THE USE OF GOES SOUNDER IMAGERY FOR THE DETECTION OF HAZARDOUS VOLCANIC ASH PLUMES

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Abstract

The ability of the GOES atmospheric sounder to track volcanic ash clouds was compared to the GOES imager for eleven eruptions of the Soufriere Hills volcano on Montserrat in the eastern Caribbean during the summer and autumn of 1997. The "split window" two-band technique, based on the brightness temperature difference of the longwave (12.0 μm) and window infrared (10.7 μm) bands was used in the evaluation, validated with high resolution 1 km visible data (0.6 μm). Since most of the volcanic events used in this study occurred in daytime, the visible channel was used to verify the presence of volcanic ash. Based on an evaluation of the cases, the sounder was deemed to be suitable for detecting significant ash plumes, but with some degradation due to lower resolution. The maximum hourly frequency of the GOES sounder is considered sufficient, but not as desirable as the 15-30 minutes attainable from the imager. Operational considerations regarding the scheduling and implementation of the sounder scan strategy are addressed. Other channels available on the GOES sounders, especially the 3.7 μm band, may also be useful, especially when combined with the split window imagery.

1. Introduction

Volcanic ash represents a serious hazard to high altitude jet aircraft along major air routes adjacent to active volcanoes. Although the most active volcanic region forms a ring around the Pacific Ocean, other areas such as the eastern Caribbean, east Africa, the Mediterranean, and central Atlantic islands (Azores, Iceland) also pose a threat. In addition to damaging the leading edge surfaces of aircraft, ash ingested into jet engines results in loss of performance, and possibly complete shutdown. A KLM Boeing 747 airliner lost power from all four engines and plunged 12,000 feet over Alaska after encountering ash from Mt. Redoubt in 1989. Fortunately, all engines were restarted, and a disaster was averted. Further encounters with volcanic ash are possible, especially considering the continued increase in international air traffic. A description of the hazards of volcanic ash to aircraft is provided by Casadevall et al. (1996).

Operational advisories of the location and height of volcanic ash clouds are issued by Volcanic Ash Advisory Centers (VAAC) worldwide. In the United States, VAACs are located in Anchorage, Alaska and Washington, DC. Figure 1 shows the locations of VAACs worldwide, and their areas of responsibility. Significant Meteorological (SIGMET) text warnings are issued by regional Meteorological Watch Offices (MWOs). MWOs in the United States include: the National Weather Service's (NWS) Aviation Weather Center, Kansas City; the NWS Alaska Aviation Weather Unit in Anchorage, Alaska; and the NWS Tropical Prediction Center (TPC) in Miami.

Due to the remote location of many volcanoes, remote sensing plays an important role in tracking the ash clouds as they drift away from erupting volcanoes. The current global network of geostationary satellites includes the United States GOES, Japan's Geostationary Meteorological Satellite (GMS), and the European Meteorological Satellite (METEOSAT). They provide visible and infrared (IR) images at intervals of 60 min or less to track the ash clouds, while polar-orbiting satellites such as the National Oceanic and Atmospheric Administration (NOAA) series provide high resolution global coverage at less frequent intervals (2-6 hours) at latitudes south of 55N.

A bi-spectral image technique for the detection of volcanic ash, originally developed using Advanced Very High Resolution Radiometer (AVHRR) IR data (1 km resolution) from the NOAA satellites, has been used for a number of years at some of the VAACs. The technique employs the brightness temperature difference between the "split window" IR channel centered near 12 μm wavelength, and the window IR channel at 10-11 μm (Prata 1989; Schneider et al. 1995). The stronger scattering and absorption of up-welling thermal radiation by volcanic ash at 11 μm, as opposed to 12 μm, results in slightly warmer brightness temperatures in the latter channel, a phenomenon referred to as "reverse absorption."

The inclusion of a split window IR channel on the improved GOES spacecraft beginning in 1994 provides medium resolution (4 km) imagery in these channels, and allows frequent (15-30 minute) monitoring of ash emitted within an hour or two of an eruption. The bi-spectral technique requires some "aging" of the ash cloud to be effective, since many eruption clouds have considerable water content in the early stages of an eruption. In Alaska, the technique has proven effective even when "aged" ash clouds are immersed in meteorological cloud systems. However, some problems have been noted in observing thin ash clouds over snow or ice-covered surfaces (Scott 1998). The effectiveness of the split window image technique in volcanic ash detection was described recently by Davies and Rose (1998), who found that 74%

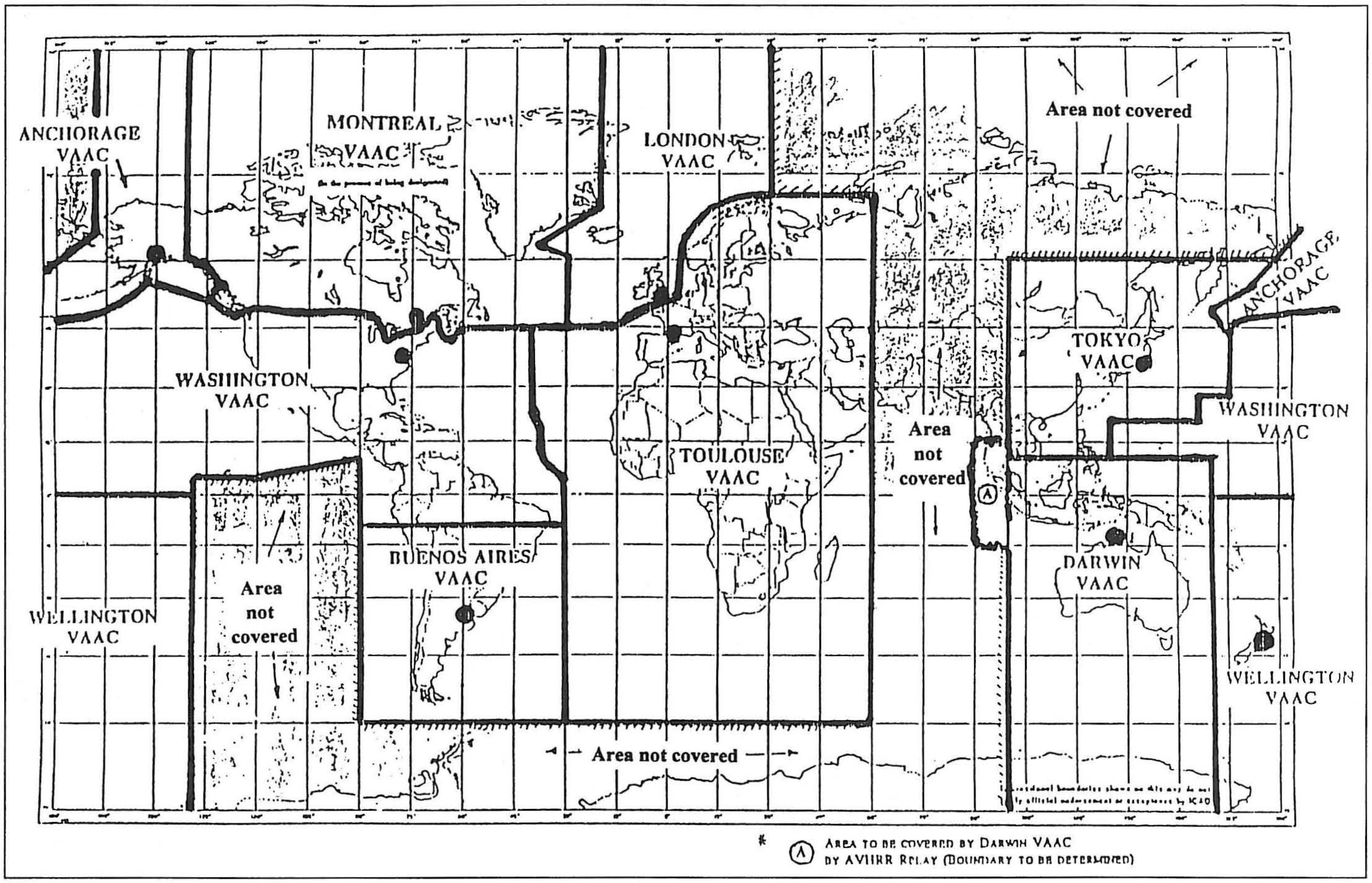

Fig. 1. Map showing the current areas of responsibility for Volcanic Ash Advisory Centers (VAACs) defined by the International Civil Aeronautical Organization (ICAO) as of September 1995.

of the eruptions of the Soufriere Hills volcano on Montserrat during 1996-97 could be identified by this means. A total of 17% of the eruptions could not be seen due to cloud cover, while 8% were not identifiable, although in theory, they should have been seen.

Currently, the Japanese GMS and polar-orbiting NOAA satellites also possess the spectral channels needed to generate the bi-spectral technique. The METEOSAT Second Generation spacecraft will also have this capability beginning around 2001, resulting in a nearly global coverage of volcanoes.

Beginning with the GOES-M spacecraft (circa 2002), however, the split window channel will be replaced with a CO_2 absorption band centered near 13.3 μm. This modification was approved in order to provide better height assignment of cloud tops and wind tracers, and will also lead to higher resolution water vapor images. The improvements in middle tropospheric winds should help provide better forecasts of tropical cyclone movement by numerical prediction models. In the meantime, the loss of the 12 μm channel will affect volcanic ash monitoring from GOES (in addition to some other derived products) for at least five years (2002-2007).

There are future plans to restore the 12 μm channel on GOES spacecraft in the latter portion of the next decade. An alternative source of this multi-spectral data may come from an experimental Volcanic Ash Mapping (VOLCAM) instrument suite, to be funded by the National Aeronautics and Space Administration (NASA). If built, VOLCAM would generate full earth IR imagery in the split window bands at a frequency of 15 minutes. Optimum IR wavelengths and bandwidths have been selected by means of radiative transfer studies to provide an approximate 40% increase in algorithm effectiveness. However, the IR images would be at a resolution of 20 km in the IR bands, significantly lower than current GOES. If selected, VOLCAM could be included in the payload for the GOES-N spacecraft, scheduled to be launched in late 2001, or possibly onboard a NASA or commercial communications satellite.

The deletion of the split window channel from the GOES imager will thus require alternative approaches to volcanic ash monitoring in the Western Hemisphere within the GOES field-of-view. While high resolution imagery in the split window channels will still be available from NOAA AVHRR, its frequency will be insufficient for monitoring low latitude volcanoes (Central America, the Caribbean, and South America). The GOES sounder system will be unmodified through the GOES-M spacecraft. The sounder includes the same channels used on the GOES imager, except that the resolution is about 10 km at the satellite sub-point, decreasing to about 15 km at mid-latitudes. The purpose of this paper is to describe the capability of using the GOES sounder instrument to track volcanic ash in place of the imager, using eruptions of the Soufriere Hills volcano on Montserrat as test cases.

Table 1. GOES Imager Channel Characteristics.

Channel Number	Spectral Peak	Name	Resolution	Purpose
1	0.6 mm	Visible	1 km	Cloud and surface features
2	3.9 mm	Shortwave	4 km	Cloud phase, low clouds at night
3	6.7 mm	Water vapor	8 km	Middle and upper level moisture
4	10.7 mm	Window	4 km	Cloud and surface temperatures
5	12.0 mm	Longwave	4 km	Low level moisture, aerosols

2. Data and Procedures

Satellite data from the GOES-8 imager and sounder covering the eastern Caribbean was collected after eleven eruptions of the Soufriere Hills volcano on Montserrat between 26 June and 6 November 1997. This volcano was quite active throughout much of 1996-97, producing periodic eruptions that spewed ash into the lower and middle troposphere, and occasionally, the upper troposphere.

The GOES imager provides data in five spectral bands as shown in Table 1. Imager data was collected for the GOES Northern Hemisphere sector in Bands 4 (10.7 μm) and 5 (12.0 μm) near the time of eruption, and as close as possible to the time (within 5 minutes) of a GOES sounder scan of this region. The Continental United States (CONUS) image sector just barely reached the longitude of Montserrat, and was not used in this study. The GOES sounder is pre-programmed to observe the

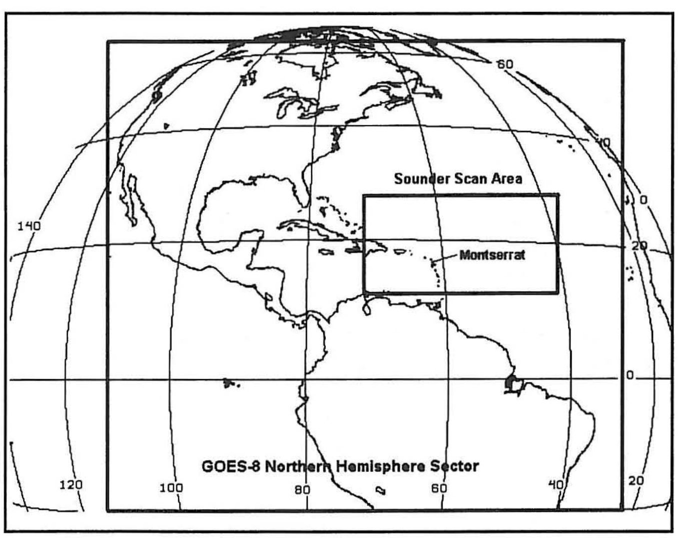

Fig. 2. Areas covered by the Northern Hemisphere sector from GOES-8 imager, and a GOES-8 "Hurricane" sounder sector (HUR-2) centered near Montserrat in the eastern Caribbean. These data were used in this study to compare the imager and sounder capabilities for monitoring volcanic ash.

Table 2. GOES Sounder Channel Characteristics.

Channel	Detector/ Absorption	Spectral Peak	Purpose
1	Longwave	14.71 mm	Stratosphere temp.
2	Longwave	14.37 mm	Tropopause temp.
3	Longwave	14.06 mm	Upper-level temp.
4	Longwave	13.96 mm	Mid-level temp.
5	Longwave	13.37 mm	Low-level temp.
6	Window	12.66 mm	Total PW
7	Window	12.06 mm	Surface temp., H_2O
8	Window	11.03 mm	Surface temp.
9	Ozone	9.71 mm	Total Ozone
10	Water vapor	7.43 mm	Low-level moisture
11	Water vapor	7.02 mm	Mid-level moisture
12	Water vapor	6.51 mm	Upper-level moisture
13	Shortwave	4.57 mm	Low-level temp.
14	Shortwave	4.52 mm	Mid-level temp.
15	Shortwave	4.45 mm	Upper-level temp.
16	Nitrogen	4.13 mm	Boundary layer temp.
17	Shortwave Window	3.98 mm	Surface temp.
18	Shortwave Window	3.74 mm	Surface temp., H_2O
19	Visible	0.67 mm	Clouds

CONUS, and one other region each hour. Typically, the additional sector observes an area of the western Atlantic or the Gulf of Mexico to analyze the environment of tropical storms when they occur, thus they are referred to as "Hurricane Sectors." Figure 2 shows the area coverage of the imager and sounder sectors used in this study. The eastern Caribbean sounder sector (referred to as "HUR-2") was scheduled only once every six hours until late September 1997, when it was reprogrammed for twelve scans per day, with several periods of three consecutive hourly scans.

The GOES sounder is described in detail by Menzel and Purdom (1994). The sounder can obtain multi-spectral data in eighteen IR bands, plus a visible band, with a sub-point resolution of 10 km, degrading to 15 km at mid-latitudes. Table 2 provides information on the sounder channels, including peak wavelengths and purpose. The sounder data can be processed to obtain retrievals of temperature and moisture through the troposphere. For the purpose of this study, the sounder images in Bands 7 (12.0 μm) and 8 (11.0 μm) were used to derive "split window" images.

When available, the HUR-2 sounder scan begins at HH+20, while hourly Northern Hemisphere sectors start at HH+15 (as well as HH+45). Although the Northern Hemisphere image sector is much larger than that of the Caribbean sounder area, the imager scanning rate is much faster than the sounder, so the imager observed the Montserrat area at about HH+22, as opposed to HH+37 for the sounder, a difference of 15 minutes. This difference is not considered significant for tracking volcanic ash clouds at the latitude of Montserrat, where they are usually observed to move or change shape rather slowly with time.

The procedure used in this study was to produce the "split window" images for both imager and sounder at each time period, and display them with the identical

Table 3. Cases analyzed for Soufriere Hills Volcano, Montserrat.

Dates (all 1997)	Sounder Scans	Sounder Time(s) (UTC)	Eruption Time(s) (UTC)	Ash Cloud Height (kft)
26 June	1	1920	1800	9
30 June	1	1920	1000	15-35
1 July	1	1320	1130	30
5 Aug	1	1320	0845	20-35
6 Aug	1	1920	1834	15-20
11 Aug	2	1920, 0120	1536	36
10 Sept	1	1920	1300	15
18 Sept	8	0920-1920	1800	10
23 Sept	6	1120-1920	1023	15
29 Sept	10	1020-2320	0927, 1423, 1948	35-40
6 Nov	5	1920-0120	1845	15

contrast enhancement. The high resolution (1 km) visible channel (0.6 μm) from the imager was used to verify the "split window" products during daylight hours. Volcanic ash is easily discernible in visible imagery as a relatively smooth, milky-textured aerosol, with some small scale variations evident as thicker patches or bands. The reflectance of volcanic ash in visible imagery is significantly less than that of clouds, except for uniformly thin cirrus. The dark background of the surrounding ocean provided excellent contrast with the ash clouds in the visible band. The only other form of "ground truth" was verification of eruptions by the Montserrat Volcano Observatory (MVO), and occasional ground-based estimates of the eruption cloud height. A few of the cases collected (i.e., November 6) extended into the night-time period, when no validating data was available. A listing of the cases is provided in Table 3. Information on the eruption times and height of the ash cloud were obtained from advisories issued by the Washington VAAC.

The imager split window product was then compared to the sounder split window for clarity in depiction of volcanic ash coverage, with visible imagery as verification. The area and shape of the ash plume was compared, and for the stronger eruptions (detectable ash persisting more than 6 hours), the ash cloud duration evident in each type of data was also noted. For the September cases, it was possible to create image loops or movies that showed the evolution of the ash clouds from both the imager and sounder.

3. Examples

a. 29 September 1997

On 29 September 1997, there were several strong eruptions of the Soufriere Hills volcano, creating ash clouds that extended well into the middle and upper troposphere (see Table 3). One of the eruptions occurred at 1423 UTC (1023 LST). The ash stretched horizontally east to west with time. The highest portion of the ash cloud (estimated to be at 35-40 kft above Mean Sea Level (MSL)) was spreading eastward at 30 kt, while the low level ash was drifting westward at about 15 kt, based on information from the Washington VAAC. Figure 3 shows a comparison of the imager versus sounder split window imagery, the Band 4 (10.7 μm) IR, and the visible image. The sounder data start time was 1620 UTC, the imager time was 1615 UTC. The region around Montserrat was nearly cloud-free on this day, providing ideal viewing conditions. It can be seen that the imager and sounder split window products showed nearly identical coverage of ash, although the sounder could not define the boundaries of the ash cloud as well, due to its lower sub-point resolution. There were also a couple of thin ash clouds well to the west of Montserrat (shown by arrows in the lower right panel), a result of earlier eruptions.

b. 11 August 1997

On 11 August 1997, a weaker eruption occurred. A thin ash cloud (determined from qualitative evaluation of visible channel brightness) became elongated north to south with time, and drifted westward across the Caribbean Sea. By 1915 UTC, more than three hours after the eruption, the ash was barely evident in the imager split window image (Fig. 4, upper left), and had become obscured by instrument noise in the sounder product (upper right). The Band 4 IR image (lower left) depicted the ash as well as, or better than the imager split window. The visible image at that time (lower right) showed that the ash was thin, as evidenced by the low-level cumulus cloud streets observed below the ash plume. It is possible that diffuse ash clouds such as this, that are limited in areal extent, would not pose a significant hazard to aviation.

4. Summary of Results

After examination of the image comparison cases for the eleven Montserrat volcanic eruptions, the following conclusions were reached regarding the utility of the GOES sounder as a tool for monitoring volcanic ash clouds:

a. For the cases where the GOES imager split window technique can detect volcanic ash, the GOES sounder usually can also, but with significant degradation of the ash cloud area coverage due to the lower resolution of the sounder. The latter is caused by the partial filling of the larger sounder pixel, which tends to reduce the observed signal.

b. The sounder split window will sometimes underestimate the areal extent of relatively *thin* ash clouds more than three hours after an eruption by 50% or more.

c. The sounder split window imagery normally will "lose" the volcanic ash cloud earlier than the imager. A possible explanation for this effect (as well as item b) is that the difference in the mid-point wavelengths for sounder bands 7 and 8 (1.03 μm) is slightly smaller than that of imager bands 4 and 5 (1.30 μm) (Rose 1998). The latter is nearly identical

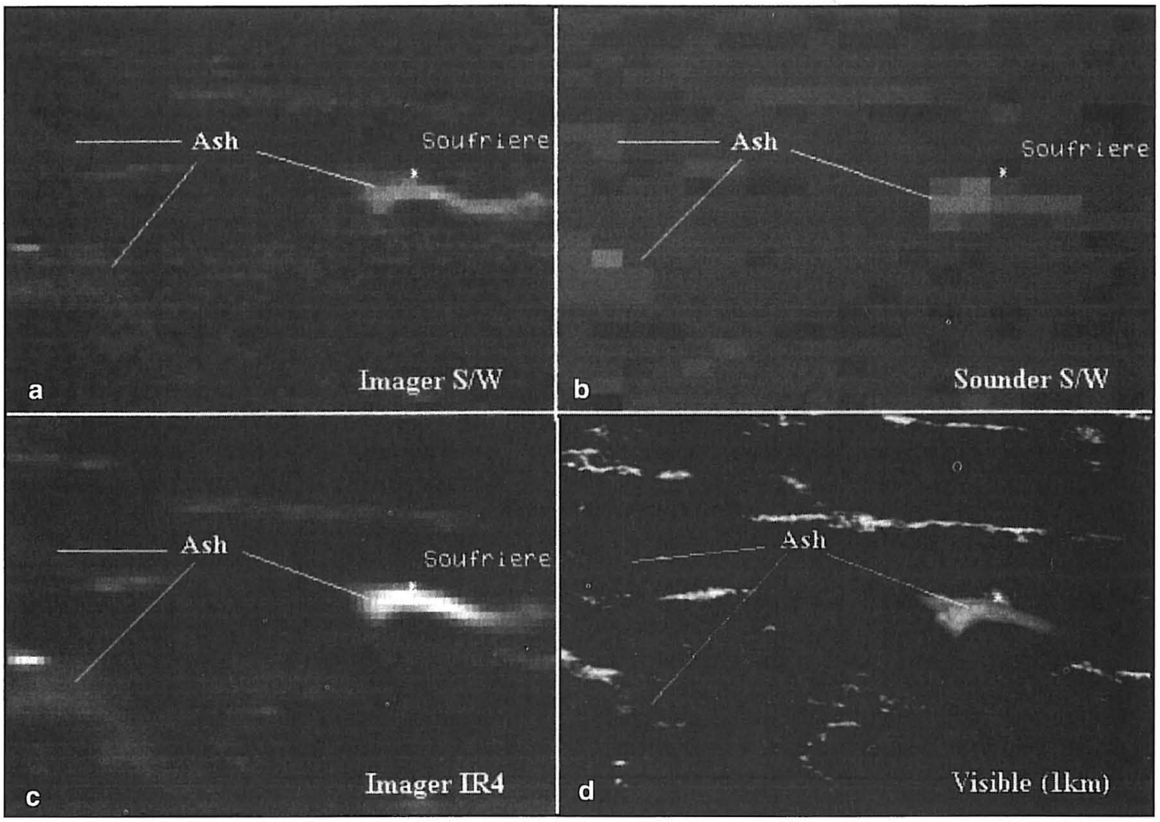

Fig. 3. The volcanic eruption clouds of Soufriere Hills, Montserrat, on 29 September 1997 at 1615 UTC (Imager) and 1620 UTC (Sounder) as seen by: a) the imager split window (S/W) (upper left), b) sounder split window (upper right), c) imager IR band 4 (IR4) (lower left), and d) imager visible band 1 (lower right).

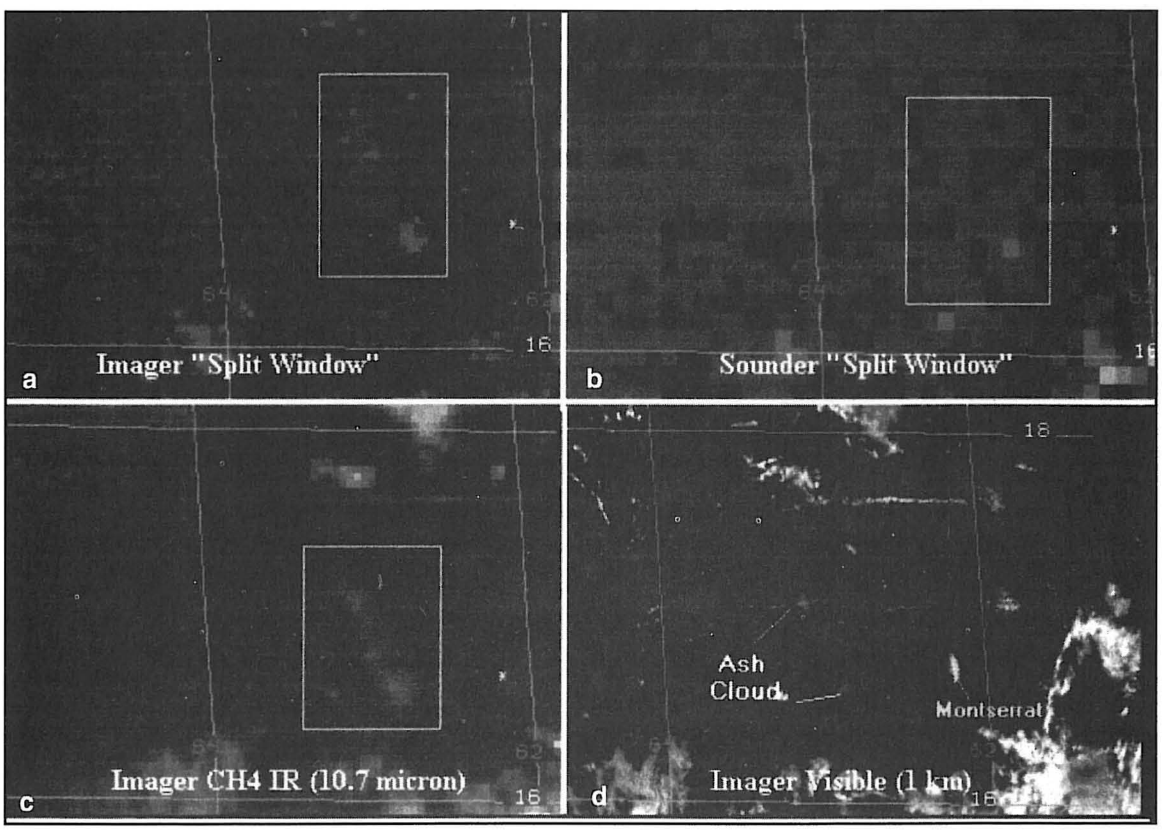

Fig. 4. As in Fig. 3, except the volcanic ash cloud from Soufriere Hills on 11 August 1997 at 1915 UTC (Imager) and 1920 UTC (Sounder). The location of Montserrat is shown by the white dots.

to that of the NOAA AVHRR. A larger difference results in better discrimination. This factor certainly should be a consideration in the design of future satellite instruments.

d. During the daytime, the availability of 1 km resolution visible imagery from GOES will minimize the negative impact of the future loss of the imager split window channel (12 μm), especially over oceanic areas. At night, access to the occasional Defense Military Satellite Program (DMSP) low-light visible images would also be helpful.

e. Although there were few evaluations of the sounder capability at night, volcanic ash detection will likely be impaired by the loss of the imager split window, although the window IR channel (10.7 μm) can also be used effectively for tracking thick ash clouds.

5. Utility of Additional Sounder Channels

In addition to the window IR and split window IR bands, there are other IR channels that may be useful in monitoring volcanic ash. An ozone and SO_2 absorption band (Band 9 - 9.71 μm) will be evaluated for potential detection of ash. Inspection of that channel during some of the Montserrat eruptions did not, however, reveal any detectable signal from the ash clouds. Stronger eruptions, with emission of ash into the stratosphere, are perhaps needed for this channel to be useful.

There are also two shortwave IR bands on the sounder, at 3.9 μm (Band 17) and 3.7 μm (Band 18). The shortwave IR has recently been found to be useful in observations of ash by means of two characteristics: (1) increased solar reflectance from the ash during daytime, and (2) absorption by sulfur dioxide (SO_2) near 4 μm. Although clouds containing water droplets are also reflective at this wavelength during daylight hours, the author has observed that the magnitude of reflectance from volcanic ash (based on brightness temperature differences) is significantly greater than that from water clouds.

An example of the possible use of these shortwave sounder channels is shown by Fig. 5. The left hand panel of this image shows the ash cloud from an eruption of Soufriere Hills on 29 September 1997 as seen in the visible channel. The middle and right hand panels are the 3.7 μm and 3.9 μm bands, respectively, from the sounder at nearly the same time. The IR images are inverted from the normal display to show warmer temperatures as lighter gray shades. The 3.7 μm band is significantly warmer (*lighter*) in the vicinity of the volcanic ash than the 3.9 μm band. It was somewhat surprising to observe such a large difference in appearance, considering the relatively small difference in wavelength. There are some cumulus cloud lines (cloud streets) also in the image, mostly north of the ash cloud. While these cloud lines are relatively narrow, they are nevertheless apparent in the IR images, and are quite a bit cooler than the ash cloud.

Recent research within the National Environmental Satellite, Data, and Information Service (NESDIS) Office of Research and Applications and the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University, has shown the value of using three IR channels from the imager (3.9 μm, 10.7 μm, and 12.0 μm) to enhance the areal depiction of volcanic ash plumes (Ellrod and Connell 1999). The inclusion of the 3.9 μm band in the three-channel product may also provide early warning of eruptions by detecting thermal anomalies sometimes observed with volcanoes, as far as 2-3 days in advance. An explanation proposed for these thermal anomalies is that they are due to rock falls from lava domes that reveal hot rocks beneath (Rose 1998). It is important to note that not all volcanoes have these lava domes. Inter-comparison of a three-channel product derived from similar channels on the sounder appears to be comparable to a similar product from the imager. Evaluations of these experimental products will continue.

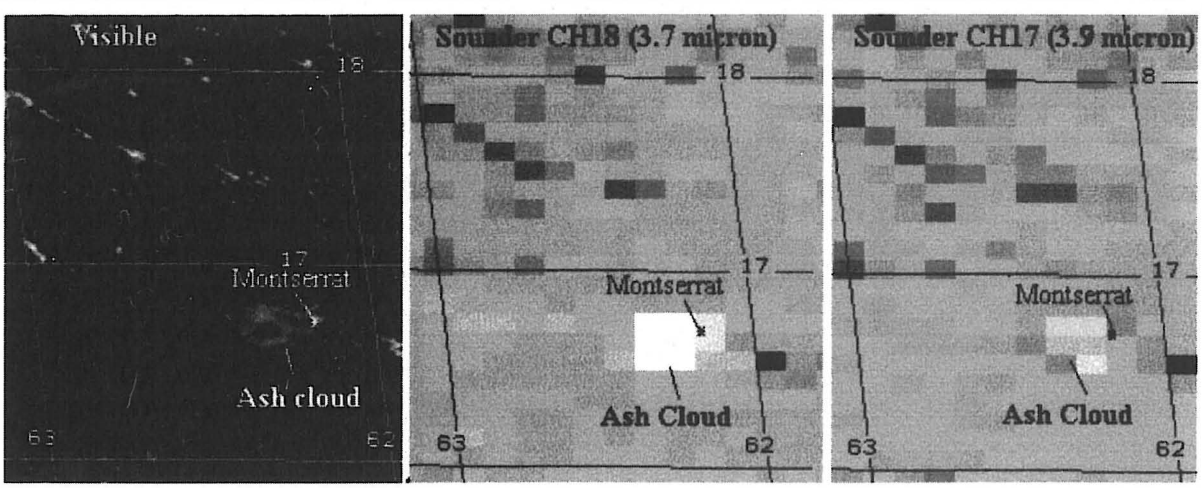

Fig. 5. GOES-8 view of the 29 September 1997 eruption as seen by the visible band (left), sounder band 18 (3.7 μm) (center) and sounder band 17 (3.9 μm) (right). The IR images have been inverted to provide better clarity of the ash cloud.

6. Operational Considerations

Some of the major operational limitations in the use of the GOES sounder for volcano monitoring are its low spatial resolution, relatively slow scan rate, limited geographical coverage, and the considerable lead time required to change the sounder schedule. The operational use of the sounder has also been prioritized for monitoring: a) the Continental United States hourly cloud products, in order to produce derived products that supplement severe weather prediction, and the Automated Surface Observing System (ASOS); b) the Gulf of Mexico to observe the return flow of moisture into the southern United States; and c) the environment of tropical cyclones in the western Atlantic and east Pacific Ocean basins during the summer months. To be an effective tool to operationally track volcanic ash clouds, the priority of using the sounder for this purpose must be increased on an event basis, the sampling frequency should be increased, and the scheduling turnaround time (currently 24 hours) must be reduced. Another factor is that once an ash cloud drifts away from its source, the sounder scan "window" must move with it in order to provide continuous coverage in strong upper flow conditions. Sounder data is currently not generated at northern latitudes, due to a limitation on the local satellite zenith angle (must be <60 degrees) in processing sounding retrievals. However, sounder images may still be useful at high latitudes.

7. Summary and Conclusions

The ability of the GOES atmospheric sounder for tracking of volcanic ash clouds was compared to the imager for eleven eruptions of the Soufriere Hills volcano on Montserrat in the eastern Caribbean. The eruptions occurred during the summer and autumn of 1997. The primary means of comparison was the "split window" technique, based on the brightness temperature difference of two GOES IR window bands centered near 12.0 μm and 10.7 μm wavelengths. Since most of the volcanic events collected for this study occurred in daytime hours, the visible channel was used to verify the presence of volcanic ash. Based on an evaluation of these cases, the sounder was deemed to be suitable for detecting and tracking thick ash plumes, but with some degradation due to its lower spatial resolution. The maximum hourly frequency of the sounder is considered sufficient, but not as desirable as the 15-30 minutes attainable from the imager. Some changes must occur in operational scheduling and implementation before the sounder can become a viable tool for operational ash detection. Other channels available on the GOES imagers or sounders, possibly the 3.7 μm or 3.9 μm bands, may also be useful, especially when combined with the split window imagery.

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