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Use of GOES thermal infrared imagery for eruption scale measurements, Soufrière Hills, Montserrat

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Abstract. GOES two-band IR data are used to estimate the magnitude of small eruption clouds (< 10^7 metric tonnes of total ash; <~10^5 tonnes of fine [1-25 μm in diameter] ash, and 5-15 km asl). The method is demonstrated on clouds from Soufrière Hills Volcano, Montserrat in 1997-99. The clouds in early 1999 were much smaller, were generally emplaced lower in the atmosphere and contained an order of magnitude less fine ash than 1997 clouds generated during the most intense phase of the eruption to date. Although GOES has an excellent capability for large eruption clouds, its use for smaller eruptions like Montserrat highlights several shortcomings, including atmospheric water vapor and instrument noise. In spite of these shortcomings, GOES time series data can measure differences in intensity of eruptions, and be of particular value in monitoring where ground-based observations are sparse.

Introduction

Current Meteorological Satellites are particularly useful for the observations of active volcanoes because they occupy favorable geostationary (GOES E and GOES W) and polar-orbiting (NOAA 12-15) platforms and because they carry dual-band thermal infrared sensors which can sense volcanic ash using the split window algorithm [*Prata,* 1989; *Rose & Schneider,* 1996; *Davies & Rose,* 1997]. Fine (diameter 1-25 μm) silicate ash particles in volcanic clouds absorb and scatter infrared radiation differently than meteorological cloud particles (ice and liquid water), allowing for the two-band IR discrimination. Here we explore such data for assessing the relative size of small eruptions of Soufrière Hills, Montserrat. We use data collected approximately every 30 minutes from the geostationary GOES E platform and an algorithm for converting thermal infrared brightness temperature (BT) and brightness temperature differences (BTD) of dual thermal infrared channels of the GOES to the mass of fine (1-25 μm diameter) silicate ash in volcanic clouds [*Wen & Rose,* 1994]. This algorithm has been applied to several larger eruptions [*Schneider et al,* 1999; *Constantine et al,* 2000; *Shocker et al,* 2000; *Rose et al,* 2000]. Here we evaluate the sensivity of the algorithm to small ash clouds. The application to small events helps define detection limits for volcanic clouds using the GOES two-band IR.

GOES Parameters

GOES channels used here (4 and 5, centered at 10.7 and 12 μm) have a spatial resolution of about 4 km at nadir. For Montserrat (16.7 N; 62.2 W) the look angle for GOES E (geostationary; 75 W) is near 90. The noise (NEΔT) for bands 4 and 5 in the detector is 0.2-0.4 K [*Kidder & Vonder Haar,* 1995] which leads to errors in the mass retrievals that are estimated from ± 0.5 to 3 tonnes/km^2, depending on environmental conditions (see below). Higher temporal resolution (~30 minutes) of GOES data sets typically include at least several images which allow comparison of retrievals on smaller (fewer pixels, with stronger signal) and larger (more pixels with weaker signals) clouds, which helps remove uncertainty in detection.

Assumptions and accuracy

Environmental and instrumental conditions that influence results are cloud opacity, high water vapor content of lower atmosphere, presence of meteorological clouds, uncertainty about the cloud temperature and shape and misalignment of the field of view of the two channels used. Discussion of all of these is beyond the scope of this paper. Cloud temperature is determined in GOES sequences from the BT of volcanic clouds in images collected right after eruption where the volcanic cloud has high optical depth. We correlate the BT of the dense cloud with radiosonde data to determine cloud height. The trajectory of this cloud in successive GOES images can then be compared with radiosonde upper level wind data to confirm the interpretations.

Validation of the retrieval method devised by *Wen & Rose* [1994] is difficult. Sampling of volcanic clouds is hazardous, and opportunities are rare and difficult to plan [*Riehle et al,* 1994]. This makes it hard to validate the algorithm in the most obvious way. We have compared the split window method with an independent ultraviolet method [*Krotkov et al,* 1999], which gives strong qualitative support for the retrieval, by demonstrating that two independent sensors see clouds with similar positions, shapes and 2D optical depth patterns. We are now trying to use distal ash fallout maps (which are quite rare) to validate results, but this method is unlikely to be totally satisfactory, because fine particles in volcanic clouds more than a few hours old fall out very slowly and may largely be carried beyond the region of identifiable fallout deposits [*Rose,* 1993; *Bonadonna et al,* 1998].

We cannot evaluate (without validation) a limit for the mass of fine ash in a volcanic cloud that can be detected at Montserrat without atmospheric correction. The detector noise (see above), that we compound when we use BTD values and the fact that several contiguous pixels need to be anomalous for a clear detection are important in the minimum scale of cloud which can be detected. We note that the lowest fine ash mass reported (table 2) is 155 tonnes. In the future we plan evaluation of detection limits based on theoretical criteria, when we complete a scheme for atmospheric correction of GOES and AVHRR data.

Relative sizes of some volcanic clouds

The mass of fine ash detected by dual band retrievals is a small fraction (<1-3%) of the total mass of ash erupted, because the dominant coarse ash falls out very quickly (<30 minutes) [*Rose et al,* 1995] and the BTD retrieval can only sense ash in the Mie region (about 1-25 μm in diameter; *Prata,* 1989). Figure 1 shows

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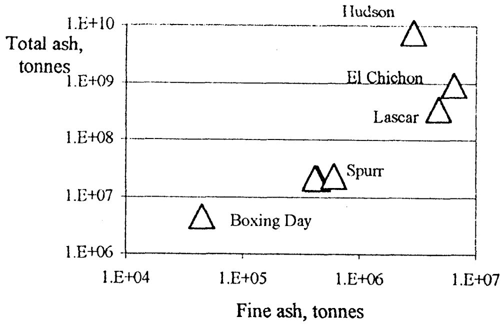

Figure 1. Ash masses in Volcanic clouds. The total mass of ash in fallout deposits from eruptions is plotted against the maximum mass of fine (diameter 1-25 µm) ash measured in volcanic clouds using two band infrared satellite data (Rose et al, 2000).

data on some studied eruptions where the fine ash mass as sensed by the BTD method plotted against the total ash mass as determined by geological field surveys of the fallout. The "Boxing Day" data point plotted in the figure represents the maximum ash mass detected in a volcanic cloud erupted at 0307 UT on December 26, 1997 from Soufrière Hills [*Mayberry,* 1999]. It is one of the very largest Soufrière Hills volcanic clouds during its activity from 1995 until late 1999, when this paper was submitted. Still, as the figure shows, the Boxing Day cloud was small in terms of ash mass, orders of magnitude smaller than other studied examples. The small masses in the Soufrière Hills volcanic clouds mean that the negative BTD discrimination used to distinguish the volcanic cloud must be pushed to its limit, and applied to clouds with small areas and weak negative BTD signals. With the Soufrière Hills data set we were interested in defining the minimum ash mass detectable by the method and also in investigating the nature of false signals in nearby meteorological clouds. In volcanic clouds that have large masses of fine ash and minimum BTD values of -5 to -15, a threshold value of <-1 K in BTD may be used to discriminate the volcanic cloud. There are nearly always some false negative pixels, usually scattered along the edges of meteorological clouds. When the cloud is small and contains little ash mass, higher threshold values (*eg* BTD= -0.4) are used and false signals are more of a problem.

Results

We examined GOES 8 data from the largest volcanic cloud events of 1997, as initially investigated by *Davies and Rose* [1998] and performed retrievals on GOES images of these clouds, using the method of *Wen & Rose* [1994]. Table 1 shows the results of the retrieval from the single image in each sequence which contained the maximum fine ash mass for each event. The 1997 retrievals were compared to ash fallout information in more detail by *Bonadonna et al* [in review] while the 26 December 1997 event was studied in great detail by *Mayberry* [1999]. Table 2 shows similar data for the largest eruptions of early 1999.

The 1997 events show higher fine ash masses, larger cloud areas and mean optical depths (Figure 2). Height estimates of the 1999 clouds are also generally lower (Figure 3). Cloud heights and the mass loading of fine ash from satellite data is shown to be a useful way to measure the relative intensity of activity. In the case of Montserrat, where a large part of the island remains evacuated but activity persists, an objective method for quantifying the scale of eruptions is an indication of whether the eruption is declining in intensity. Because of its 24 hour coverage, synoptic view and its viewpoint far above the low cloud cover that masks the volcano from the ground, GOES is more advantageous for measurements than any ground-based method. At Montserrat, GOES observations confirmed smaller scale of activity in early 1999 from a measurement of intensity that was not possible by other means.

Discussion

Comparison of fine ash masses can be used as a measure of intensity of eruptions, and regularity of satellite data offers a way to continually measure this. In 1999 eruptions, the lower heights and ash content reflect weak activity compared to 1997. The generally declining intensity of the Montserrat activity as expressed by seismicity since 1997 has caused a relaxation of alert status (MVO daily reports, GVN Bulletins) and the ability to measure eruption intensity may be of use in assessing ash hazards to aircraft and health [*Baxter et al,* 1998]. In the case of Montserrat there is extensive ground-based monitoring that aids in assessing the state of the volcano, but in cases of limited ground monitoring at restless volcanoes, GOES can provide valuable monitoring information by assessing the relative scale of eruptions.

The compilation of retrieval data on very small eruptions (Table 2) is new and allows us to use a specific case study to estimate a minimum detection limit for GOES 8 retrievals. In table 2 the smallest reported fine ash mass is 155 tonnes, reported for an eruption cloud with only 3 anomalous pixels. The one sigma error in this mass is estimated at ±100 tonnes. Below this threshold, recognition of a volcanic cloud is entirely based on spatial relationship to the volcano, and where the volcanic ash produces an anomaly which is no more coherent than surrounding scattered

Table 1: Retrieval Results for GOES 8 data from Soufriere Hills Eruptions in 1997

Date 1997	Time of Max Mass, UT	Total No of Pixels	Effective Radius, µm	Mean Opt Depth	Cloud Area km^2	Mean pixel mass, tonnes	Total fine ash mass, tonnes	Cloud Hgt km
June 25	14: 09: 05	314	8.4	1.9	5024	329	103220	11.8
Aug 7	16: 09: 05	319	6.7	0.6	5104	78	24815	9.3
Sept 26	15: 38: 59	104	8.6	2.9	1664	516	53665	11.3
Sept 27	13: 09: 03	211	7.5	0.7	3376	103	21680	10.9
Nov 6	15: 39: 07	125	7.4	1.2	2000	184	22943	10.8
Dec 26	10: 39: 06	479	7.7	0.4	7664	65	30936	15

Table 2: Retrieval Results for GOES 8 data from Soufriere Hills Eruptions in 1999

Date 1999	Time of Max Mass, UT	Total No of Pixels	Effective Radius, µm	Mean Opt Depth	Cloud Area km^2	Mean pixel mass, tonnes	Total fine ash mass, tonnes	Cloud Hgt km
Jan 13	11: 09: 06	30	3.4	0.9	480	71	2120	5.6
Mar 7	17: 09: 05	17	2.6	0.9	272	62	1060	4.4
Mar 26	23: 39: 06	13	2.6	0.9	208	60	780	4.4
Apr 11	07: 09: 09	3	2.3	0.8	48	52	155	4.2
Apr 14	10: 39: 02	21	2.9	0.7	336	50	1040	4.1
Jun 17	11: 39: 06	29	6.8	1.3	464	180	5200	10
Jul 20	12: 38: 22	154	8.3	0.8	2464	130	20400	11.1

false signals. We also report results of study of GOES imagery of several more eruptions of 1999 (Table 3) where clouds were not detected either because of a data gap, general cloudiness or because of weak signal (<~150 Metric Tonnes of fine ash). Users of GOES data for volcanic cloud studies should realize that all of the Montserrat eruptions are more than an order of magnitude smaller than previously studied examples (Figure 1), which means that the magnitude of BTD in all is low, close to the limits of noise. Because of this, false BTD anomalies, typically only single pixels, are likely to occur in the regions not occupied by volcanic clouds. False signals seen with the BTD threshold set at zero can be eliminated by sliding the BTD threshold from zero down to -0.2K or even to -0.5 K, but the size of the volcanic cloud may be curtailed greatly aa well as false signals.

The Montserrat BTD discrimination methodogy is also subject to limitations because of effects of water vapor in the lower troposphere. High humidity can cause positive BTD differences of several degrees for clear sky over ocean surfaces [*Coll and Casselles*, 1997], and *Rose & Prata* [1997] found that volcanic cloud pixels with low optical depth in the moist tropical atmosphere could have BTD shifted by as much as +3K. This results in fewer pixels being identified as volcanic ash, and frequently the split window "sees" only the higher optical depth cores of volcanic clouds [*Mayberry,* 1999]. Atmospheric corrections, based on work by *Coll & Casselles* [1997] are now being devised and evaluated.

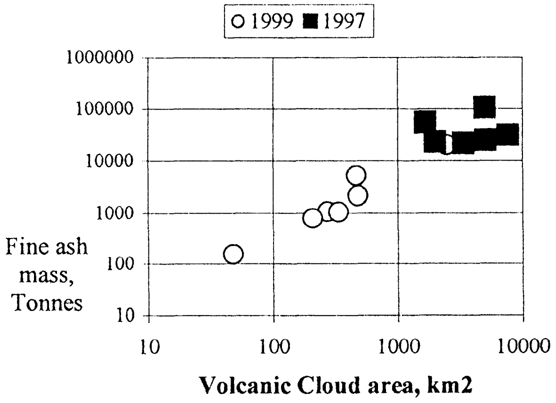

Figure 2. Ash masses in measured in volcanic clouds of Soufrière Hills, Montserrat, for eruptions of 1997 and early 1999. The total fine ash mass measured is plotted against the cloud area. Data is from tables 1 and 2.

The 1999 eruptions resulted mainly from explosions which resembled some 1997 events. Seismic signals of the early 1999 events lasted 16 - 30 minutes, while durations of the 1997 explosions were as long as one hour [*Bonadonna et al*, in review]. Even the smallest events of 1999 lasted longer than ten minutes and their height might generally scale to their eruption rate, following models such as those shown in *Sparks et al* [1997]. Early 1999 volcanic clouds are generally more than an order of magnitude smaller than the 1997 ones and they also are less dense, with lower average ash mass per pixel (Figure 2).

In spite of its utility in both volcanology and ash cloud hazard mitigation, two-band infrared capability will unfortunately be discontinued from 2002 until about 2007 on GOES satellites. Although the new GMS satellite was planned to extend split window capability at least to the western Pacific, this satellite was destroyed at launch in December 1999.

Conclusions

GOES satellite data can be used to estimate the masses of fine (1-25 µm diameter) volcanic ash in volcanic clouds over many orders of magnitude. In 1997 GOES data analysis show that Montserrat volcanic clouds contained 20,000 to 100,000 tonnes of fine ash, while in 1999 the fine ash in Montserrat volcanic clouds ranged from ~150 to 20,000 tonnes. In addition, the heights of the clouds can be obtained by GOES brightness temperature data. Eruption magnitude can be related to both cloud height and fine ash masses and the 24 hour capability of measuring eruption magnitude is useful in activity monitoring. Big eruptions are more important for hazard considerations and we must develop real time

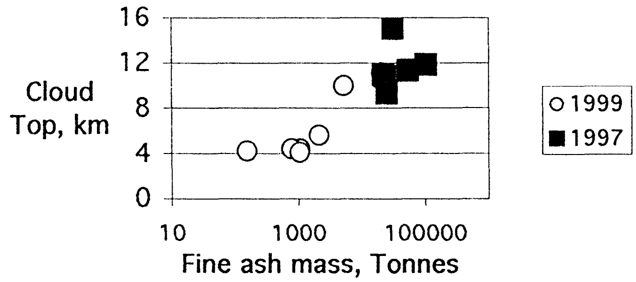

Figure 3. Ash masses in measured in volcanic clouds of Soufriere Hills, Montserrat, for eruptions of 1997 and early 1999. The total fine ash mass measured is plotted against the cloud height. Data is from tables 1 and 2.

Table 3: Other Eruptions Analyzed in 1999

Date, 1999	Comments
Mar 1	No images available due to satellite problems
Mar 30	Ash cloud did not rise high enough
Apr 1	No ash cloud visible
Apr 2	No ash cloud visible
Apr 8	No images available
Apr 25	No ash cloud visible; too many meteorological clouds
May 10	Ash cloud did not rise high enough
May 20	No ash cloud visible
Jul 7	No ash cloud visible; too many meteorological clouds
Jul 21	No ash cloud visible

methods of assessing magnitude. This example shows that GOES can produce data that assesses the scale of eruptions, including very small events, so that continous montoring of GOES data during low level activity could offer important data for monitoring sparsely instumented volcanoes.

Although we can recognize and measure them, small masses of ash in all the Soufrière Hills volcanic clouds (even the 1999 ones are more than an order less than other eruptions) means that the ash signal is weak. Outlining weak clouds using thresholds of BTD near 0 results in numerous isolated and weak (BTD=-0.1-0.3 K) false signals in adjacent meteorological clouds. This problem should be expected for small eruptions. It should be realized that during the past several years, when the use of split window methods has expanded for aircraft hazard mitigation, there have been only small magnitude eruptions, where false signals are more likely to confuse, because strong ash signals are absent. A detailed discussion of this problem has recently been written by *Prata et al* [2000]. Use of satellite methods for mitigation of volcanic cloud hazards to aircraft is important, and we emphasize that the small volcanic clouds which can be confused with false signals contain very small ash masses, orders of magnitude smaller than the Spurr eruptions of 1992 [*Schneider et al,* 1995; *Rose et al,* 2000].

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