EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 79 NUMBER 42

OCTOBER 20, 1998

PAGES 505–516

GOES Imagery Fills Gaps in Montserrat Volcanic Cloud Observations

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GOES satellite imagery offers great potential to lessen the risk of volcanic ash clouds to aviation, and the situation at Montserrat in the Caribbean is providing the proof. Many transatlantic, commercial, and private aircraft use airspace around Montserrat, where the Soufriére Hills Volcano has been erupting since 1995.

Worldwide over the last 15 years, more than 80 airplanes have reported encountering volcanic ash along flight paths. Encounters cannot be avoided because onboard radar cannot detect fine-grained ash particles—those with a radius of 15 microns or less. In recent years volcanic cloud encounters are estimated to have caused hundreds of millions of dollars worth of damage and in a few cases have caused in-flight engine failure [*Casadevall et al.*, 1996].

The Montserrat Volcano Observatory (MVO) is charged with notifying aviation if volcanic clouds there rise above 10,000 feet. In August 1997, the Soufriére Hills Volcano began generating ash columns as high as 35,000 feet as often as four times a day. However, ground observations of such columns are often obscured by meteorological cloud cover. Even when weather clouds are not present, convective ash cloud mushrooming often obscures the top of the column from ground observation. Trajectory models help forecast the position of drifting volcanic clouds, but the height of the ash columns must first be determined.

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Because of the long duration of the eruption, researchers have been able to extensively evaluate GOES potential around Montserrat and find that the satellite imagery can indeed fill the gaps, providing near real-time information on ash cloud height and trajectory projection. Further, the unprecedented quality of the image data, with its high temporal resolution, may aid in interpreting a variety of other volcanic processes and events. For example, researchers have been able to document and measure the changing intensity and character of eruptions through the study of evolving cloud shapes and analysis of data on the mass of fine silicates in the clouds.

The collection of Montserrat GOES-8 data began in late 1996 and there is now more imagery and information available than in all previous volcanic cloud datasets from all other sources combined. However, it is two-band infrared data that is collected and, according to scientists, GOES satellites will lose their two-band capability for the years 2002-2007. An initiative for a new satellite system has begun. Meanwhile, research continues.

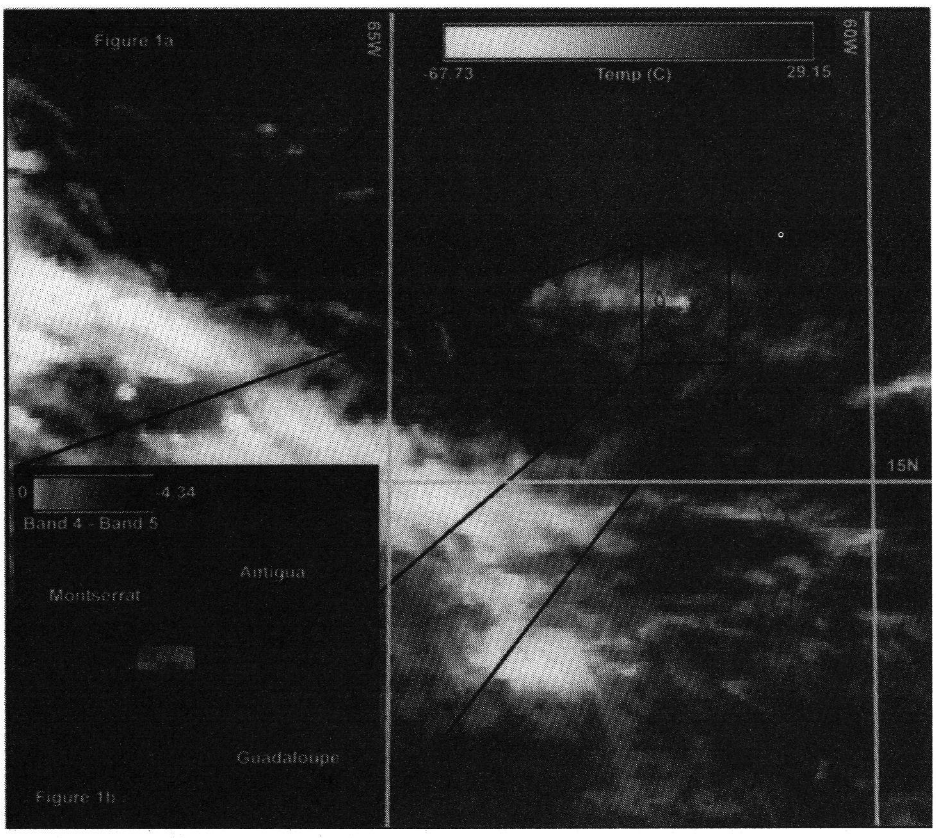

Fig. 1. a) Band 4 brightness temperature image at 1515 UT on September 22, 1997, showing an explosion that began at 1446 UT. b) Corresponding BTD image at 1515 UT highlighting the position of the volcanic ash cloud. Original color image appears at the back of this volume.

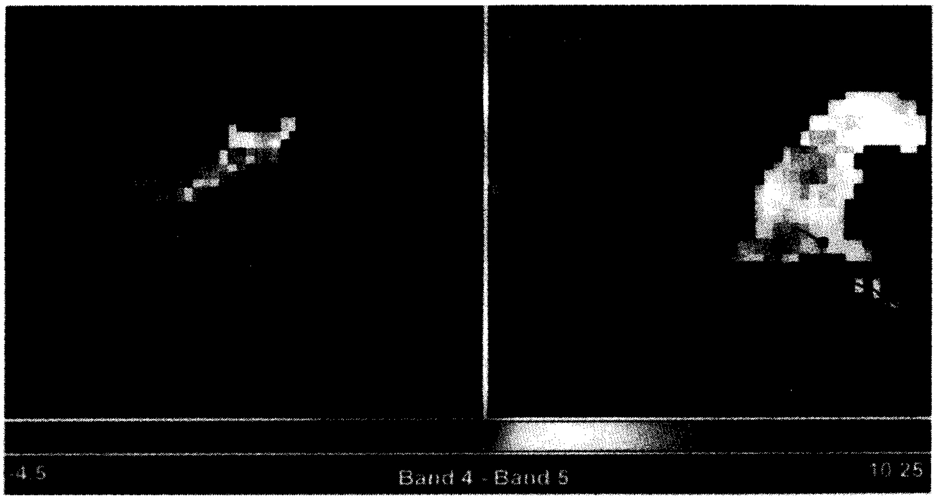

Fig. 2. Two BTD images of an explosion that generated an ash column and associated pyroclastic flow that entered the sea, at 1830 UT on November 6, 1997. a) An image observed at 1915 UT; b) An image observed at 1945 UT. Low pixel values represent the volcanic ash cloud, and high pixel values represent the associated steam cloud generated by hot pyroclastic material entering the sea causing the evaporation of sea water. Original color image appears at the back of this volume.

Montserrat is at the northern end of the Lesser Antilles volcanic arc (Figure 1), a volatile region of the Caribbean already made famous by the 1902 eruption of Mount Pelée on Martinique. The Soufriére Hills Volcano began erupting on July 18, 1995, after a 2-year period of seismic unrest [*Aspinall et al.*, 1998]. Before this eruption there had been no documentation of volcanic activity since western colonization of the island during the early 17th century [*Young et al.*, 1998]. Eruptions have continued at least through August 1998, according to MVO's daily reports on its Web site (http://www.geo.mtu.edu/volcanoes/west.indies/soufriere/govt/), although recent activity has been less intense. The volcano's eruptive behavior has frequently caused ash to enter the troposphere. Banded seismic tremor, which has been regularly observed there, is often associated with vigorous ash venting which can produce persistent ash plumes at low levels. Also, small-scale collapse of lava spines originating from the volcanic dome may easily produce ash clouds that convect up to altitudes of a few thousand feet, while larger-scale multiple collapses of the dome are capable of generating convective ash cloud heights of tens of thousands of feet. Until the later half of 1997, these large events were infrequent. However, between August and October 1997, the eruption underwent a cyclic behavioral pattern in which 91 explosions generated volcanic ash columns to heights of 12,000 to 35,000 feet, often two to four times a day.

GOES Imagery

Satellite remote sensing of volcanic plumes can be used to identify the height to which volcanic clouds convect [*Sawada*, 1987]. Except for once-daily total ozone mapping spectrometer data [*Seftor et al.*, 1997], two-band infrared remote sensing [*Wen and Rose*, 1994; *Rose and Schneider*, 1996] is the only way to directly map the location of volcanic ash clouds. This allows refinement of data from cloud trajectory models by providing frequent updates on mass estimates and the positions of clouds at points downwind. Sensors onboard GOES 8, 9, and 10 collect data simultaneously in five spectral bands at a useful spatial resolution. GOES satellites also offer significant temporal improvement over polar-orbiting meteorological satellites, as data are available as frequently as every 15 minutes, therefore potentially allowing near real-time monitoring of active volcanoes.

The Montserrat Satellite Dataset

Archived at the Laboratory for Atmospheric Remote Sensing, Michigan Technological University, is GOES 8 band 4 (10.3-11.3 microns) and band 5 (11.5-12.5 microns) imagery covering the Montserrat eruption. Researchers looked for 115 volcanic events during 1997 that generated ash clouds between 8000 and 35,000 feet as documented by the MVO Web site. Activity looked for included persistent pyroclastic flows, dome collapse, explosions, and periods of vigorous ash venting. GOES band 4 and band 5 raw sensor counts were converted to radiance values using standard calibration techniques, and radiance values were converted to brightness temperatures by inverting the Plank function. The image data were rectified to an equal area projection (Lambert azimuthal) from the standard GOES image format and resampled to a 4-km spatial resolution. By subtracting band 5 from band 4, brightness temperature difference (BTD) images were used to detect the volcanic cloud and meteorological cloud [*Rose and Schneider*, 1996]. Statistics of the search, as well as an explanation of how to access the entire dataset, are at Web site http://www.geo.mtu.edu/volcanoes/soufriere/west.indies/govt/pubs/agu-goes/. Excluding data loss because of instrument or computer technical difficulties, 74% of events searched for were visible in GOES-8 images, a further 17% could not be detected because of "thick" meteorological cloud coverage, and 8% of events which theoretically should have been visible were not detectable. Over 800 scenes spanning over 400 hours of volcanic cloud activity are now archived and available for future research.

Figure 1 illustrates the use of satellite imagery in determining near real-time ash cloud height and trajectory estimates. Figure 1a is a band 4 brightness temperature image of the Lesser Antilles on September 22, 1997. It clearly shows low- to medium-level meteorological cloud covering Montserrat at 1515 UT. A relatively small dome explosion occurred at 1446 UT, followed by a period of intensive ash venting, according to the MVO Web site. However, because of meteorological cloud coverage, MVO personnel were unable to determine the height to which the ash column convected. The BTD image at 1515 UT (Figure 1b) clearly highlights the position of the volcanic ash. Comparison of the volcanic cloud shape with that of radiosonde atmospheric temperature profiles collected twice daily at the weather observatory on Guadeloupe provides a height estimate of the ash column because wind directions change with height and the cloud shape elongation from the vent can be matched. Also, if infrared sensing is done before the cloud develops transparency, the cloud temperature as measured by the thermal infrared bands can be matched with the radiosonde temperature profile to obtain height information.

For Montserrat, if this technique were implemented as part of the monitoring program, ash cloud height estimates could potentially be made within 15 minutes of an initial ash cloud generating event (an absolute maximum would be 29 minutes as images are normally received every 15-30 minutes and each sector requires less than 15 minutes to scan). Integrating this information into an atmospheric modeling program would allow local aviation authorities to modify pre-existing flight path plans.

An Interpretative Tool

Utilization of GOES imagery is not limited to volcano ash cloud tracking and aviation hazard mitigation. Its high temporal resolution allows investigators to interpret volcanic processes and events. *Rose and Schneider* [1996], using the silicate mass-concentration retrieval algorithm of *Wen and Rose* [1994], demonstrated how the intensity of the March 1996 eruption of Popocatépetl Volcano,

Mexico, varied over a 12-hour period. Adopting a similar strategy to analyze the Montserrat dataset could retrospectively lead to important information on volcanic sequences there. Preliminary analysis shows that it is possible to distinguish between continuous ash venting, single ash cloud generating events (such as an explosion or singular large pyroclastic flow), and multiple ash cloud generating events.

The shear variety of the Montserrat images should lead to other important volcanological satellite observations. One unknown quantity is the high humidity in the Lesser Antilles and its effect on the BTD technique. Eight percent of events searched for remain undetected even though cloud cover conditions for detection were favorable. *Rose et al.* [1995] reported that ice in the 1994 Rabaul eruption cloud, which originated from seawater entering the eruptive vent, suppressed the spectral signature of the volcanic ash cloud. However, the entry of ocean water into a volcanic vent is not required to create suppression of the thermal signal. *Rose et al.* [1997] have shown that high humidity in the tropical atmosphere suppresses extant radiance in the 10-12 micron range and possibly shifts the temperature differences enough to lose detection. Either high water vapor content or the presence of water droplets in the volcanic cloud from a variety of causes could potentially cause such a suppression. Researchers believe such conditions may occur in the Lesser Antilles and sometimes suppress negative values in BTD images.

MVO personnel reported that two of the explosions undetected by GOES were extremely steam-rich. A high initial steam concentration of an explosion cloud would also contribute to the suppression of negative BTD ash values. If the water content in a volcanic ash cloud plays such an important role in its detection, then what about those events that generate pyroclastic flows that enter the sea? BTD images such as shown in Figure 2 may help to clarify this. The image is of an explosion on November 6, 1997, which produced a quickly convecting ash cloud and voluminous pyroclastic flow that entered the sea. The negative pixels of the ash cloud can be clearly identified; however, also present is a distinctly separate cloud of high positive pixel values. Is this the formation of a water vapor cloud resulting from evaporating seawater caused by hot pyroclastic material entering the sea? Could this spectral characteristic be used to identify such an event?

The variety and volume of the Montserrat data should provide answers to questions addressing the effects of atmospheric humidity, steam-rich explosions, and flows entering the sea. What is clearly apparent is that GOES imagery as a volcanic interpretative tool has not yet been used to its full potential. This Montserrat dataset will give the volcanological community a chance to rectify this. Among other things, researchers expect to be able to interpret reactions within volcanic clouds, such as water droplet development and subsequent evaporation. The frequency of imaging allows for considerable advantages because the volcanic clouds evolve spectrally as well as dynamically.

Use of Two-band Infrared Channels

The use of geostationary two band infrared data offers important input to the management of volcanic cloud hazard data. Currently the Washington Volcanic Ash Advisory Center (VAAC) provides some meteorological interpretation, but it would seem important that the MVO get immediate access to geostationary data and do local interpretation that relates better to the activity. This kind of approach is now being followed by the U.S. Geological Survey at the Alaska Volcano Observatory. The upcoming loss of GOES two-band capacity is regrettable, researchers say, considering the impact it could have in places like Montserrat. The initiative that is underway is for a new geostationary Aviation Hazard Satellite system (VOLCAM) with specially optimized volcanic cloud detectors. VOLCAM is planned to contain both a UV spectrometer to map and retrieve SO_2 and ash information in daylight and an infrared three-band detector which can map and retrieve data on both SO_2 and ash day and night. The goal is to have the new sensors in place by the time of the GOES data gap.

Acknowledgments

The GOES 8 data for this study was received at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, and provided via routine data link by NCAR's Research Applications Program where David Johnson was personally helpful. M.D. thanks Mike Dolan and Dave Schneider for coaching and review help, and Peter Francis for comments on the manuscript. Dolan has also coordinated data organization throughout this entire project and set up the Web site for data dissemination. This work was funded by the British Geological Survey (M.D.) and by NASA (W.R.). Published by permission of the Director of the British Geological Survey.

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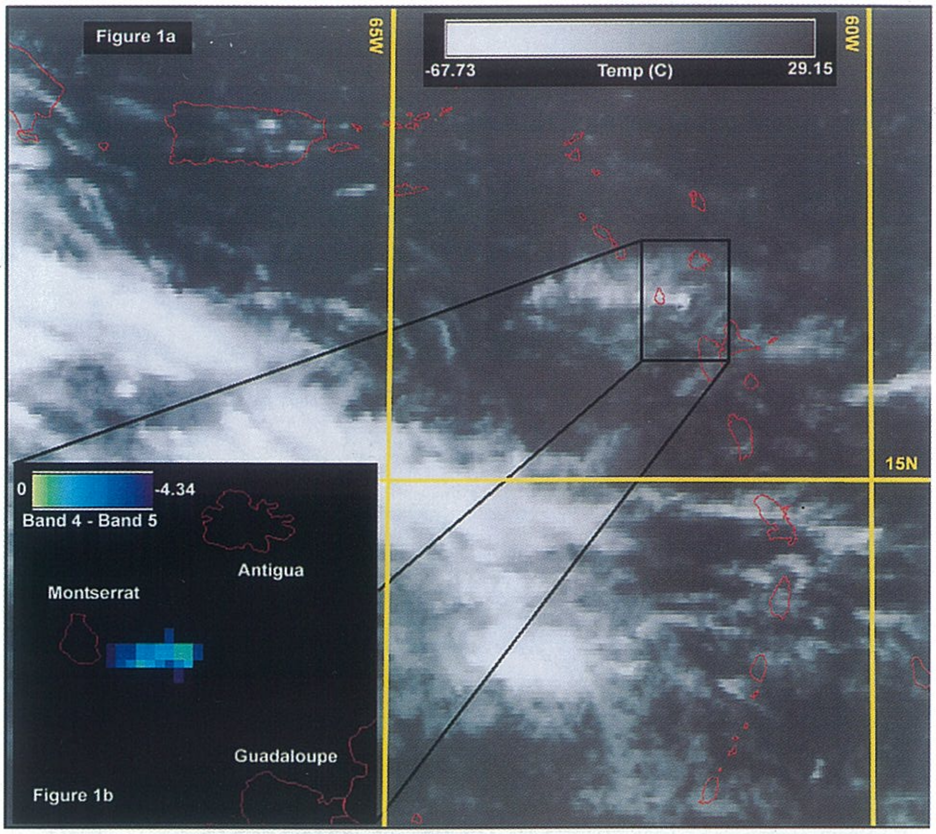

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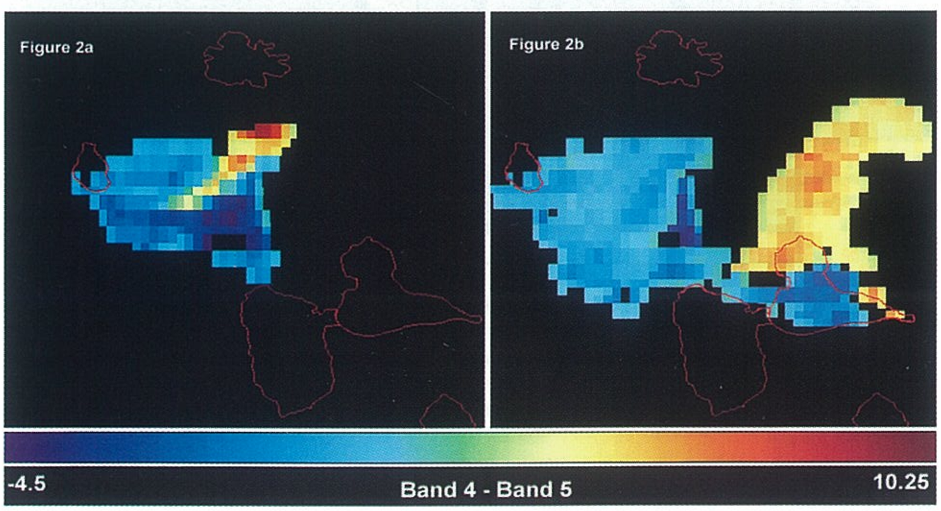

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