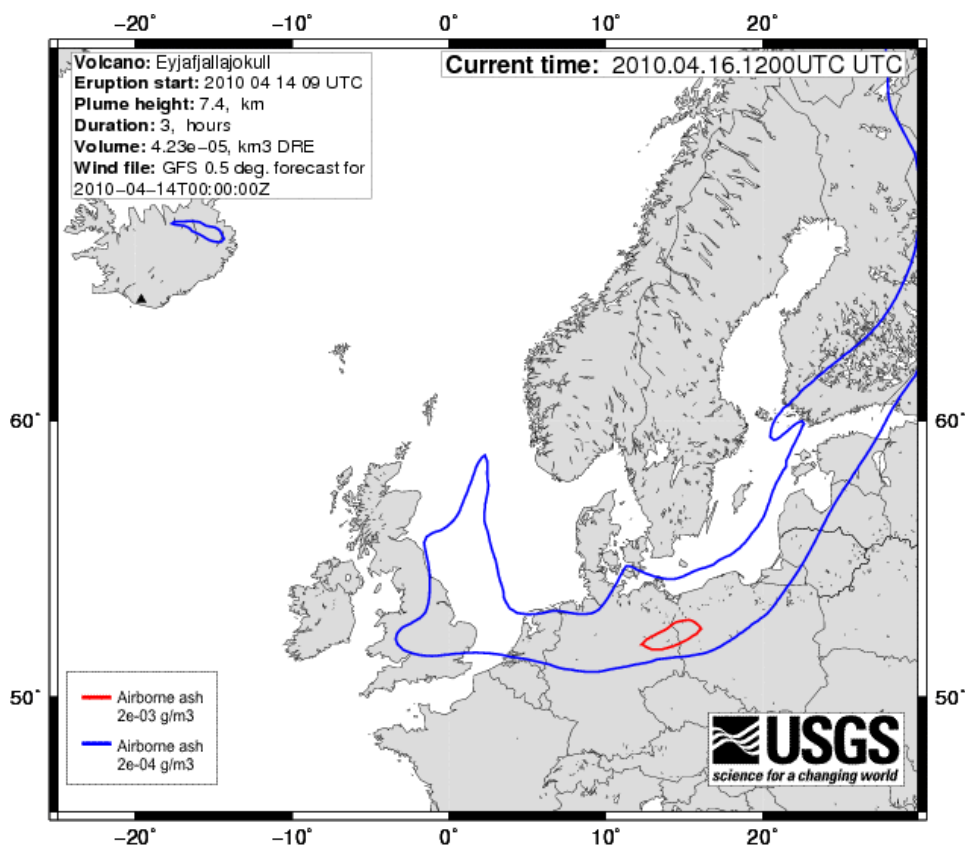![USGS logo] **USGS** *science for a changing world*

U.S. Geological Survey

User's Guide and Reference to Ash3d: A 3-D Eulerian Atmospheric Tephra Transport and Deposition Model

By Larry G. Mastin, Michael J. Randall, Hans F. Schwaiger, and Roger P. Denlinger

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KEN SALAZAR, Secretary

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
Volume		
cubic foot (ft^3)	0.02832	cubic meter (m^3)
Flow rate		
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Mass		
pound, avoirdupois (lb)	0.4536	kilogram (kg)
Pressure		
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
pound-force per square inch (lbf/in^2)	6.895	kilopascal (kPa)
pound per square foot (lb/ft^2)	0.04788	kilopascal (kPa)
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)
Density		
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in Kelvins (K) may be converted to degrees Celsius (°C) as follows:

°C=K-273.15

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to mean sea level (MSL).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

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Abstract

Ash3d is a three-dimensional Eulerian atmospheric model for tephra transport, dispersal, and deposition, written by the authors to study and forecast hazards of volcanic ash clouds and tephra fall. In this report we explain how to set up simulations using both a web interface and an ASCII input file, and how to view and interpret model output. We also summarize the architecture of the model and some of its properties.

Introduction

Atmospheric dispersal of volcanic ash represents the most widespread of volcanic hazards and the hazard with the greatest potential for economic impact. The economic effects of ash distribution were demonstrated during the 2010 eruption of Eyjafjallajökull volcano in Iceland, when flight cancellations and delays throughout Europe caused billions of dollars in economic loss to airlines and travelers [*Harris et al.*, 2012]. This event also demonstrated that volcanic hazards are not limited to areas near the volcano. Flight cancellations and delays during the 2011 eruption of Puyahue/Cordon Caulle in Chile extended halfway around the world to Australia and New Zealand, for example.

The most effective way to reduce risk from dispersed volcanic ash is by forecasting where it will go and what areas it will affect. Modern numerical weather prediction (NWP) models now enable us to routinely forecast ash movement in a three-dimensional, time-changing wind field. Modern computer power

gives us the ability to forecast where ash will go, and what areas it will affect, within minutes during eruptions.

In this report, we introduce a new model for atmospheric transport, dispersal, and deposition of tephra. The model, called Ash3d, is an Eulerian model that uses wind fields from NWP models to calculate tephra transport. Its results have been compared with observations from several eruptions thus far. Ash3d provides a variety of output that can be used in research and operational situations. A companion paper [*Schwaiger et al.*, 2012] describes the model physics in detail. This paper describes the model's setup and use and is intended for volcanologists with no expectation of special knowledge in numerical modethods or modeling. We begin with a brief overview of Ash3d, explain how to set up simulations using a simplified web interface, and then describe simulations using an ASCII input file and standard Linux utilities. Ash3d is still in development, hence its capabilities and documentation are likely to be revised in coming years.

Model overview

Ash3d models the transport of volcanic ash by dividing the atmosphere into a three-dimensional grid of cells (Figure 1) and calculating the flow of mass through cell walls. During the eruption, tephra is injected at a constant rate into the column of cells above the volcano (Figure 1c). Using a 3-D time-dependent wind field imported from a numerical weather prediction model, downwind advection and diffusion of ash is numerically calculated with a diffusion rate determined by a user-specified diffusivity. Individual ash particles fall at a rate determined by their settling velocity in air, and deposit when they reach the ground surface.
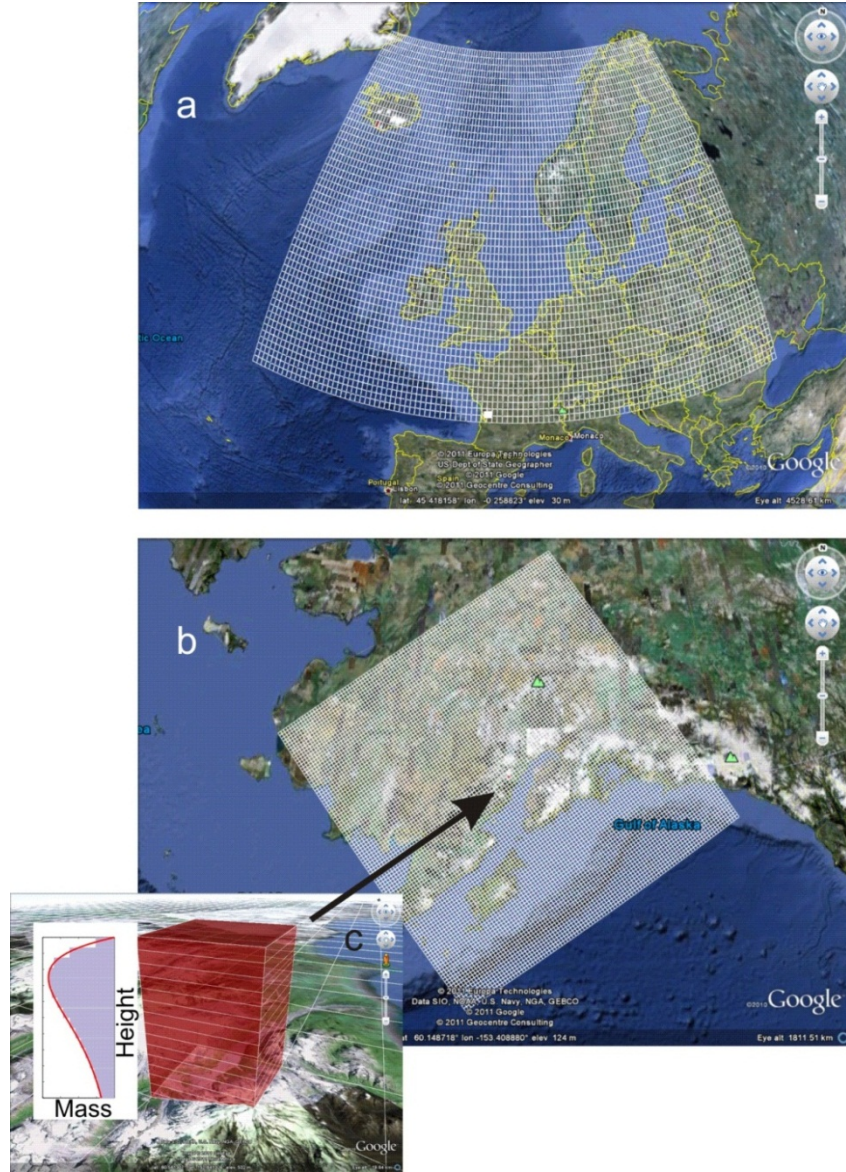
Figure 1. Example model grids illustrated in Google Earth[12]. (a) Latitude-longitude grid over the North Atlantic. (b) Projected grid over Alaska. (c) Closeup of cells over Redoubt volcano, showing a vertical distribution of ash specified by equation (1), using a shape factor (*k*) of 4.

Initial conditions

Ash3d does not calculate the dynamics of a rising plume. Instead, it injects tephra into a column of nodes above the volcano (Fig. 1c). Users may specify that the ash be concentrated in a single cell, distributed evenly throughout the column, or distributed vertically following the Suzuki equation (Figure 1c) [*Carey*, 1996; *Suzuki*, 1983]

$$\frac{dQ_m}{dz} = Q_m \frac{k^2 \left(1 - z/H\right) \exp\left(k\left(z/H - 1\right)\right)}{H\left[1 - \left(1 + k\right)\exp(-k)\right]}, \tag{1}$$

where Q_m is the total mass of erupted material in a given time step at a given particle size, H is the total plume height, z is a given elevation in the plume, and the shape factor k is an adjustable constant that controls ash distribution with height. A low value of k gives a roughly uniform distribution of mass with elevation, while higher values concentrate mass near the plume top.

During an eruption, Ash3d injects tephra into these nodes at a constant rate. The grain-size distribution inserted into each node in the column is the same at each elevation and for each eruptive pulse. Default values are described under the Web Interface section.

Transport

Ash3d solves for the conservation of mass in each cell by tracking the mass concentration q with time t,

Advection-Diffusion $\qquad \frac{\partial q}{\partial t} + \nabla \cdot \left(\left(\mathbf{u} + \mathbf{v_s}\right)q\right) - \nabla \cdot \left(K\nabla q\right) = Q$, $\qquad$ (2)

where $\mathbf{u}$ is the 3-D wind vector, $\mathbf{v_s}$ is the settling velocity, K is the diffusivity, and Q is a source term, which is non-zero only in the column of nodes above the volcano. By default, Ash3d calculates the settling velocity of each particle size using equations of Wilson and Huang [1979] for non-spherical particles. Alternative models that can be used include an optional Cunningham slip correction factor [*Seinfeld and*

Pandis, 2006, p. 407], which can increase the fall rate for small (<30 μm) particles at high elevation; Stokes flow; and modifications to Wilson and Huang by Ganser [1993] and Pfeiffer et al. [2005].

The advection term of equation (2) (the second term on the left-hand side (LHS)) is calculated explicitly using the Donor Cell Upwind method of solution (see Schwaiger et al. [2012] for details). The diffusion term (third LHS term) is calculated implicitly at the end of each time step. The diffusivity, K, can be spatially variable and can be a function of the local meteorological conditions. We have found that modeled clouds match well with observed ones when K=0, and have set it to this value for simulations using the web interface.

Deposition

Ash3d tracks the mass flux of each grain size across cell boundaries and accumulates a deposit once tephra falls through the cell boundary that represents the ground surface at a particular location.

Examples of model output

Ash3d output includes data files of the deposit (Figure 2a) and animations of the moving cloud (Figure 2b), that can be opened in Google Earth®. Also available are ASCII files of deposit or cloud properties that can be imported into GIS software such as ArcMap® (Figure 2c), and kml (Figure 2d) or text (Figure 2e) files illustrating the arrival time, thickness, and (optionally) grain-size distribution of tephra at airports or other locations. Ash3d can also write out ASCII, binary, or NetCDF files containing the 3-D structure of the cloud at specified times. Post-processing scripts are also available that generate deposit maps and gif animations of cloud movement (cover illustration). Details are provided below.
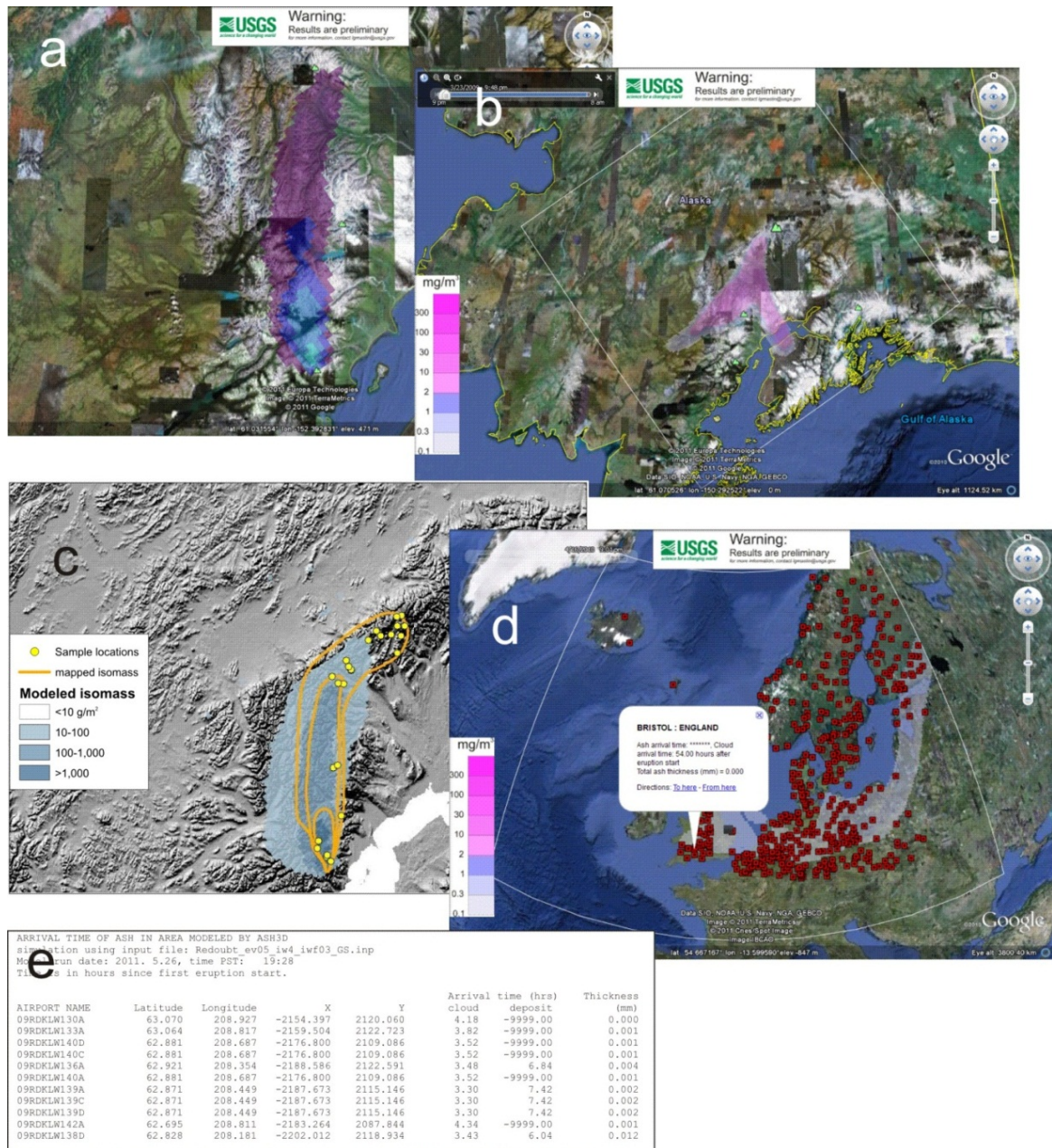
Figure 2. Examples of Ash3d output from simulations of Redoubt event 5 [*Mastin et al.*, in press] (a,b, c, e) and Eyjafjallajökull on April 16, 2010 [*Mastin et al.*, 2010] (d). (a) deposit thickness illustrated in Google Earth®. (b) Cloud concentration (pink shading) in Google Earth®. (c) deposit isomass (blue shading) in ArcMap®. (d) Cloud concentration (gray shading) and airports impacted (red squares) in Google Earth®. (e) Thickness at sample locations.

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The web interface

Ash3d was written in Fortran 90/95. The program and associated scripts are executed on a Linux operating system and have been used to simulate hundreds of eruptions since around 2010. We strive to make it a useful operational tool , and for this purpose we designed a web interface that allows any user to quickly run the model and view results. We simplified the interface by disabling choices regarding, for example, the number of eruptive pulses, number of grain sizes, the kind of numerical weather prediction model used for the wind field etc. that can normally be specified in Ash3d, and keeping only those few that are critical: volcano name, plume height, eruption start time, duration, and number of hours of simulation. We also automatically adjust model resolution so that usable results can be obtained in about 10 minutes or less.

Using the interface

The Ash3d web interface is located at *http://vsc-ash.wr.usgs.gov*. After logging in with a username and password assigned to you, you will see a home page similar to Fig. 3 showing a list of jobs that you have executed. Jobs that have been executed within the last 10 days will provide a link on the right-hand side to the results (under "Run Status"); older jobs are deleted automatically.
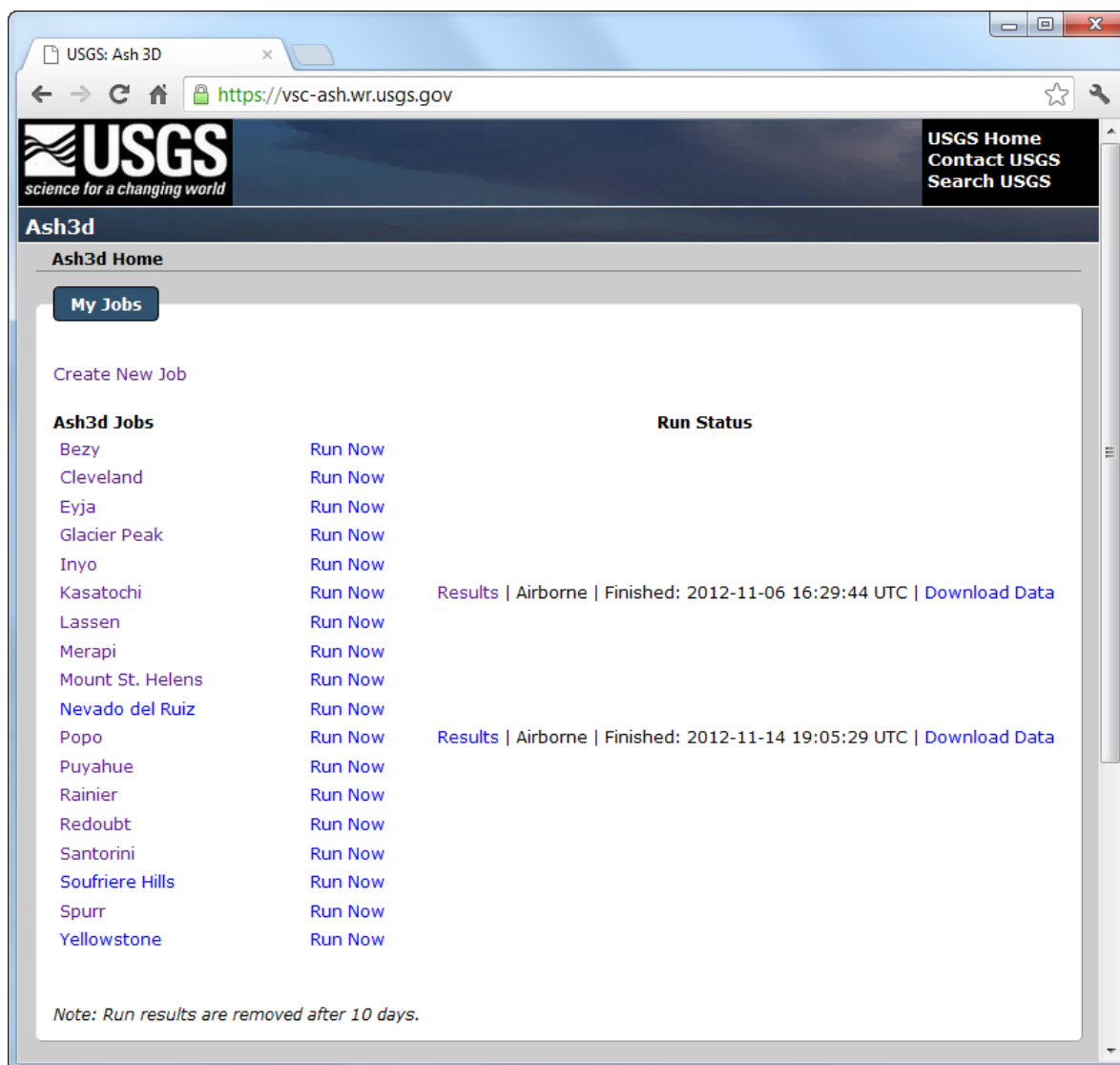
Figure 3.   The Ash3d home page.

Specifying input values

After clicking "Create New Job" in the upper left of the home page, or clicking on any of the existing jobs, you will be sent to an Ash3d Job page which appears similar to Figure 4. This page contains the following items:

Figure 4. the Ash3d job page on the Ash3d web site.

Times: The time for which the wind field used by Ash3d is valid (top row) and the current time, in both local for your computer (second row) and UTC (third row). For forecast model runs, Ash3d uses a wind field provided by the NOAA Global Forecast System (*http://www.emc.ncep.noaa.gov/index.php?branch=GFS*) numerical weather prediction model, downloaded four times daily, for 0000, 0600, 1200, and 1800 UTC. These model results are typically available on the Ash3d web interface within five hours after they're posted by NOAA (i.e. 0500, 1100, 1700, and 2300 UTC). For the case illustrated in Fig. 4, the wind file for 1200 UTC was already available by 1549 UTC.

Name: Name that you would like to apply to the current job.

Automatic run: Check this box if you would like to run this job automatically whenever a new wind file arrives. **Note**: automatic runs are executed indefinitely, whenever a new wind file arrives, until you uncheck this box or delete this job. Automatic runs are also only executed if Ash3d is run in forecast mode, which is the case if the eruption start time is given as "now" or in "HH:MM (24 hr)". Repeat model runs will always be executed at the same time relative to the start of the wind file. For example, if you specify an eruption start time that is six hours after the start of the wind file, either by choosing "now" or "HH:MM (24 hr)", future automatic runs will also use an eruption start time six hours after the start of that wind file.

Run type: You may choose either Airborne ash, Ash Deposit, or both. Airborne ash simulations use a single fine grain size (0.01 mm) with a negligible settling velocity and are intended to simulate only the movement of the cloud, not the settling of ash to form the deposit. For airborne simulations, the erupted volume in the ash cloud is set to 5% of the total erupted volume based on empirical studies suggesting a few to several percent of the erupted mass makes it into the distal cloud [*Dacre et al.*, 2011; *Devenish et al.*, 2012]. Ash deposit simulations use seven grain-size bins (4, 2, 1,

0.5, 0.25, 0.125, and 0.0625 mm) and only calculate transport within several hundred kilometers of the volcano, where the deposit may fall. If "both" is specified, Ash3d runs two simultaneous simulations, one for the deposit and another for the cloud movement.

When complete: you may choose to receive an e-mail when execution is complete and results are ready to view.

Volcano/Site: start entering the name of a volcano in this text box and the interface will display the names of volcanoes in the Smithsonian Institution's Global Volcano Network list (*http://www.volcano.si.edu*) that start with these letters. You must choose one of the volcanoes whose name appears. When the latitude, longitude, and elevation labels below this text box are filled with their appropriate values, you will know that this entry was successful.

Eruption Start Time: You may choose "Now", "HH:MM (24 hr)", or "Specific Date/Time".

- "**Now**" will assign the current date and time as the eruption start time.

- "**HH:MM (24 hr)**" will assign an eruption start time by hour and minute for today or, if the time is earlier than that of the most recent wind file, for tomorrow. The time entered will be interpreted as either UTC or local time (local to your computer) depending on how your time preferences are set in the "Update My Information" link at the bottom of the page. If, for example, the current wind file is valid for today at 1200 UTC, entering an hour and minute of 0800 UTC will assign a start time of 0800 UTC TOMORROW. For the same wind file time, entering an eruption start time of 18:00 UTC would assign an eruption start time of 1800 UTC TODAY.

- "**Specific Date/Time**" allows you to enter any date from 1 January 1948 to today. If this option is chosen, the eruption is assumed to be in the past; hence, the "automatic run" checkbox, which allows future simulations to start automatically when a new wind file arrives, is automatically

disabled. If you choose a date and time that is more than two weeks old, Ash3d will use a wind field taken from a different numerical weather prediction model; the global *NCEP/NCAR Reanalysis 1 model* with a 2.5 degree resolution (*http://www.esrl.noaa.gov/psd/data/gridded/data.nmc.reanalysis.html*). For more recent times, Ash3d will use recently downloaded files from the NOAA Global Forecast System model.

Simulation Duration is the number of hours over which Ash3d calculates transport of the cloud. This value should be between 3 and 48 hours. Longer simulation times are not allowed because they risk exceeding the time window for which wind files are available and use wind forecasts whose reliability diminishes with time. This value is used primarily for airborne ash simulations. For deposit simulations, Ash3d calculates transport until 48 hours after the eruption starts or until 99% of the tephra has deposited, whichever is shorter.

Eruption duration: Enter a value in hours up to 24.

Plume height: Values are given as feet or kilometers above sea level. The units are set under "Update My Information" at the bottom of this page.   The NOAA/NCEP models used by Ash3d extend to a pressure level of about 1 kPa, which is roughly 34 km above sea level in the atmosphere. If you enter a plume height greater than 34 km, a warning label will appear indicating that wind vectors at elevations greater than ~34 km are assumed to be the same as the wind vectors at the highest pressure elevation.

Erupted volume is the total volume of erupted magma in cubic kilometers dense-rock equivalent (DRE), automatically calculated from the plume height, eruption duration, and volcano summit elevation using the empirical relationship between plume height and eruption rate from Mastin et al. [2009b, Eq. 1]. If the volume calculated is less than 0.001 km^3, the volume is set to 0.001 km^3 to prevent errors.

Running the model

Once the input parameters are set and the <return> key or the "Save Changes" button in the lower left is pressed, a "Model runs" box (Figure 5) appears at the base or the right-hand side of the Ash3d job window.

Model Runs			
Requested	**Type**	**Status**	
2012-11-14 22:03:32 UTC	Airborne	Running	
2012-11-14 20:48:51 UTC	Airborne	Results	Download Data | Delete
2012-11-14 20:48:51 UTC	Deposit	Results	Download Data | Delete

Figure 5.   Model Runs box, which appears in the Ash3d job page. Once changes in the input parameters are saved, a "Run Now" hyperlink is active in this list. When clicked, it initiates the simulation and changes the message to "pending" or "running", as seen above. Lines below the "Running" line give results and download links for previous simulations for this job.

Pressing the "Run Now" hyperlink in this box places this job in the queue and changes the label in the Status column to "pending", and then to "running". You can remain on this page, change to other pages in the Ash3d web interface, or log out without affecting the simulation. Once complete, the label in the Status column will change to "Results" and other hyperlinks will appear that allow output to be downloaded or the simulation deleted. Similar links appear in the Ash3d home page (Figure 3). **Note:** Airborne simulations typically complete in 2-3 minutes whereas deposit simulations may take ten minutes or so due to the larger number of grain sizes whose movement must be calculated. For airborne ash, simulation times increase with plume height and simulation duration. For ash deposit runs, the time required to run the model typically increases with plume height and eruption duration.

Model domain

As an Eulerian model, the geographic area covered by the model must be specified prior to execution. This presents a challenge; we want the domain to cover the area of the cloud or deposit, which could be east, west, north, or south of the volcano depending on wind direction; but we don't know the wind direction *a priori*. In order to set the model domain, we run a preliminary simulation at very low resolution (25×25×10 cells) over an area centered on the volcano that is large enough to completely cover the cloud or deposit. This simulation generally takes less than a minute to run. The calculated area of the deposit or cloud is then used to outline a smaller domain which is run at higher resolution (100×100×10 cells) and produces the final output.

Model results page

Upon completion, the status label in the Model Runs box changes to a hyperlink called "Results" that takes the user to a page showing model results (Figure 6). The Model Results page includes:

- A sidebar giving source parameters, the date and time of simulation and a link to download additional model output.

- A gif image (Figure 6, right) showing the distribution of the deposit or, for airborne simulations, the moving cloud.

- A list of airports impacted by ash (Figure 6, bottom). For airborne simulations this list includes the arrival time of the cloud overhead and the number of hours during which the cloud remains overhead. For deposit simulations the list includes the arrival time of ash on the ground and the final deposit thickness.

- A system output log, written out during model execution (out of view in Figure 6).

Clicking the "Download Data" link in the sidebar downloads a zip file containing additional maps, input files, a log file, and kmz files that can be opened in Google Earth®. A list of these files is given in

Table 1. Detailed description of some of these files follows.
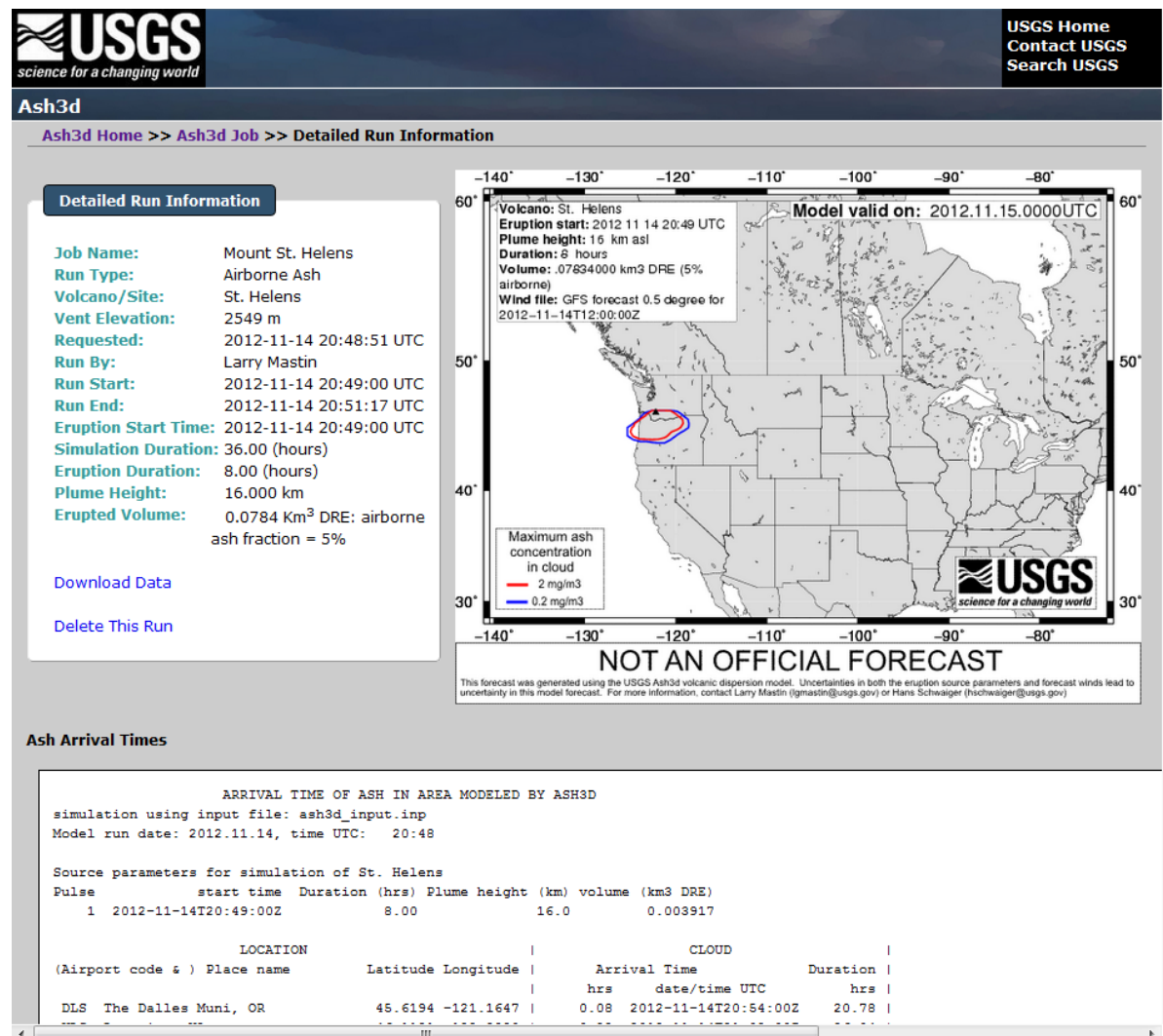
Figure 6. Results page for a deposit simulation at Mount St. Helens

Table 1. Files included in the zip file of model output. Those with an "x" in column "A" are generated during airborne simulations; those generated during deposit simulations contain an "x" in column "D".

File name	A	D	Description
ash3d_input.inp	x	x	ASCII input file used to run this model. The contents of this file are explained below.
Ash3d.lst	x	x	Log file that records messages written out during the simulation.
AshArrivalTimes.txt	x	x	Text file giving the arrival time of the ash cloud or deposit at airports. For deposit simulations, this file also gives the final deposit thickness and the number of hours the ash will be depositing. For cloud simulations this file gives the number of hours the cloud remains overhead. Contents of this file are also displayed in the Results page of the web interface.
AshArrivalTimes.kmz	x	x	kmz file showing the locations of airports over which the ash cloud has moved (airborne simulations) or the deposit has landed (deposit simulations).
CloudArrivalTime.kmz	x		Static map of cloud arrival times in hours after the eruption start.
CloudConcentration.kmz	x		Animation of cloud movement. Colors indicate maximum ash concentration at a given x,y location.
CloudHeight.kmz	x		Animation of cloud movement. Colors indicate height of the cloud top at a given x, y location.
CloudLoad.kmz	x		Animation of cloud movement. Colors indicate integrated mass load of the cloud.
Deposit.kmz		x	Animation of changing deposit thickness with time and of final deposit thickness.
DepositArrivalTime.kmz		x	Static map of deposit arrival time in hours after the eruption start.
deposit.gif		x	Map showing contours of deposit thickness. This image is also displayed in the Results page of the web interface.
deposit_mm.gif		x	Map showing deposit thickness in contours of 0.1, 0.3, 1, 3, 10, 30, 100, and 300 mm.
Time-stamped gif files of cloud concentration (e.g. 2012.04.11.1200UTC.gif)	x		Maps of cloud concentration, with contours of 0.2 and 2 mg/m^3. The time of the image is given in the file name (e.g. 2012.04.11.1200UTC.gif and in the upper right-hand corner of the gif image. The time interval between these images may be 0.5, 1, 2, 3, or 6 hours depending on the length of the simulation.
cloud_animation.gif	x		Animated map of cloud movement, with contours of concentration (0.2 and 2 mg/m3), generated by combining time-stamped gif images. This animation is also displayed in the Results page of the web interface.

Model output files

gif images of the ash cloud or deposit

The output from airborne ash simulations includes a series of gif files showing the location of the cloud at a given time with contours for ash concentration that coincide with current satellite detection thresholds for mass load [*Prata and Prata*, 2012] (0.2 mg/m^3, outer line) and agreed thresholds for medium to high ash concentration [*International Civil Aviation Organization*, 2010] (2 mg/m^3, inner line), (Figure 7).   An animated gif image (cloud_animation.gif) is generated by combining these static images. In order to see the animation it may be necessary to open the gif image with Microsoft Internet Explorer®, as many default picture viewers like Picasa® will not show the animation.

Figure 7. Gif image of an ash cloud from Mount St. Helens. The source parameters for this run are in the legend on the upper-left. The current time is given in the upper right.
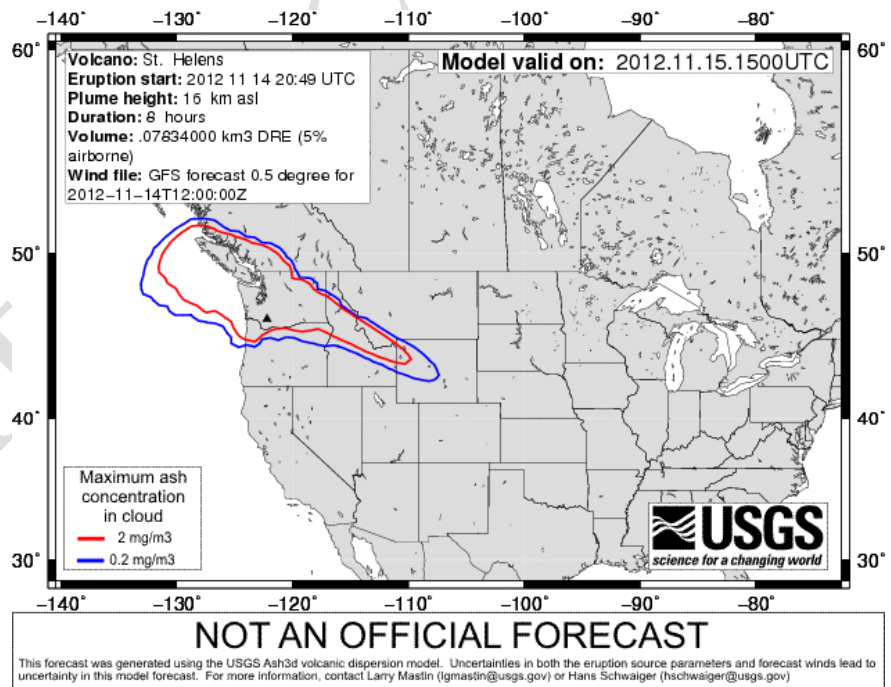
The output from deposit simulations includes two gif images of the deposit. One (Figure 8) shows contour values of ash thickness (0.8, 6, 25, and 100 mm) that separate zones of ash impact termed "trace", "minor", "substantial", "heavy", and "severe", modified from ash impact severity terms as

delineated by the USGS and the U.S. National Weather Service[6]. The second (not shown) displays

contours of 0.1, 0.3, 1, 3, 10, 30, 100, and 300 mm. Ash3d actually calculates mass load of the deposit

(kg/m^2), and then converts this to deposit thickness assuming a deposit density of 1,000 kg/m^3.

Measured densities of real deposits range from <500 [*Sarna-Wojcicki et al.*, 1981] to >1300 kg/m^3

[Scollo et al., 2007], hence the thickness is approximate. Using a density of 1,000 kg/m^3, the deposit

thickness in millimeters is numerically equal to the mass load in kg/m^2.

Figure 8.   Gif image of the deposit distribution of a simulation from Mount St. Helens. Eruption source parameters are on the upper left.
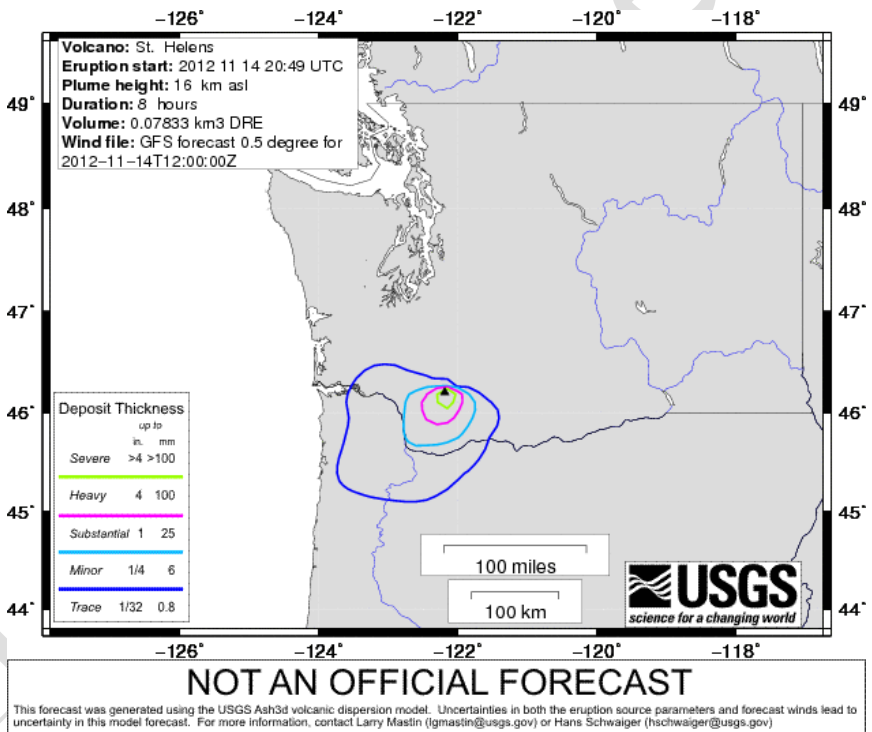
kmz files

Files having the suffix kmz can be opened by Virtual Globes software such as Google Earth[®].

These are zipped keyhole markup language (kml) files that graphically display animations of cloud

movement, cloud or deposit arrival times, the thickness distribution of the deposit, and arrival times of

ash at airports.

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[6] *http://www.arh.noaa.gov/essd/docs/Volcanic%20Ashfall%20Event_product%20and%20statement%20guidelines.pdf*

Using an example eruption from Mount St. Helens, Figure 9 illustrates the location of the cloud as displayed by the file CloudConcentration.kmz. The movement of the cloud and the appearance of impacted airports can be animated using the timeline in the upper left (label 4, Figure 9).   The cloud that's visible in the Google Earth window is actually a set of polygons, each of which has the size and location (in 2-D) of one of the cells in the Ash3d model. When viewed from the side in Google Earth®, these polygons are located at an elevation that corresponds to the top of the cloud.
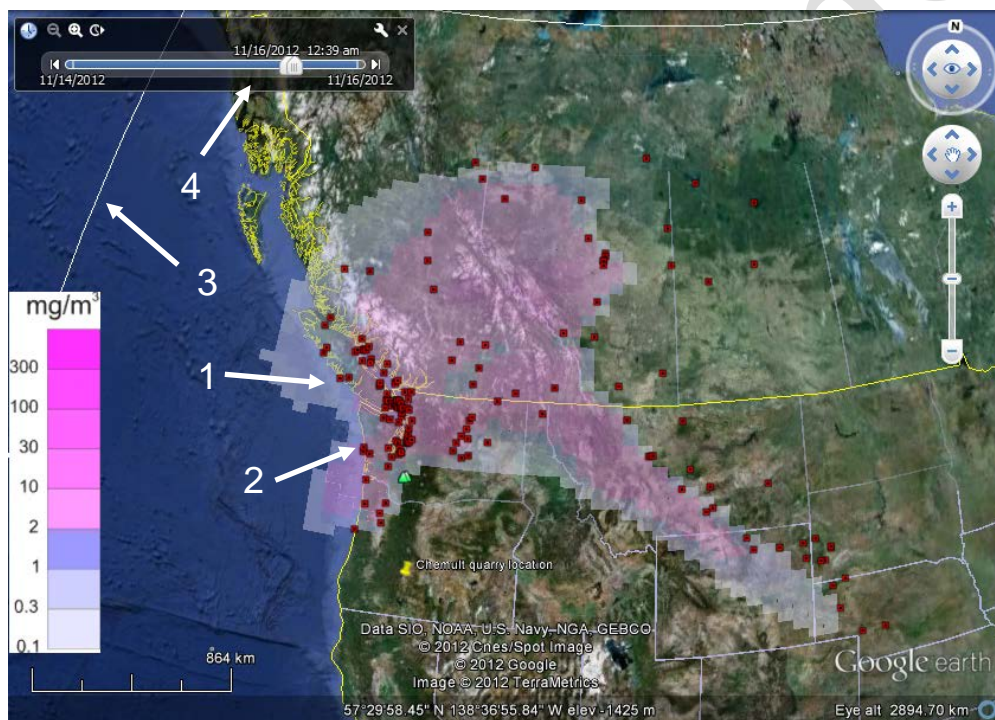
Figure 9.   Google Earth® view of model output from a Mount St. Helens simulation from the files CloudConcentration.kmz and AshArrivaltimes.kmz. Cloud concentration (mg/m^3) is shown in pink (1); impacted airports shown as red squares (2); the model boundary is shown by the white box (3). Cloud movement can be animated using the timeline (4).

To view the concentration at a particular location in the cloud, place the mouse over that location. When zoomed in, the boundaries of that node will appear (Figure 10), and the concentration

value will be displayed. This display is a 2-D representation of the 3-D cloud, hence the value of ash

concentration displayed is actually the maximum in a vertical column of nodes at that x and y location.

Deposit thickness, cloud load and other properties are similarly displayed in other kmz files.

Figure 10. Mousing over a cloud polygon causes its outline to appear (a)

 and its value (here ash concentration) to be displayed.
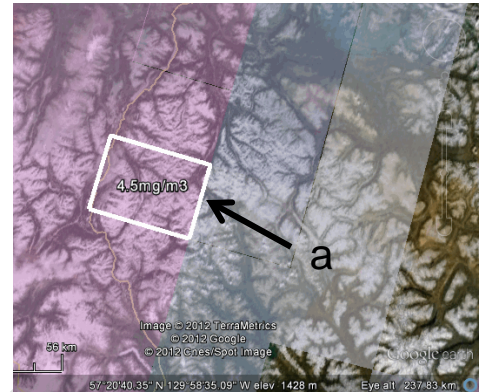
Also in Figure 9 are the locations of airports (red dots) impacted by ash, from the file

AshArrivalTimes.kmz. Placing the mouse arrow over any of the airport symbols causes the airport name

to be displayed, and clicking on an airport symbol opens a dialog box (Figure 11). For airborne

simulations, the box displays the arrival time of the cloud and the number of hours the cloud remains

overhead. For deposit runs, it displays the deposit arrival time and accumulating thickness at that

location. In deposit simulations, airports where >0.1 mm deposit has landed are indicated with white

symbols.

Figure 11. Clicking on an airport symbol opens a dialog box giving the   arrival

 time of the ash cloud or deposit.
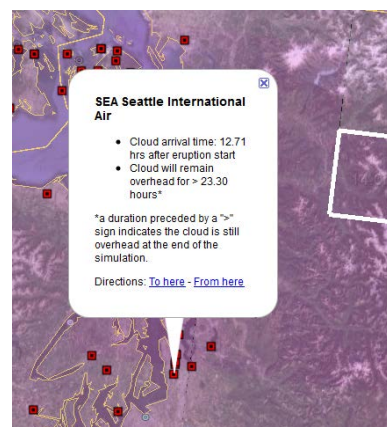
Troubleshooting kmz animations

Occasionally animations do not display properly when viewing a kmz file. Common problems and solution are:

1. *The clouds from all times are overlapping in the Google Earth window.* Ensure that the two caliper pincers on the timeline are pressed together (b, Figure 12). If they are not, the timeline is set to display a time range rather than a point in time.

2. *Pressing the animation button doesn't make the cloud appear.* Check the timeline to make sure that the start and end times displayed correspond to the beginning and end of the simulation. If they indicate a larger time span, you may have another folder checked in "My Places" or "Temporary Places" on the left sidebar. Make sure that all other folders with time data are unchecked and try the animation again.

3. *The animation runs too slowly or too fast, or doesn't loop.* These settings can be adjusted by clicking on the wrench icon on the timeline (c, Figure 12).

Figure 12. Closeup of the time slider in Google Earth®.

Manipulating the contents of a kmz file
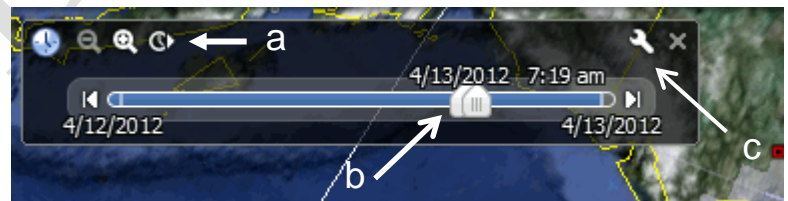
On the left sidebar of Google Earth, under "Temporary Places", one can view the contents of the kmz file (Figure 13). The contents include a legend, a graphical USGS disclaimer, the model boundary, and a folder containing forecasts. Each sub-folder in the Forecasts folder contains an image of the cloud at a time which is specified by the folder name, in year, month, day, hour, and decimal hour (UTC). To view the cloud at just one of these specified times, uncheck the box next to the Forecasts folder, and then check a box next to a single subfolder.

Individual polygons in a subfolder may also be displayed (Figure 14) by right-clicking that subfolder, choosing "Properties", and checking the box labeled "Allow this folder to be expanded".
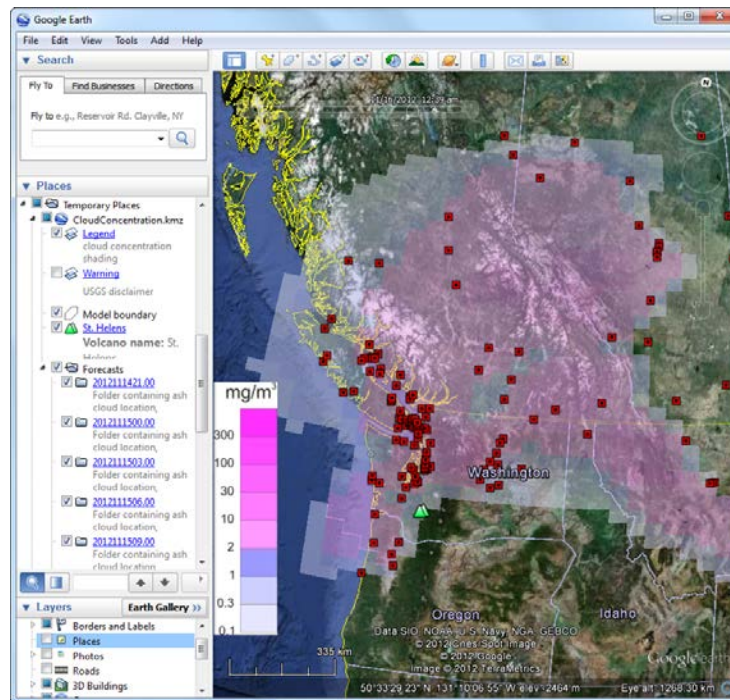
Figure 13. Google Earth® window with left sidebar visible, illustrating the contents of the CloudConcentration.kmz file.
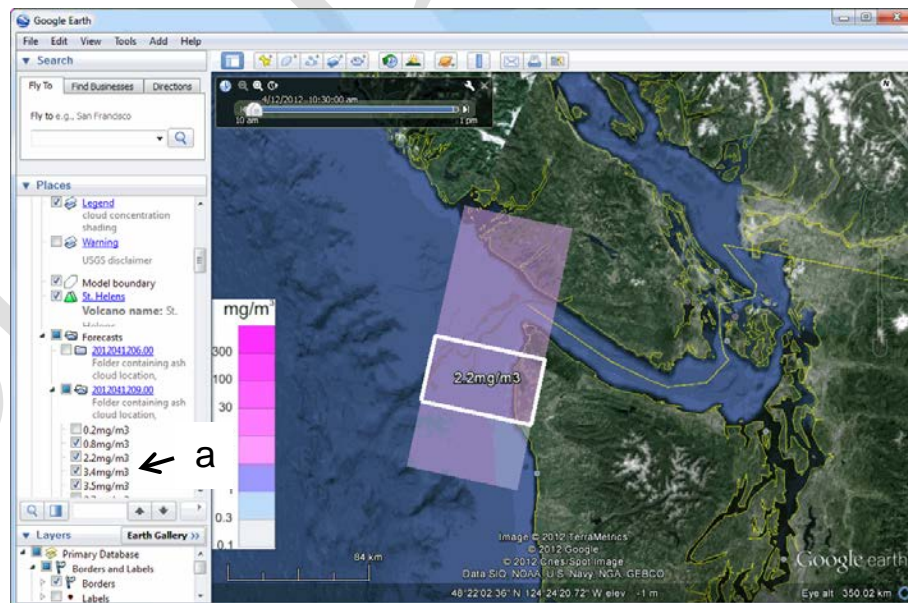
Figure 14. As in Fig. 13, but a subfolder has been set so that individual polygons can be viewed in the left sidebar (a)

Modeling from the Command Line

The Linux command line provides a more versatile but less user-friendly environment for running Ash3d simulations. We do not offer support for installing or running Ash3d on computers outside the USGS, but we are willing to work with collaborators who wish to run Ash3d in a more advanced environment than is possible through the web interface. Below, we explain how to set up and run a simulation in a Linux environment. Ash3d is in a state of continuing development, and we recommend that potential users consult the authors for updates before following these instructions.

Model input using an ASCII input file

The Ash3d executable reads from an ASCII input file that supplies information on source parameters, output file types, and other options. A file for a simulation at Redoubt volcano is illustrated in the Appendix. All elements in blue are comments; actual input parameters are shown in black. If these files are viewed in a Linux text editor such as vi or gedit that converts syntax elements for a shell script into colors, the same color scheme will be visible, allowing users to easily discriminate comments from parameters. The input file is further divided into blocks, delimited with lines of asterisks. Each of these blocks is described below.

Block 1: Volcano name, projection parameters, model domain boundaries

The lines in this block primarily define the size, shape, and location of the model domain.

Line 1 gives either the **volcano name** or the volcano's number from the Catalog of Active Volcanoes of the World [*Siebert et al.*, 2010]. If the CAVW number is given, Ash3d looks up the eruption source parameters (ESP) for this volcano in the ESP spreadsheet of Mastin et al. [2009a]. In the example file, the volcano name is given.

Line 2 gives the **projection parameters** for this simulation. These parameters are used to ensure that the grid coordinate system is compatible with the numerical weather prediction (NWP) model data to be

used. Ash3d uses 3-D wind fields from NWP models. Some of those models, such as the NOAA National

Center for Environmental Prediction's (NCEP) Global Forecast System (GFS) model, are run on a spherical

earth, hence the wind vectors are given in a 3-D grid of latitude, longitude, and elevation. Other models,

such as NOAA's North American Model are run using a grid that is projected onto a planar coordinate

system. After Ash3d reads the NWP wind data, it must know the type of projection in order to find the

portion of the NWP model grid that lies within the Ash3d model domain. Ash3d also interpolates the NWP

wind field onto a new grid whose x and y axes must be parallel to that in the NWP model. For these reasons,

it is necessary to know whether the NWP model uses a projected grid, and if so, the projection parameters

for that grid. The types of NWP model output that Ash3d can read, and their projection parameters, are

given in Table 2.

Table 2.   List of Numerical Weather Prediction models that Ash3d can read, and their projection parameters. The right-
hand column gives the highest pressure level in the atmosphere and the approximate elevation to which this
corresponds.

iwindFormat (Block 3 line 1)	NWP model type	Coordinate system used	Highest pressure level
1	1-D wind sounding	latitude/longitude must be specified in the Ash3d input, Block 1, line 2.	
2	unassigned		
3	North American Regional Reanalysis, AWIPS grid 221 (North America, 32 km resolution)[1]	Lambert Conformal Conic projection longitude of origin (λ_0)=-107° latitude of origin (ϕ_0)=50° latitude of first tangency (ϕ_1)=50° latitude of second tangency (ϕ_2)=50° Earth radius (R)=6367.47 km	10 kPa (17 km)
4	unassigned		
5	North American Model AWIPS grid 216 (Alaska, 45 km resolution)[2]	Polar Stereographic projection longitude of projection point (λ_0)=-135° latitude of projection point (ϕ_0)=90° scale factor at projection point (k_0)=0.933 Earth radius (R)=6371.229 km	10 kPa (17 km)
6	North American Model AWIPS grid 105 (polar, 90 km resolution)[3]	Polar Stereographic projection λ_0=255°, ϕ_0=90°, k_0=0.933 R=6371.229 km	
7	North American Model AWIPS grid 212 (continental U.S., 40	Lambert Conformal Conic projection λ_0=-95°, ϕ_0=25°, ϕ_1=25°, ϕ_2=25°	5 kPa (21 km)

	km resolution)[4]	R=6371.229 km	
8	North American Model AWIPS grid 218 (continental U.S., 12 km resolution)[5]	Lambert Conformal Conic projection λ_0=-95°, ϕ_0=25°, ϕ_1=25°, ϕ_2=25°, R=6367.47 km	5 kPa (21 km)
9	unassigned		
10	North American Model AWIPS grid 242 (Alaska, 11km resolution)[6]	Polar Stereographic projection λ_0=-135°, ϕ_0=90°, k_0=0.933 R=6371.229 km	10 kPa (17 km)
11-19	unassigned		
20	NOAA Global Forecast Systsem (global, 0.5° resolution)[7]	latitude/longitude, spherical earth, radius (R) =6371.229 km	10 kPa (17 km)
21	European Community Medium-Range Weather Forecasting model (ECMWF) 0.25 degree resolution	latitude/longitude, spherical earth, radius (R)=6367.47 km	0.1 kPa (>50 km)
22	NOAA Global Forecast System low-resolutoin (global, 2.5°)[8]	latitude/longitude, spherical earth, R=6367.47 km	1 kPa (34 km)
23	NOAA NCEP/DOE AMID II reanalysis(global, 2.5° resolution)[9]		10 kPa (17 km)
24	NASA MERRA reanalysis (global, 1.25° resolution)[10]		0.1 kPa (>50 km)
25	NOAA NCEP Reanalysis 1 (global, 2.5° resolution) [11]	latitude/longitude, spherical earth, R=6367.47 km	1 kPa (34 km)

[1] http://dss.ucar.edu/pub/narr
[2] http://idd.unidata.ucar.edu/
[3] http://motherlode.ucar.edu:8080/thredds/catalog/fmrc/NCEP/NAM/Polar_90km/catalog.html
[4] http://motherlode.ucar.edu:8080/thredds/catalog/fmrc/NCEP/NAM/CONUS_40km/conduit/catalog.html
[5] ftp://nomads.ncdc.noaa.gov/NAM/Grid218
[6] http://motherlode.ucar.edu:8080/thredds/catalog/fmrc/NCEP/NAM/Alaska_11km/catalog.html
[7] http://motherlode.ucar.edu:8080/thredds/catalog/fmrc/NCEP/GFS/Global_0p5deg/catalog.html
[8] http://motherlode.ucar.edu:8080/thredds/catalog/fmrc/NCEP/GFS/Global_2p5deg/catalog.html
[9] http://dss.ucar.edu/pub/reanalysis2
[10] http://gmao.gsfc.nasa.gov/merra/
[11] http://www.esrl.noaa.gov/psd/data/gridded/data.nmc.reanalysis.html

The first two parameters on this line are `latlonflag` and `projflag`, where:

`latlonflag` is an integer whose value is 0 if coordinate system is projected, 1 if coordinates are in latitude and longitude

`projflag` is an integer that indicates the projection type:

1=Polar Stereographic

2=Albers Equal Area (not currently functional)

3=UTM (not currently functional)

4=Lambert Conformal Conic

Numbers that follow these are projection parameters that are different for different map projections. These parameters are explained in the comment lines above this block of input. Below are some examples of this input line. The comment in blue following the hash mark (#) gives the projection type.

```
0 1 -135.0 90.0 0.933 6371.229        #Polar stereographic
```

Parameters 3-6 are λ_0, the longitude of the projection point; ϕ_0, the latitude of the projection point; k, the scale factor at the projection point; and R, the Earth radius used in kilometers.

```
0 4 -95. 25.0  25.0 25.0 6371.229    #Lambert Conformal Conic
```

Parameters 3-7 are λ_0, the longitude of the projection origin; ϕ_0, the latitude of the projection origin; ϕ_1, the latitude of the first secant; ϕ_2, the latitude of the second secant; and R, the Earth radius used.

Line 3 gives the x and y (or longitude and latitude) values of the **lower left corner** of the grid. These values must be in the same coordinate system defined by the projection parameters on line 2.

Line 4 gives the **model domain width and height**, in degrees if latitude and longitude are used, or kilometers if a projected coordinate system is used.

Line 5 gives the **vent location**, also in the same units as the specified coordinate system. This line may take either two or three values. The first two values are required and correspond to the x and y (or longitude and latitude) coordinates of the vent. A third, optional, value gives to the volcano's elevation in

kilometers. If no elevation is given, Ash3d assigns the volcano an elevation equal to that of the topography at this location, or zero if topography is not used in this model run. For the web interface, topography is not used.

Line 6 gives the **horizontal grid spacing** in the model, in kilometers if a projected grid is used, or degrees if latitude/longitude are used. If the width and height of the model domain are not an integral number of cell distances, the location of the upper right corner of the model domain is adjusted to be an integral number of cell distances from the lower left corner.

Line 7 gives the **vertical grid spacing** of cells in the model. The units of this input parameter are always kilometers.

A note about grid spacing and model run time

When setting up a model domain, there is a trade-off between model resolution and simulation time. Model run time is approximately proportional to the number of nodes, the number of grain sizes, and the number of time steps. On a computer with a 2.56 GHz Intel Xeon processor and 8 Gb of storage, with a Geekbench rated floating-point performance score of 4326[7], the runtime per node per time step per grain size ranges from 0.16 to 0.60 µs. Thus a simulation with a model domain of 200x200x20 nodes with 6 grain sizes and 2500 time steps (a few tens of hours simulation time) would take ~0.5-2.0 hours to run using a single processor.

Line 8 gives the **diffusion coefficient** K and a second input that determines the vertical distribution of mass in the column of nodes above the volcano. If the second parameter is a number, it is assumed to be the **Suzuki constant** k for the model run. If the second parameter is the word 'point', all mass is placed in a single cell at the top of the plume. If the second parameter is the word 'line', the mass is distributed evenly throughout the column of nodes above the volcano. This distribution is the same for all eruptive pulses.

---

[7] *http://browser.primatelabs.com/geekbench2/242143*

Line 9 gives the **number of eruptions or eruptive pulses** in the simulation. The eruptions or eruptive pulses may be either contiguous or non-contiguous in time. Their duration should not be shorter than the average time step in the model (about a minute).

Block 2: Eruptive pulses

The number of lines in this block equals the number of eruptions or eruptive pulses specified in line 9 of Block 1. A line of input contains three integers followed by four real numbers, for example:

```
2009 03 23 12.5   0.25  15.0   0.0018
```

The first four numbers represent the **year**, **month**, **day** and **hour** (UTC) of the start of the eruption. The following three numbers represent the **eruption duration** in hours, the **plume height** in kilometers, and the **erupted volume** (DRE) in cubic kilometers. Ash3d converts the erupted volume to a mass assuming a magma density of 2500 kg m^{-3}.

If the year is zero as in the example input file, the model is run in forecast mode where the hour is interpreted as the number of hours after the start time of the wind file. In addition, if the duration, plume height, or erupted volume is negative, it is replaced with the default ESP value for that volcano from the spreadsheet of Mastin et al. [2009a].

Block 3: Wind files and simulation time

Line 1 of block 3 gives two integers, iwind and iwindFormat. iwind may have values 1 through 4 as described in Table 3. :

Table 3. List of possible values of iwind and their meanings

Value	Meaning
1	Read from 1-D wind sounding
2	Read from 3-D gridded ASCII files
3	Read directly from a single NetCDF file
4	Read directly from multiple NetCDF files

If iwind=1, Ash3d reads from an ASCII file of a 1-D wind sounding having the format shown in Table 4. This option can be used if no numerical weather prediction data are available or if data from a single radiosonde measurement is deemed more reliable than NWP model results. If this option is used, then `latlonflag` (Block 2, line 1, first parameter) should be 1, indicating that no cartographic projection is used.

Table 4. Example 1-D wind sounding file in the format used by Ash3d when `iwindformat=1`. This example gives the wind sounding at Redoubt volcano during event 6 of the 2009 eruption [*Wallace et al.*, in review]. Items in blue are comments. Lines 4 and later give the elevation (m), the wind speed in m s^{-1}, and the wind direction in degrees clockwise from true north, respectively.

```
Input wind file for Ash3d
0  29                #Wind time (hrs), number of levels of wind
-1454.327 -3482.752  #x, y Coordinates of wind profile (m)
-1    4.63  24       #elevation (m), wind speed (m/s), direction (clockwise from N)
198   4.52  24
405   4.67  25
617   4.62  24
833   6.58  33
1054  8.7   38
1281  10.4  41
1512  12.81 48
1748  12.69 53
1991  11.41 55
2241  11.01 57
2498  10.6  61
2763  9.85  70
3035  10.04 82
3315  11.79 94
3605  12.75 104
3905  12.59 112
4216  12.83 121
4541  14.51 131
4878  15.3  135
5228  14.93 134
5969  12.05 128
6778  10.99 134
7666  11.11 152
8656  10.66 152
9824  3.95  195
11294 6.77  273
13190 7.3   292
15833 9.2   290
```

When `iwind`=2, Ash3d reads a 3-D wind field in ASCII format that is converted from NetCDF format using a Java script that was originally written before Ash3d was modified to read NetCDF files directly. This option is no longer used.

`iwind`= 3 or 4 indicates that the wind files are in NetCDF format; iwind=3 for a single NetCDF file, and iwind=4 for multiple NetCDF files. The two options were created to accommodate different posting conventions for different kinds of wind files. For example, Global Forecast System output files posted at Unidata (*http://unidata.ucar.edu*) for current and forecast conditions include a separate file for every three-hour time step. Alaska 11km North American Model forecasts posted at Unidata are given as a single file for multiple time steps.

The second parameter, `iwindFormat`, indicates the type of NWP file to be read. The values of `iwindFormat` for each NWP file type are listed in Table 2.

Line 2 gives the integer `iHeightHandler`, which indicates how Ash3d should respond if it finds that the plume height exceeds the highest level in the NWP model. Numerical weather prediction models give 3-D wind fields with the vertical coordinate in pressure levels. For the GFS 0.5 degree model, the highest pressure level is ~1 kPa, which corresponds to about 34 km elevation. The wind field at higher elevation is unknown from these models. If the input plume height is higher than the highest elevation in the NWP model, Ash3d responds in one of the following ways: if `iHeightHandler`=1, Ash3d execution stops and writes out the following message:

```
Checking the vertical height of the mesoscale model ...
    Error: The mesoscale model grid extends to about 34. km elevation,
    but the maximum plume height extends to        50. km.
    The grid is designed to extend 30% above the maximum plume height,
    Program stopped.

    If you wish to run the simulation anyway, using
    extrapolated wind velocities at higher elevation, change the value
    of iHeightHandler to 2 in the ESP input file and rerun the model.
```

If `iHeightHandler=2`, Ash3d continues execution and uses the wind vectors in the top-most pressure level in all higher pressure levels. It also writes the following message to stdandard output and to the log file, Ash3d.lst:

```
Checking the vertical height of the mesoscale model ...
Warning: The highest node in the simulation domain is ~  45.0 km.
The higest in the mesoscale file is lower, about ~  34.2 km.
Because you have specified that
iHeightHandler=2, all wind velocities of nodes higher than the highest
mesoscale nodes will have wind velocities equal to that of the highest
nearby mesoscale node.
```

Line 3 gives the simulation time in hours. The simulation time is assumed to start at the time of the first eruption or eruptive pulse. Ash3d checks the time duration of the wind files to ensure that the entire simulation time is contained within the time of the wind files.

Line 4 is a "yes" or "no" parameter that specifies whether to stop computation when 99% of the the erupted mass has deposited. Setting this parameter to "yes" allows for faster execution if users are primarily interested in simulating deposition. If simulating ash-cloud transport is of primary interest, users may prefer to set this parameter to "no".

Line 5 specifies `nwindfiles`, the number of wind files to be read. If more than one wind file is to be read, the parameter `iwind` in Block 3, line 1, must equal 4. Ash3d assumes in that case that each wind file contains a single time slice. It examines the time stamp on the last wind file to ensure that its time is after the end time of the model simulation, and the time stamp on the first wind file to ensure that it is before the beginning of the first eruption or eruptive pulse.

Block 4: Output options

Most lines in this block specify types of output options.

Lines 1-15 require "yes" or "no" to indicate whether a particular type of output should be written. These types of output are listed in Table 5. along with the names of files written out.

Table 5.   List of the types of output speficied in the first 15 lines of Block 4

Line	Output type	File name(s)
1	ESRI® ASCII file of final deposit thickness, in millimeters	DepositFile___final.dat
2	kml file of final deposit thickness	Deposit.kml
3	ESRI® ASCII files of deposit thickness (mm) at specified times	DepositFile_xxx.xhrs.dat[1]
4	kml file of deposit thickness at specified times	Deposit.kml
5	ESRI® ASCII files of ash-cloud concentration at specified times. This gives the maximum concentration (in mg m^{-3}) of any cell in the column of cells at any given x, y location.	CloudConcentration_xxx.xhrs.dat
6	kml file of ash-cloud concentration at specified times. This gives the maximum concentration (in mg m^{-3}) of any cell in the column of cells at any given x, y location.	CloudConcentration.kml
7	ESRI® ASCII files of ash-cloud height (km)	CloudHeight_xxx.xhrs.dat
8	kml file of ash-cloud height	CloudHeight.kml
9	ESRI® ASCII files of ash-cloud load (tonnes per square kilometer)	CloudLoad_xxx.xhrs.dat
10	kml file of ash-cloud load	CloudLoad.kml
11	ESRI® ASCII file of deposit arrival times (hours since eruption start)	DepositArrivalTime.dat
12	kml file of deposit arrival time	DepositArrivalTime.kml
13	ESRI ASCII files of cloud arrival times (hours since eruption start)	CloudArrivalTime.dat
14	kml file of cloud arrival times	CloudArrivalTime.kml
15	3-D ash concentration at specified times	specified as input

[1]xxx.x is a number that gives the time in hours since the start of the simulation.

The **ESRI® ASCII files** noted in Table 5. are ASCII files written in a format that can be directly imported

into Arc® GIS products for display. They contain a six-line header followed by a 2-D matrix containing

values of, for example deposit thickness, or other properties specified in Table 3. The header looks like:

```
NCOLS    140
NROWS    140
XLLCORNER  -2616390.
YLLCORNER   1742330.
CELLSIZE   5000.000
NODATA_VALUE -9999.
```

The parameters XLLCORNER and YLLCORNER give the coordinates of the lower-left corner of the model domain

in meters (if it is a projected grid) or degrees (if the grid is latitude/longitude). The cell size is in the same

units as the corner coordinates. **Note:** the cell size printed out in these headers is the spacing in x only.

Ash3d can generate grids whose x and y spacing are unequal, and this is typically the case for simulations

generated using the web interface. But Arc products require the x and y spacing to be equal. **Note:** If you

plan to import the ESRI® ASCII files into Arc products, make sure to specify equal x and y cellsize on line 6

of block 1.

The **kml files** are written using Keyhole Markup Language and can be opened by Google Earth® or other virtual globe software. The kml files can be zipped using the following Linux command, which reduces file size by about 90-95% and creates a kmz file that can also be opened in Google Earth:

```
zip -r CloudLoad.kmz CloudLoad.kml
```

The **3-D ash concentration file** specified in line 15 of Table 4 contains the full 3-D distribution of each grain size in the model domain at specified times.

The following lines complete this block of input:

Line 16 specifies the **format of the the 3-D ash concentration file.** Options are 'ascii", 'binary', or 'netcdf'. NetCDF is a standard format for atmospheric model data and is most frequently used by us.

Line 17 gives nWriteTimes, the number of times data are to be written out to the files above. Data may be written out at uneven intervals (e.g. 0.2, 3, 3.4, and 12 hours after the eruption start) or at even intervals (e.g. every two hours, starting 2 hours after the eruption start).

Line 18 gives the times at which output is written:

If nWriteTimes>0, line 18 should contain nWriteTimes numbers, in increasing order, which specify the times in hours after the start of the eruption at which the above data are to be written.

If nWriteTimes=-1, line 18 should contain a single number indicating the time interval in hours between write times.

Block 5: Input wind files

This block should contain a number of lines equal to nWindFiles (Block 3, line 5). Unless iwindFormat (Block 3, line 1) is 1 or 2, these files should be in NetCDF format and should consist of output from one of the model types listed in Table 1. Each line gives the file name and path. In the example file, Ash3d reads a single wind file named latest.nc, located in the subdirectory Wind_nc. Ash3d opens this file and does a preliminary read to ensure that it covers the time period and geographic region specified in input.

Downloading and converting wind files for use by Ash3d

The NetCDF files used by Ash3d are available at several repositories which are listed in footnotes to Table 2. Here we give an example illustrating how we download and convert two of these files, the NOAA National Center for Environmental Prediction (NCEP) North American Model for Alaska, run on an 11km nodal resolution; and the NASA MERRA global 1.25° reanalysis. The first of these examples is the NWP model specified as input in the example input file.

1) We use a shell script with the following `wget` command,

```
wget \
http://motherlode.ucar.edu:8080/thredds/fileServer/fmrc/NCEP/NAM/Alaska_11km/files/NAM_Alaska_11km_20110909_0000.grib2,
```

which retrieves the output file for 9 September 2011, 00Z from the motherload repository at the University Corporation of Atmospheric Research (UCAR). (This repository only holds current model output, so this particular date may be unavailable at the time you read this).

The data are compressed in grib2 format (http://en.wikipedia.org/wiki/GRIB). We convert them to NetCDF format using the NetCDF-java package distributed through Unidata (http://www.unidata.ucar.edu/software/netcdf-java/). This package is distributed as a single .jar (Java archive) file, `netcdfAll-4.1.jar`, which we place in the directory `~/ncj`. We then run the following command:

```
java -Xmx2048m -classpath ~/ncj/netcdfAll-4.1.jar ucar.nc2.dataset.NetcdfDataset \
                -in NAM_Alaska_11km_20110909_0000.grib2 -out latest.nc –IsLargeFile
```

This command takes the grib2 file `NAM_Alaska_11km_20110909_0000.grib2` and converts it into the NetCDF file, `latest.nc`, which is used as input to the Ash3d model. In order for Ash3d to properly read this file, we must set `iwindformat` to 10 (block 3, line 1). Model nodes in these files are set up on a grid of 11 km latitude and longitude on a polar stereographic projection. Therefore we must also set `latlonflag` to 0 and `projflag` to 2 (Block 1, line 2), and use the projection parameters given in the example input file.

Note: if reading from NCEP/NCAR global reanalysis files (iwindFormat=25), then `nWindFiles` should equal 1 and Block 5 should contain a single line giving the path to the directory that contains the NCEP/NCAR global reanalysis files. Subdirectories within this directory should be named by year (e.g. "2012").

Block 6: Arrival times at airports

The input lines in this block specify whether arrival times and other information at specific locations are to be written to output. Normally, Ash3d reads from a text input file containing the latitude and longitude (or x and y locations) of a list of points. For the web interface, this is a global list of airports, but when hand-editing the ASCII input file, other lists, such as sample locations, may also be specified. Ash3d can then generate either text or kml files listing the subset of these locations where ash was deposited or where the cloud passed overhead. Ash3d can also write out the grain-size distribution of points at those locations. All but line 4 require "yes" or "no" parameters.

Line 1 indicates whether to write out ash arrival times at these locations to an ASCII file. If "yes" is given, an output file is generated called `AshArrivalTimes.txt` in the format shown in Figure 2e.

Line 2 indicates whether the ASCII output file should give a grain-size distribution of the tephra deposit at each location.

Line 3 indicates whether to write out a kml file showing the locations that will be impacted by ash. If "yes" is given, a file named `AshArrivalTimes.kml` is generated that plots each impacted location as a red placemarks as shown in Fig. 2d.

Line 4 gives the name and path of the file containing airports or other locations of interest.

Line 5 indicates whether Ash3d should use the projection utility to calculate projected coordinate locations. This parameter should be set to "yes" if a projected coordinate system is used. If set to "yes", projections are performed using the projection parameters given in Block 1, line 2.

Block 7: Grain size groups

Ash3d can run an unlimited number of grain sizes, although the required run time increases roughly in proportion to the number of grain sizes. To reduce model run time, Ash3d stops calculations for individual grain sizes once they have deposited. When simulating ash clouds, one very small grain size (0.01 mm for example) with a very low settling velocity is frequently adequate to display general cloud movement. When simulating deposits, it is best to use at least a half dozen grain sizes: fewer grain sizes tend to produce secondary thickness maxima as an artifact [*Mastin et al.*, in press].

Line 1 of Block 7 consists first of an integer giving the number of size bins (nsize). Optionally, a second integer can be provided which specifies the fall model to be used (FV_ID). If FV_ID is not given or FV_ID=1, the Wilson and Huang [1979] model is used. If FV_ID=2, the Wilson and Huang model with a slip-flow correction is used [*Seinfeld and Pandis*, 2006]. If FV_ID=3, the modification to the Wilson and Huang model outlined by Pfeiffer et al. [2005] is used. If FV_ID=4, the model of Ganser [1993] is used. If FV_ID=5, Stokes flow for spherical particles with a slip-flow correction is used.

Subsequent lines. The first line is followed by nsize lines, one for each bin size. These lines may contains two, three, or four numerical parameters:

- If two parameters, Ash3d reads the first as the mass fraction of that size bin, and the second as the settling velocity in m s^{-1}. Ash3d uses this as a constant settling velocity, independent of elevation.

- If three parameters, Ash3d reads the first as grain size in millimeters, the second as the mass fraction, and the third as the density in kg m^{-3}. Ash3d calculates settling velocity of these particles assuming a shape factor (*f*) of 0.44, which is the average of values measured by Wilson and Huang [1979]. The settling velocity in this case depends on air density and viscosity. Air density is calculated from the pressure and temperature at a

given elevation (obtained from the NWP model data). The viscosity is calculated from Sutherland's Law [*Jacobson*, 2005, p. 201].

- If four parameters, Ash3d reads the first three as before, and the last as the shape factor f, defined as $f=(b+c)/2a$, where a, b, and c are the semimajor, intermediate, and semiminor axes of an ellipsoid.

Block 8: Locations of vertical profiles

In some cases it has been useful to plot vertical profiles through the ash cloud, as for example, when ground-based LiDAR data were available over Europe during the 2010 eruption of Eyjafjallajökull. In that case, the lines in Block 8 appeared as follows:

```
4                               #number of locations for vertical profiles (nlocs)
12.4   51.4                     #Leipzig
11.3   48.2                     #Munich (Maisach)
11.0   47.4                     #Schneefernerhaus (Zugspitze)
11.0   47.8                     #Hohenpeissenberg
```

The first line contains an integer indicating the number of locations (nlocs) where vertical profiles are to be recorded. If nlocs=0 (as in the example input file), no lines follow in this block. Otherwise, nlocs lines follow, giving the locations for each profile in the coordinate system appropriate for this model run (in this case, degrees longitude and latitude, respectively). The blue comment lines give the names of these locations.

Upon execution, Ash3d writes out text files with the names vprofile01.txt, vprofile02.txt, vprofile03.txt, vprofile04.txt, containing vertical profiles at each of these locations. Below is a truncated illustration of the output contained in vprofile01.txt:

```
Vertical profile data for location
x:     12.400
y:     51.400
                        Output is ash concentration in mg/m3
                        elevation (km) ---->
date-time         hrs             0.250              0.750              1.250
2010041601.12,   40.120,      0.000E+00,       -0.106E-65,        0.931E-62, . . .
2010041601.34,   40.345,      0.000E+00,       -0.927E-62,        0.288E-58, . . .
2010041601.57,   40.570,      0.000E+00,       -0.655E-58,        0.336E-54, . . .
2010041601.80,   40.796,      0.000E+00,       -0.201E-53,        0.234E-49, . . .
```

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```
2010041602.02,    41.024,    0.000E+00,    -0.323E-49,    0.678E-46, . . .
2010041602.25,    41.251,    0.000E+00,    -0.419E-47,    0.509E-44, . . .
2010041602.48,    41.479,    0.000E+00,    -0.934E-45,    0.246E-41, . . .
  .
  .
  .
```

The header gives the x and y coordinates of this location. The numbers in the first row of the table, "0.250", "0.750", "1.250", etc., are the elevations (km) of each cell center in the model. Each row of data following contains the date and time (UTC, in yyyymmddhh.hh), the number of hours after the beginning of the eruption, and the concentrations (mg m^{-3}) of tephra at each elevation. Ash3d writes out a line of output every 10 time steps as long as the cloud is passing overhead.

Block 9: Comment lines and topography

Line 1 of this block gives the name of the output file containing the 3-D cloud structure, if this output is specified in line 15 of Block 4.

Line 2 gives the title of the simulation. If the 3-D cloud structure is written out to a NetCDF file (as specified in line 16 of Block 4), this title is included in that file.

Line 3 gives an optional comment that may be written out to the same NetCDF file.

Line 4 allows users to specify whether topography is used in this model simulation. Ash3d uses either of two world topography databases, the GEBCO_08 Global Topography[8] and ETOPO01[9]. The GEBCO_08 database gives both topography and bathymetry of the ocean basins, though Ash3d assigns zero elevation to all points whose elevation lies below sea level (locations like Death Valley, where elevation is below sea level are deemed infrequent enough not to present a major problem). The GEBCO_08 database has a 30 arc-second resolution (<900m), while the ETOPO01 database has a 1 arc-minute resolution. Both have a finer resolution than all NWP models.

Line 5 specifies the topography file format and the smoothing length of topography. The first parameter is an integer whose value is 1 if ETOPO01 topography is used, and 2 if GEBCO_08 topography is

---

[8] http://comlmaps.org/how-to/layers-and-resources/physical-environment/gebco-30-second-bathymetry
[9] http://www.ngdc.noaa.gov/mgg/global/global.html

used. The second parameter is a real number indicating the smoothing length (in km) of the topography. The topography is smoothed over a particular region in order to minimize spurious or isolated patches of deposit that develop as a model artifact due to topography. Topography is smoothed using a cubic spline interpolant.

Line 6 gives the name of the topography file used. These files are in NetCDF format.

Running Ash3d

Ash3d and its associated scripts have been written on a Linux operating system. We have installed it to date on several Linux computers running Ubuntu® Fedora®, and CentOS®. Before running Ash3d, make sure that the directory containing the executable program (Ash3d) is in your PATH setting, and type:

```
Ash3d infilename
```

After being launched, Ash3d checks the input data for errors and writes the input parameters to standard output and to the log file Ash3d.lst. Ash3d then begins the simulation, writing a table of output containing the following information.

```
Starting volume (km3 DRE)   =      0.0000
maximum number of time steps =     2475

              Time                 |--------------Volume (km3 DRE)-------------|   Cloud Area
  step       (hrs)  yyyymmddhh:mm   Deposit      Aloft      Outflow      Total        km2
   10*       0.036  2011091613:02   0.00000      0.00029    0.00000      0.00029      2400.0
   20        0.077  2011091613:04   0.00001      0.00058    0.00000      0.00058      3200.0
   30        0.117  2011091613:07   0.00001      0.00086    0.00000      0.00087      3200.0
   40        0.158  2011091613:09   0.00002      0.00114    0.00000      0.00117      4000.0
   50        0.198  2011091613:11   0.00004      0.00142    0.00000      0.00146      4800.0
   60        0.239  2011091613:14   0.00006      0.00169    0.00000      0.00175      5200.0
   70        0.279  2011091613:16   0.00009      0.00171    0.00000      0.00180      5600.0
    .
    .
    .
```

This output continues until either the time equals the specified simulation time, or 99% of the tephra mass has been deposited, depending on the stated input conditions (Block 3, line 3). At the end the simulation time (10 hours in this case), Ash3d writes out statistics that include the execution time, the simulation time, the total volume accounted for in the model, the maximum deposit thickness and statistics on cloud load:

```
    .
    .
    .
   820       8.677  2011091621:40   0.00170      0.00009    0.00000      0.00179     108800.0
   830       9.016  2011091622:00   0.00171      0.00008    0.00000      0.00178     109200.0
```

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```
 840        9.355   2011091622:21    0.00172    0.00006    0.00000    0.00178    108800.0
 850        9.695   2011091622:41    0.00172    0.00006    0.00000    0.00178    109600.0
 860*      10.000   2011091623:00    0.00173    0.00005    0.00000    0.00178    113600.0
*=files written out

 Number of airports impacted by ash =  36

  Execution time              =          61.3900 seconds
  Simulation time             =       36121.7520 seconds
  Execution time/CPU time     =         588.3980
  Ending deposit volume       =           0.0017 km3 DRE
  Ending total volume         =           0.0018 km3 DRE

  Maximum deposit thickness (mm)   =      1.7039
  Area covered by >0.01 mm (km2)   =     42000.0


  Writing out ESRI ASCII deposit file

  Closing kml cloud concentration file

  Closing kml cloud height file

  Closing kml cloud load file

  Closing kml deposit file
  Writing kml deposit arrival time file

  Writing ASCII deposit arrival time file

  Writing to kml cloud arrival time file

  Writing to ASCII cloud arrival time file


 Ash load    cloud area
    T/km2          km2
      0.2   113600.0
      1.0    59600.0
      2.0     8800.0
      4.0        0.0
      6.0        0.0
```

Ash3d can also be run interactively with no command-line arguments given. In this case, the user will be prompted for the name of the input file. After entering the input file name, Ash3d will ask if it should load a concentration file. If 'no', the simulation proceeds as if the input file was given on the command-line. If 'yes', then the name of a netCDF output file from a prior Ash3d run is requested. The user is then prompted for the time step to be used for initializing the concentration. This output netCDF file must be compatible with the parameters in the input file. This feature provides a way for lengthy simulations to be restarted if there was an error in an earlier run (power failure, IO error, etc.)

Getting help at the command line

Online help for running Ash3d can be obtained by typing the following at the command line:

```
Ash3d -h     or    Ash3d -h run
```

```
              : gives information on how to execute  call help_run()

Ash3d -h input
              : gives information on input file format  call help_input(0)

Ash3d -h make
              : gives information on the different make options  call help_make()

Ash3d -h wind
              : gives information on the different wind
              files, where to get them, etc.
 call help_wind()
```

Concluding remarks

Ash3d is in a continual state of development. The current document explains the capabilities of the

model in its current form, version 489 in our svn repository. However we expect significant changes in

future years. This document may be superseded by later versions.

Appendix: Example Ash3d input file

```
#The following is an input file to the model Ash3d,
#Created by L.G. Mastin and R. P. Denlinger, U.S. Geological Survey
#
#GENERAL SOURCE PARAMETERS. DO NOT DELETE ANY LINES
#  LINE 1 of this block gives the volcano name or CAVW number.
#      If the CAVW number is given, Ash3d looks up the default eruption source
#          parameters for this volcano in the ESP table of Mastin (2009, USGS
#          Open-File Report 2009-1133)
#  LINE 2 of this block identifies the projection used and the form of
#          the input coordinates and is of the following format:
#        latlonflag projflag (variable list of projection parameters)
#    projflag should describe the projection used for both the windfile(s) and
#    the input coordinates.  Currently, these need to be the same projection.
#    For a particular projflag, additional values are read defining the projection.
#    latlonflag = 0 if the input coordinates are already projected
#              = 1 if the input coordinates are in lat/lon
#    projflag   = 1 -- polar stereographic projection
#          lambda0 -- longitude of projection point
#          phi0    -- latitude of projection point
#          k0      -- scale factor at projection point
#          radius  -- earth radius for spherical earth
#             = 2 -- Alberts Equal Area
#          lambda0 --
#          phi0    --
#          phi1    --
#          phi2    --
#             = 3 -- UTM
#          zone    -- zone number
#          north   -- flag indication norther (1) or southern (0) hemisphere
#             = 4 -- Lambert conformal conic
#          lambda0 -- longitude of origin
#             phi0 -- latitude of origin
#             phi1 -- latitude of secant1
#             phi2 -- latitude of secant2
#           radius -- earth radius for a spherical earth
#  LINE 5 gives the vent location.  It can take either two or three variables
#      If two variables are given, they are taken to be x and y of the vent
#      If three are given, the third is taken to be vent elevation.  If no
#          vent elevation is given, Ash3d uses the elevation of the topography
#          at this location (or zero, if topography is not used).
#  LINE 8 gives the diffusion coefficient and a parameter determining the
#        vertical distribution of mass.  The vertical distribution may be
#        specified by:
#      A numerical value for the Suzuki constant, assuming that the Suzuki
#          equation is used to specify the vertical distribution of ash in
#          the column of nodes above the volcano.
#      The word 'point'  if all ash is to be concentrated in a single cell at
#          the plume top.
#      The word 'line' if ash is to be distributed evenly in the column of
#           nodes from the ground surface to the plume top.
****************** BLOCK 1 ************************************************
Redoubt                          #Volcano name (character*30) or IAVW number
0 1 -135.0 90.0 0.933 6371.229 #Proj flags and params
-1454.327 -3482.752              #x, y of LL corner of grid (km, or deg. if latlonflag=1)
1000.0   1000.0                  #grid width and height (km, or deg. if latlonflag=1)
-954.327 -2982.752               #vent location        (km, or deg. if latlonflag=1)
20.0      20.0                   #DX, DY of grid cells  (km, or deg.)
1.000                            #DZ of grid cells     (always km)
```

```
000.     4.                      #diffusion coefficient (m2/s), Suzuki constant
1                                #neruptions, number of eruptions or pulses
***************************************************************************
#ERUPTION LINES (number = neruptions)
#In the following line, each line represents one eruptive pulse.
#Parameters are (1) start time (yyyy mm dd h.hh (UT)); (2) duration (hrs);
#             (3) plume height;                 (4) eruped volume (km3)
#If the year is 0, then the model run in forecast mode where mm dd h.hh are
#interpreted as the time after the start of the windfile.
#Furthermore, if the duration, plume height or erupted volume is negative, it
#   is replaced with ESP value for that volcano.
****************** BLOCK 2 *************************************************
0 0 0 1.0   0.25  15.0    0.0018
***************************************************************************
#WIND OPTIONS
#Line 1:  iwind, iwindFormat.  Ash3d will read from either a single 1-D wind
#         sounding, or gridded, time-dependent 3-D wind data, depending on
#         the value of the parameter iwind.
#   For iwind = 1, read from a 1-D wind sounding
#               2, read from 3D gridded ASCII files generated by the Java script
#                  ReadNAM216forAsh3d or analogous.
#               3, read directly from a single NetCDF file.
#               4, read directly from multiple NetCDF files.
#   The parameter iwindFormat specifies the format of the wind files, as follows:
#     iwindFormat =  1: ASCII files (this is redundant with iwind=2
#                    2: NAM_216pw 45km files (provided by Peter Webley)
#                    3: NARR_221 32km (see http://dss.ucar.edu/pub/narr)
#                    4:  unassigned
#                    5: NAM_216 files from idd.unidata.ucar.edu
#                    6: AWIPS_105 90km from idd.unidata.ucar.edu
#                    7: CONUS_212 40km from idd.unidata.ucar.edu
#                    8: NAM_218 12km
#                    9:  unassigned
#                    10: NAM_242 11km http://motherlode.ucar.edu/
#                    20: NCEP GFS 0.5 degree files
#                           (http://www.nco.ncep.noaa.gov/pmb/products/gfs/)
#                    21: ECMWF 0.25deg for Hekla intermodel comparison
#                    22: NCEP GFS 2.5 degree files
#                    23: NCEP DOE Reanalysis 2.5 degree files
#                           (http://dss.ucar.edu/pub/reanalysis2)
#                    24: NASA MERRA
#                    25: NOAA/NCAR Global Reanalysis 1
#                      http://www.esrl.noaa.gov/psd/data/gridded/data.nmc.reanalysis.html
#Line 2:  iHeightHandler. Many plumes extend  higher than the maximum height
#         of numerical weather prediction models. Ash3d handles this as
#         determined by the parameter iHeightHandler, as follows:
#     iHeightHandler = 1, stop the program if the plume height exceeds mesoscale height
#                      2, wind velocity at levels above the highest node
#                         equal that of the highest node.  Temperatures in the
#                         upper nodes don't change between 11 and 20 km; above
#                         20 km they increase by 2 C/km, as in the Standard
#                         atmosphere.  A warning is written to the log file.
****************** BLOCK 3 *************************************************
3  10           #iwind, iwindFormat
2               #iHeightHandler
10              #Simulation time in hours
yes             #stop computation when 99% of erupted mass has deposited?
1               #nWindFiles, number of gridded wind files (used if iwind>1)
***************************************************************************
#OUTPUT OPTIONS:
#Lines 1-15 require "yes" or "no" indicating whether a particular file type is
#         to be written out.  The file types are given in the comments on
#         each line.
```

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```
#Line 16 indicates the type of 3-D ash concentration file to write, and is
#          used only if 'yes' is given in line 15.  The options here are
#            'ascii', 'binary', or 'netcdf'.
#Line 17: nWriteTimes  = the number of times output are to be written out
#          to the kml, ascii, or 3-D ash concentration files.   Data
#          may be written out at uneven intervals (e.g. 0.2, 3, 3.4, and
#          12 hours after the eruption start) or at even intervals
#          (e.g. every two hours, starting 2 hours after the eruption start).
#    if nWriteTimes>0, the following line contains nWriteTimes
#                numbers specifying the times of output, in hours after the
#                eruption start.
#    if =-1, write times are assumed to be at even intervals.  The time
#                interval in hours is given by a single number on the
#                following line.
#Line 18: WriteTimes   = Hours between output (if nWritetimes=-1), or
#            times (hours since start of first eruption) for each output
#            (if nWriteTimes >1)
****************** BLOCK 4 *************************************************
yes      #Write out ESRI ASCII file of final deposit thickness?
yes      #Write out       KML file of final deposit thickness?
yes      #Write out ESRI ASCII deposit files at specified times?
yes      #Write out       KML deposit files at specified times?
yes      #Write out ESRI ASCII files of ash-cloud concentration?
yes      #Write out       KML files of ash-cloud concentration?
yes      #Write out ESRI ASCII files of ash-cloud height?
yes      #Write out       KML files of ash-cloud height?
yes      #Write out     ASCII files of ash-cloud load (T/km2) at specified times?
yes      #Write out      KML files of ash-cloud load (T/km2) at specified times?
yes      #Write ASCII file of deposit arrival times?
yes      #Write KML file of deposit arrival times?
yes      #write ASCII file of cloud arrival times?
yes      #Write KML file of cloud arrival times?
yes      #Write out 3-D ash concentration at specified times?
netcdf   #format of ash concentration files         ('ascii', 'binary', or 'netcdf')
-1       #nWriteTimes
2        #WriteTimes (hours)
**************************************************************************
#WIND INPUT FILES
#The following block of data contains names of wind files.  The number of
#     lines in this block should equal nWindFiles as given in Block 3, line 5.
#     NOTE:  If iWindFormat=25 in Block 3, line 1, then nWindFiles
#     should equal 1, and Block 5 should contain a single line giving
#     the path of the directory containing NCEP/NCAR Reanalysis files.
#     Subdirectories within this directory should be named by year.
****************** BLOCK 5 *************************************************
Wind_nc/latest.nc
**************************************************************************
#AIRPORT LOCATION FILE
#Lines 1-3 require 'yes' or 'no' indicating whether you would like to write out:
#     Line 1:  an ASCII file listing the arrival time of ash at airports or
#              other locations listed in an airports file
#     Line 2:  a listing of Grain-size distributions in the ASCII file of
#              ash arrival times at airports or other locations
#     Line 3:  a kml file indicating the airports or other locations impacted
#              by ash, along with ash arrival times at those places
#     Line 4:  The name of the file containing airports & other locations of
#              interest.
#     Line 5:  whether to convert coordinates given in the airports file from
#              lat/lon to projected coordinates. (This option is no longer used:
#              coordinates in airport files are now assumed always to be in
#              latitude/longitude).
****************** BLOCK 6 *************************************************
yes              #Write out ash arrival times at specified locations to ASCII FILE?
```

```
no                    #Write out grain-size distribution to ASCII airports file?
yes                   #Write out ash arrival times to kml file?
GlobalAirports.txt    #Name of file containing aiport or other locations
yes                   #Have Proj4 calculate projected coordinates?
*****************************************************************************
#GRAIN SIZE GROUPS
#Line 1 contains an integer (nsize) that gives the number of size bins or
#       settling velocity groups.  An optional second parameter (FV_ID)
#       may specify the fall model used.  If no second parameter is given,
#       FV_ID=1 and the fall  model of Wilson and Huang (1979, EPSL v.
#       44, pp. 311-324) is used, with a shape factor f=0.55 which is the
#       average of values measured by them.  Other options for FV_ID are:
#          2  Wilson and Huang fall model with Cunningham Slip factor
#          3  W & H modification of Ganser (1993, Poder Tech., 77:143-152)
#          4  W & H modification of Pfeiffer et al. (2005, JVGR 140:273-294)
#          5  Stokes flow for spheres with Cunningham slip
#Subsequent lines: there should be by nsize lines.  If those lines contain:
#    2  numbers, Ash3d interprets them to be the mass fraction of particles in
#               that bin, and the settling velocity.  It then calculates fall
#               assuming a constant settling velocity regardless of elevation.
#    3 numbers, Ash3d interprets them to be:
#               --size (mm) in that bin
#               --mass fraction in that bin
#               --density of particles (kg/m3) in that bin.
#             Ash3d calculates the settling velocity of each grain size as a
#             function of elevation using the formula of Wilson and Huang
#             (1979, EPSL, 44:311-324), assuming the particles have a shape
#             factor of f=0.44, which is the average of particles measured
#             by Wilson and Huang.  This calculation also includes a slip
#             factor for small particles.
#    4 numbers, Ash3d interprets the first three as before.  The fourth number
#               is assumed to be the shape factor f, defined by Wilson and
#                Huang as (b+c)/2a, where a, b, and c are the semimajor, inter-
#                mediate, and semiminor axes of an ellipsoid.
****************** BLOCK 7 ***************************************************
9                              #Number of settling velocity groups
16.00000    0.0521261 800.0    #Grain size (mm), mass fraction, and density (kg/m3)
8.000000    0.0701093 800.0
4.00000     0.0739961 800.0
2.00000     0.0689340 800.0
1.00000     0.1516470 800.0
0.50000     0.1830613 1000.0
0.25000     0.1554387 1083.0
0.12500     0.2060758 1790.6
0.06250     0.0386144 2000.0
*****************************************************************************
#Options for writing vertical profiles
#The first line below gives the number of locations (nlocs) where vertical
# profiles are to be written.  That is followed by nlocs lines, each of which
#contain the location, in the same coordinate system specified above for the
#volcano.
****************** BLOCK 8 ***************************************************
0                              #number of locations for vertical profiles (nlocs)
*****************************************************************************
#netCDF output options
#    Line 1: Name of the output file containing 3-D cloud structure
#    Line 2: Title of this simulation as written in NetCDF 3-D output file
#    Line 3: Optional comment for NetCDF 3-D output file
#    Line 4: Indicates whether topography is to be used ("yes" or "no")
#    Line 5: the first parameter is the topofile format.  This equals 1 if
#            GTOPO30 topography is used (i.e. if the etopo.nc file is used,
#            or 2 if the GEBCO_08.nc topography file is used.
#            The second parameter gives smoothing length, in kilometers.
```

```
#               Increasing the smoothing length decreases the number of
#               spurious points in the deposit created by abrupt topography.
#               Smoothing lengths of 30-50 km have yielded reasonable results.
#     Line 6: Topofile name.  This may be either "etopo.nc" (if GTOPO30
#               topography is used), or GEBCO_08.nc, if using the GEBCO topography
#               database.
****************** BLOCK 9 **************************************************
3d_tephra_fall.nc               # Name of output file
Redoubt forecast                # Title of simulation
no comment                      # Comment written to NetCDF file
no                              # use topography?
1 20.                           # Topofile format, smoothing length
etopo.nc                        # topofile name
```

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