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ARAC SIMULATIONS OF THE ASH PLUME FROM THE DECEMBER 1997 ERUPTION OF SOUFRIERE HILLS VOLCANO, MONTSERRAT

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1. INTRODUCTION

Ash clouds generated by erupting volcanoes represent a serious hazard to military and civil aviation. The dispersion modeling system of the Atmospheric Release Advisory Capability (ARAC) has been used to model the cloud resulting from the eruption of the Soufriere Hills volcano, Montserrat in December 1997. A clone of parts of the ARAC system, now being installed at the Air Force Weather Agency (AFWA), will enable AFWA to provide hazard guidance to military operations in the vicinity of erupting volcanoes. This paper presents ARAC's modeling results and discusses potential application of similar calculations for AFWA support during future events.

2. ERUPTION DESCRIPTION AND PLUME BEHAVIOR

The Soufriere Hills volcano on the island of Montserrat erupted early in the morning (approximately 3 am local time, or 0700 UTC) of 26 December 1997. The eruption was caused by failure of the edifice, and subsequent collapse of the andesite lava dome (Calder et al., 1998). The dome collapse generated pyroclastic flows and surges that were emplaced within about 30 minutes over a 9 km^2 sector south of the volcano, and the adjacent sea. A hot turbulent ash-cloud boundary layer developed above the pyroclastic currents, and rapid convection of this buoyant layer generated a high-level ash plume. Thus the high-level plume was not associated with a vertical explosion of gas-charged magma from a vertical vent; the main vertical magma conduit was not exposed in this eruption.

The eruption plume ascended to 14.3 km, based on the plume-top temperature measured by the GOES-8 satellite. Fine ashfall from this plume veneered all December 26 deposits on Montserrat. Much of this fine ash was deposited as accretionary lapilli, probably caused by incorporation of steam into the ash plume when the hot deposits entered the ocean. Of about 44 million m^3 of dome material involved in the eruption, roughly 6 million m^3 may have been incorporated as fine ash into the plume.

This "co-ignimbrite" mechanism for generation of high-level plumes is less common than vertically-directed explosions, but it has been observed elsewhere. At Redoubt volcano, Alaska, in 1990, the high-level plumes produced by this mechanism proved a hazard to aircraft in the Anchorage air corridor.

A low-level plume was produced by sustained semi-continuous low-flux ash-gas emission from the lava dome. This plume moved slowly westward while the upper-level plume curved southward and southeastward over the central part of the eastern Caribbean Sea.

Satellite imagery from 1800 UTC on 26 Dec shows the upper-level plume was distinctly separated from the island by then, confirming the explosive release had previously ended. However our constraints from ground observations are much better than this; we know that the pyroclastic currents that generated the ash cloud were emplaced within a half-hour, and that the plume rise was probably largely complete by roughly 0800 UTC on 26 December.

Imagery from 0815 UTC on 27 December shows the lower-level plume was still attached to the island, indicating the low-level release continued at least that long.

3. SATELLITE IMAGERY

The ash plume was detected by several satellites, including visible imagery from GOES-8, the Total Ozone Mapping Spectrometer on NASA's Earth Probe, and the Advanced Very High Resolution Radiometer on NOAA-14. A GOES-8 visible image from 1800 UTC on 26 Dec 98 (Figure 1) shows the plume spreading southeast over Saint Vincent. The low-level plume can be seen extending westward from Montserrat.

Plume distribution sketches based on GOES-8 visible imagery have been prepared at various times following the eruption (Calder et al., 1998). These sketches illustrate the evolution of the plume and allow comparison with the ARAC results, as discussed below.

A plume distribution sketch (ibid.) based on imagery from the GOES-8 satellite valid at 0845 UTC on 26 Dec 97 (Figure 2) shows the plume initially moved to the southeast from Montserrat. Based on the wind fields discussed above, this was mainly an upper-level plume which moved rapidly in the strong upper-level northwesterly flow. The low-level plume is not specifically identified in the sketch, but is present. The plume covers Guadaloupe and Dominica, where light ashfall was reported.

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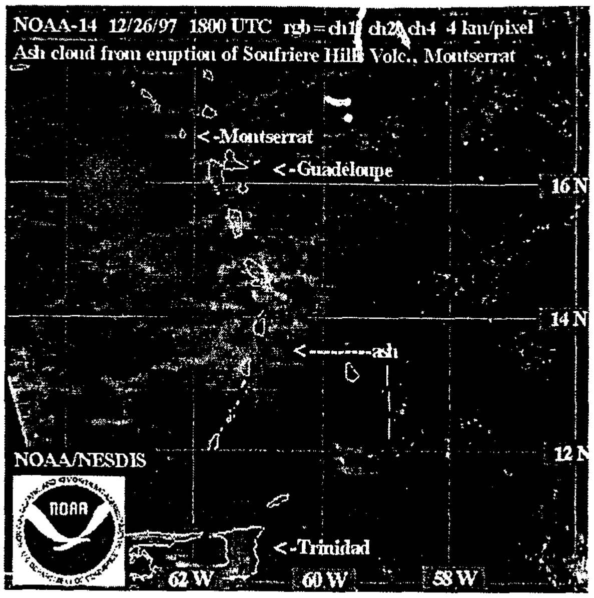

Figure 1. NOAA/NESDIS GOES-8 satellite imagery from 1800 UTC on 26 Dec 97, showing the Montserrat volcano plume.

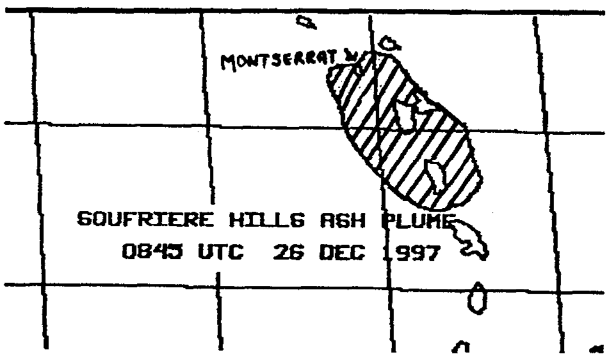

Figure 2. Sketch representing GOES-8 imagery from 0845 UTC on 26 Dec 97.

A sketch (ibid.) based on GOES-8 imagery from 1445 UTC on 26 Dec (Figure 3) shows the upper level plume extended to the southeast, across Saint Vincent--where light ashfall was reported--and then east to approximately 57 deg west. The low-level plume is specifically identified, extending westward from Montserrat to about 65 deg west.

Another sketch (ibid.), based on an image at 1945 UTC on 26 Dec (Figure 4), shows the upper-level plume extending farther east to about 53 deg west, while the low-level plume extended from Montserrat to 67 deg west.

A sketch (ibid.) from 0815 UTC on 27 Dec 97 (Figure 5) shows the low-level plume was still connected to Montserrat (suggesting the low-level ash release was still occurring), while the upper-level plume is illustrated with a dense core over the central Caribbean, then pushing southward over northeastern Venezuela, and extending as a thin cloud eastward over the Atlantic.

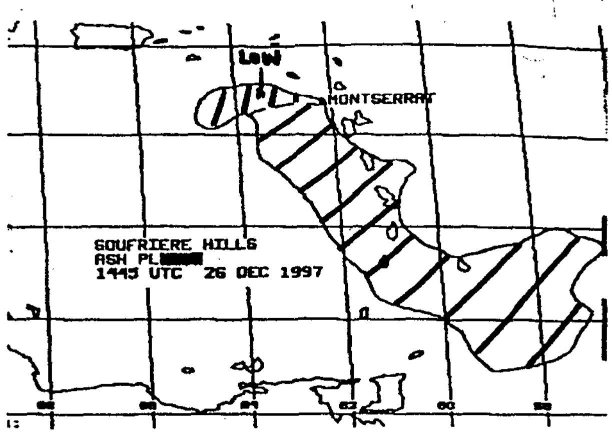

Figure 3. Sketch representing GOES-8 imagery from 1445 UTC on 26 Dec 97.

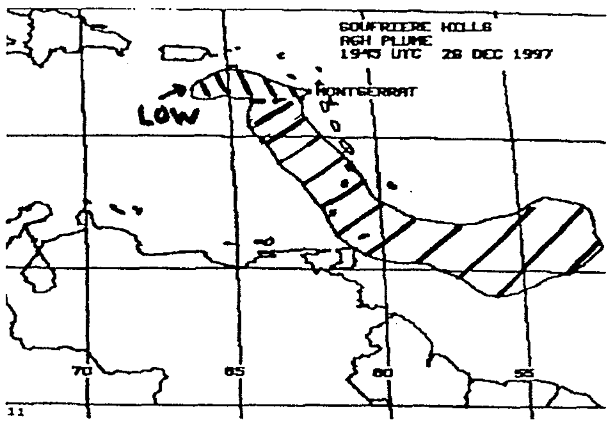

Figure 4. Sketch representing GOES-8 imagery from 1945 UTC on 26 Dec 97.

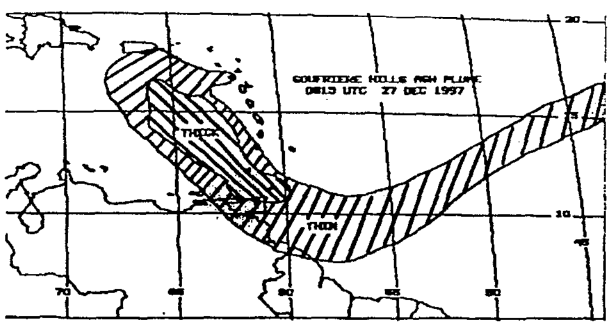

Figure 5. Sketch representing GOES-8 imagery from 0815 UTC on 27 Dec 97.

4. ARAC DESCRIPTION

ARAC operates a suite of models which are used to evaluate the consequences of a wide range of actual or potential releases of hazardous materials in the air (Sullivan et al., 1993). The ARAC system generates a time-varying series of three-dimensional mass adjusted wind fields, which are used to drive the ADPIC Lagrangian particle dispersion model. As input to its wind field calculations, ARAC can use a variety of data sources, including observational data and gridded data output from numerical weather prediction models. This capability enables ARAC to respond to events occurring worldwide in near real time.

ARAC does not currently have an ongoing volcano support mission, but it had previously modeled the 1991 Mt Pinatubo eruption to support the U.S. Air Force (Sullivan and Ellis, 1994), and the Mt Spurr eruption in 1992 (Ellis and Vogt, 1993). For its own internal training, ARAC frequently models significant atmospheric releases, and so would typically consider modeling this eruption in normal events. Its additional motivation for modeling the eruption was to demonstrate its capability for volcano plume modeling to the Air Force Weather Agency, which is implementing parts of the ARAC system for support to military operations.

5. WIND DATA

ARAC used data from the Naval Operational Global Atmospheric Prediction System (NOGAPS) model, generated by the U.S. Navy's Fleet Numerical Meteorological and Oceanographic Center (FNMOC), as the basis of its Montserrat calculations. The data were valid at 1.0 deg latitude/longitude resolution, at the 16 standard pressure levels. FNMOC provides ARAC with NOGAPS analyses and forecasts out to 72 hr, twice each day based at 0000 UTC and 1200 UTC. For this study, ARAC used analysis and 6 hr forecast data from each cycle. No observed wind reports were used in this study.

Wind data from each NOGAPS set were used for 6 hr intervals centered on the valid times of the data sets (e.g., from 0900-1500 UTC for analysis data valid at 1200 UTC), with linear interpolation between subsequent sets. Conditions were assumed to be neutrally stable throughout the study, and a diurnal cycle of mixing layer height was assigned.

The NOGAPS wind flow pattern at 0900 UTC on 26 Dec 97 was quite uniform horizontally, with little variation at most levels over the central and eastern Caribbean Sea. However considerable vertical shear was present (Figure 6). Below about 3500 m MSL, easterly trade winds at 5-12 m/sec were present. From 3500 m to 6000 m MSL, the winds backed with height, becoming northeasterly. At 6000 m MSL, a north-south divergence zone over the Antilles separated northwesterly flow over the central Caribbean from northerly or northwesterly flow over the eastern Caribbean. Above about 7000 m MSL, the flow across the region was northwesterly, and wind speeds increased to about 22 m/sec at 10,000 m MSL.

The meteorological situation during and following the eruption was quite steady. The pattern of low-level easterlies, a transition region from about 3500 m to about 6500 m with backing winds, and upper level northwesterly winds, persisted for at least a day. By 2100 UTC on 27 Dec 97, the depth of the easterly trade winds had increased to 5000 m. The transition region also extended through a deeper layer, to about 9000 m.

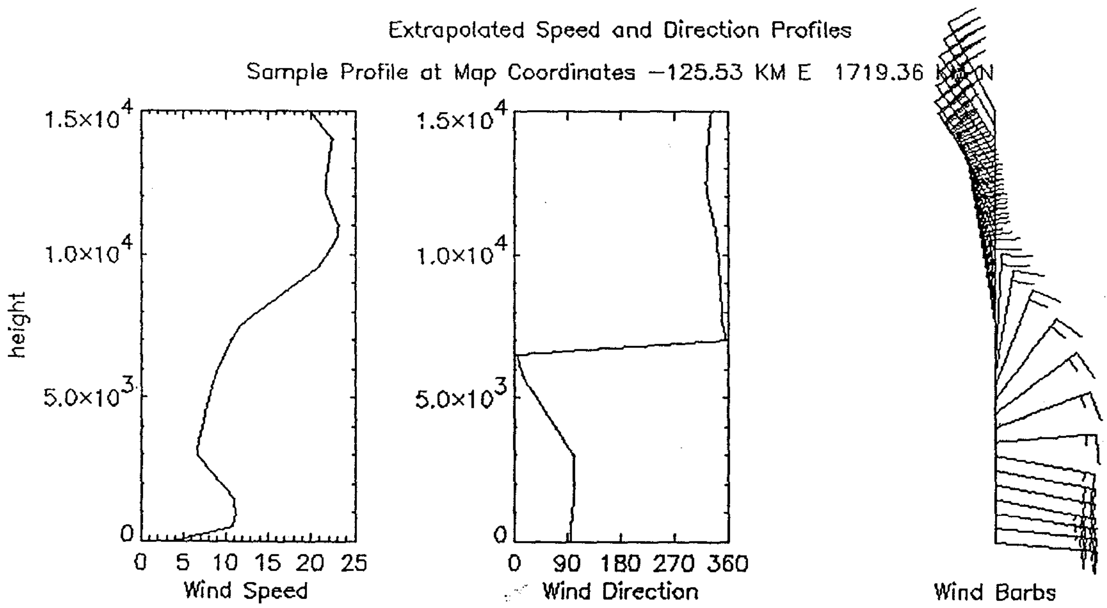

Figure 6. Wind profile from a point west of Montserrat at 0900 UTC on 26 Dec 97.

6. ARAC DISPERSION MODEL INPUTS

Because the lower part of the plume was released over a much longer time, the plume was divided into a lower source and an upper source in ARAC's calculations. The lower source was a column 4000 m in diameter, extending from the surface to 3000 m AGL, with its center of mass estimated at 1500 m AGL. The upper source was a column 8000 m in diameter, extending from the surface to 14,000 m, with its center of mass at 8000 m AGL.

In view of uncertainties on mass flux in the plume, simple "unit release rates" were specified to indicate when the release rate was relatively greater or smaller. The units of this release were g/sec, but of course the release value must be scaled upward by many orders of magnitude to match the actual release rate.

Both sources (upper and lower) began at 0701 UTC on 26 Dec with the same release rate (10 units). At 0731 UTC both sources continued, but the release rate was reduced to 1 unit. At 0800 UTC the upper source was turned off, while the lower source continued at 1 unit until it was turned off at 1200 UTC on 27 Dec.

7. ARAC MODELING RESULTS

A plot of the ARAC dispersion model output valid at 0900 UTC on 26 Dec 97 (Figure 7), showing an integrated view of all the simulated released material, indicates the upper-level plume was spreading southeast from Montserrat. This is consistent with the

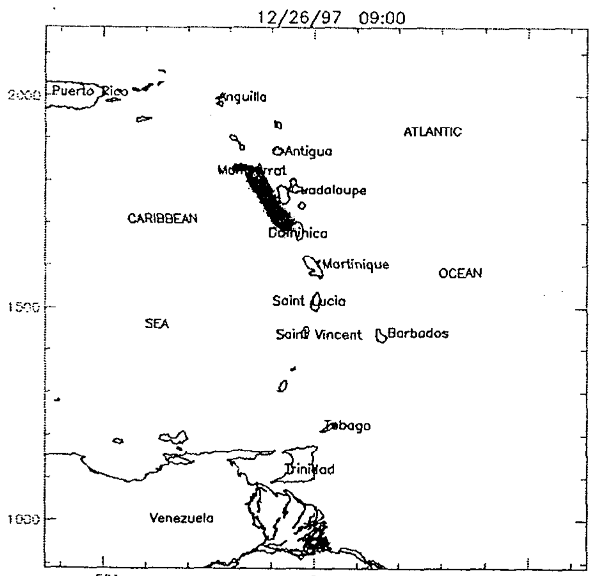

Figure 7. ARAC calculation showing position of ash plume at 0900 UTC on 26 Dec 97.

satellite sketch valid at 0845 UTC (Figure 2), but the ARAC plot is much narrower and its center line is farther west than that of the sketched plume. However, the sketch is rough and does not attempt to indicate variations in plume density. The ARAC plot shows a small but identifiable low-level plume.

An ARAC plot from 1500 UTC (Figure 8) is in excellent agreement with the sketch from 1445 UTC (Figure 3). The low-level plumes are almost identical in orientation and extent, although the tip of the sketch plume bends slightly southwest. The upper-level ARAC plume shares many features with the satellite sketch: they show the plume extended southeastward, primarily over Saint Lucia and Saint Vincent but to some extent also over Martinique; the thin leading edge of the plume extended eastward over Barbados; and the plume remained north of Tobago. The sketch shows a bulge across Dominica and Martinique which might be due to local winds.

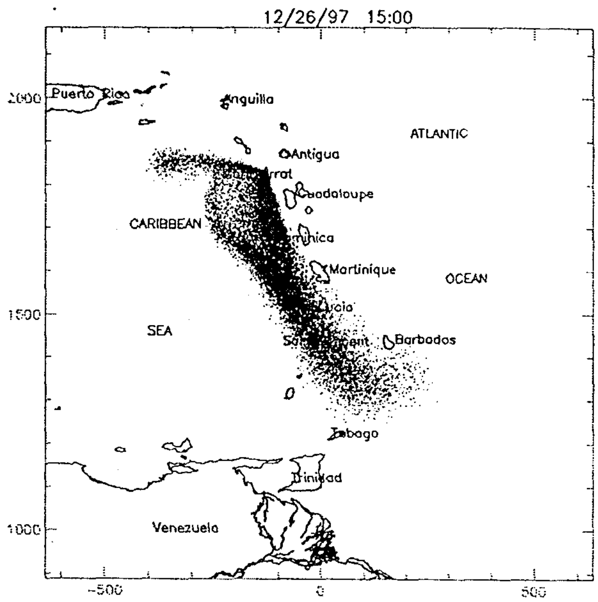

Figure 8. ARAC calculation showing position of ash plume at 1500 UTC on 26 Dec 97.

An ARAC plot valid at 1900 UTC (Figure 9) matches the GOES-8 image from 1800 UTC (Figure 1) and the sketch from 1945 UTC (Figure 4). The model shows a low-level plume extended westward from Montserrat with the leading edge south of the eastern part of Puerto Rico, slightly short of the plume tip on the sketch. In both model and sketch, the upper-level plume had pushed to the southwest, so almost none of the plume was over Saint Lucia, while Saint Vincent and Tobago were covered by the central core of the plume. The leading edge of ARAC's upper plume extended eastward over the Atlantic, but not as far eastward as in the sketch.

Good agreement is also seen between the ARAC plot from 0700 UTC on 27 Dec (Figure 10) and the sketch from 0815 UTC (Figure 5). The ARAC plume extends west-north-westward from Montserrat to the southern coast of Puerto Rico. An extensive clear area (broader in the model than in the sketch) lies to the west of Guadaloupe, Martinique, and Saint Lucia, and the thick part of the plume lies well to the west of the

Antilles. The southern part of the plume curves across Trinidad and northeastern Venezuela, and then drifts eastward over the western Atlantic Ocean. The sketch shows the plume continuing its curve northeastward over the Atlantic, but the ARAC plot does not extend far enough east to compare this feature.

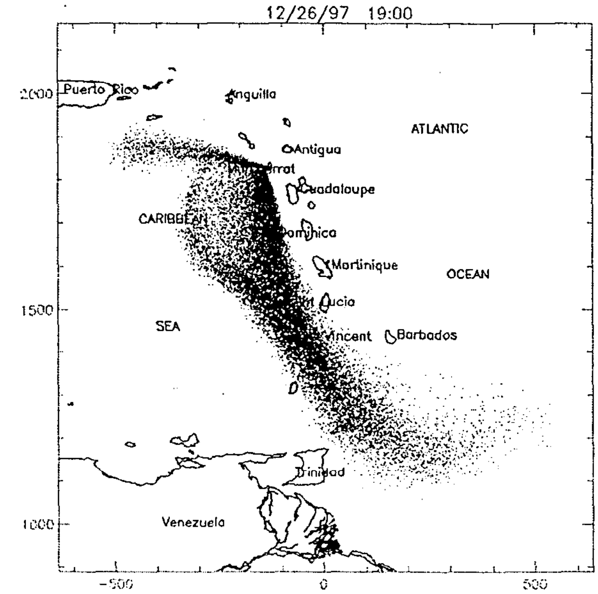

Figure 9. ARAC calculation showing position of ash plume at 1900 UTC on 26 Dec 97.

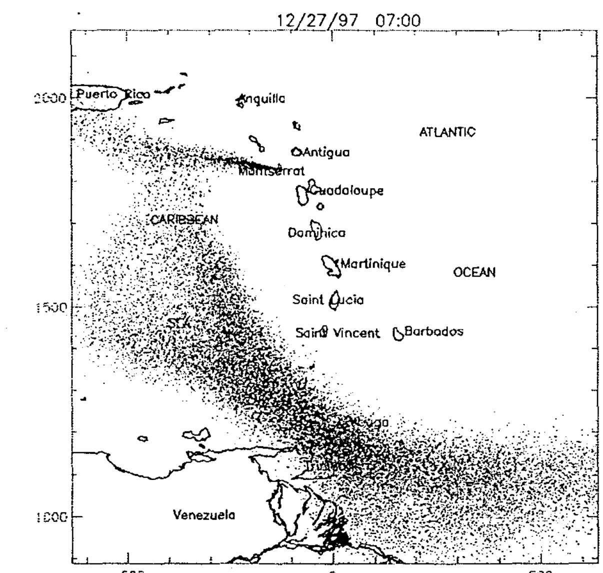

Figure 10. ARAC calculation showing position of ash plume at 0700 UTC on 27 Dec 97.

8. AFWA INTEREST IN ARAC APPLICATION

AFWA is known for high quality meteorological satellite information and fine-scale numerical weather prediction products, but has not maintained a significant presence in the nuclear, chemical, biological and particulate dispersion arena. AFWA's mission is to enhance our nation's combat capability with a variety of weather products, including forecasts of conditions which could impair operations. As a result of recent world events, AFWA has renewed interest in dispersion applications. Also, volcano ash impacts on previous Department of Defense (DoD) operations (e.g., the airlift from Clark Air Base in the Philippines during the 1991 Mt Pinatubo eruption) indicated an AFWA ash dispersion forecast capability would be very useful, as volcano ash plumes like the Soufriere Hills event create a significant flight hazard to both civil and military aviation.

Following the successful AFWA partnership with the National Weather Service Aviation Weather Center, AFWA is leveraging the ARAC capability to provide DoD mission planners and operators with timely and accurate forecasts of ash, smoke and other dangerous plumes related to natural, accidental or deliberate disasters.

9. SUMMARY

This paper demonstrates the capability of the ARAC models to simulate accurately the behavior of a complex multi-section volcanic plume in the presence of strong wind shear. The model may be used to minimize hazards to aircraft in the vicinity of erupting volcanoes.

10. ACKNOWLEDGMENT

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