



Comparing Simulations of Umbrella-Cloud Growth and Ash Transport with Observations from Pinatubo, Kelud, and Calbuco Volcanoes

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Supplementary



Figure S1. Effect of wind model used on the direction of cloud movement in the Pinatubo eruption. Winds were not modified in these runs. Other model inputs are as given in Table 1. Figure S1c is the same as Figure 2a. Blue lines in each figure are the cloud outlines for the times explained in the caption to Fig. 2a.





Figure S2. Effect of meteorological model on simulation results for the Kelud eruption. (a) simulation using the ERA Interim model and other inputs as in Table 2. (b) Results using the ERA5 model and other inputs the same. (c) Outlines of the larger observed cloud, at 1619, 1659, 1709, 1739, 1809, 1839, 1909, and 1939 UTC on 14 February, 2014. Black lines give the downwind axis of the cloud, visually drawn from the figures, along with the orientation, in degrees clockwise from true north.



Figure S3. Effect of meteorological model on simulation results for the Calbuco phase 2 eruption. (a) simulation using the ERA Interim model and other inputs as in Table 3. (b) Results using the ERA5 model and other inputs the same. (c) Outlines of the observed cloud (using the "larger" boundaries), at 0408, 0438, 0508, 0538, 0638, 0708, 0738, 0808, 0838, 0938, 1008, and 1038UTC on 23 April, 2015.



Figure S4. Effect of modifications to the wind field on the Pinatubo cloud growth pattern. In (a-e), the wind direction was rotated counterclockwise by *r* degrees and wind speed was multiplied by the factor *s*. Other model inputs were as given in Table 1. (f) is a duplicate of Fig. 2a showing the growth pattern of the observed cloud. The ERA5 meteorological model was used in these simulations.



Figure S5. Effect of Pinatubo umbrella cloud-top height on the direction of ash dispersal. The wind field was not modified for these simulations. Cloud outlines are at 1-hour intervals, as in Fig. 2a. Figure S5d is a duplicate of Fig. 2a, provided here for reference.



Figure S6. Channel-7 brightness temperature of the Kelud cloud from MTSAT-1R images. Red and magenta hand-drawn polygons were used to calculate the area and radius of the cloud in Fig. 4. Green lines in the images are the Java coastline. The yellow stars are at the approximate vent location.



Figure S7. Channel-7 brightness temperature of the Calbuco phase 2 cloud from GOES-13 images. Blue and red hand-drawn polygons were used to calculate the area and radius of the cloud in Fig. 5. Green lines in the images are the Chile coastline. The yellow stars are at the approximate vent location.



Figure S8. Calbuco cloud area versus time at for four different horizontal model resolutions: 0.2° (**a**), 0.1° (**b**), 0.05° (**c**), and 0.03° (**d**). Red lines give modeled cloud area considering umbrella growth; blue lines give modeled cloud area not considering umbrella growth; black dash line gives theoretical cloud area assuming growth of an umbrella cloud having the MER and atmospheric properties (N, C, ke) given in Table 3. Green and red crosses are the areas of clouds delineated in Fig.S7.



Figure S9. Outline of the Calbuco phase 2 modeled cloud (blue to gray lines) and the observed cloud (red) (outer outline in Fig. S6l) at 1038 UTC on 23 April 2015. Different lines represent (from blue to gray) model results using a horizonal nodal spacing (dx) of 0.2, 0.1, 0.05, and 0.03° latitude and longitude. Example cell sizes are shown in the lower right.



Figure S10. effects of a fine tail in the grain-size distribution on the modeled deposit at Calbuco. (ac) three size distributions for aggregates of fine ash used in simulations. The size distributions follow a skewed Gaussian curve, each with a mode at ϕ =2.4, but different degrees of skewness. (a) gives a skewness of 0, identical to the size distribution in Table 4. (b) gives a skewness of 0.78, and (c) gives a skewness of 0.93. (d-f) are deposit maps simulated using these three size distributions for aggregates. All simulations assume no umbrella, and have other inputs as given in Tables 3 and 4.



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