8.13 A FIRST LOOK AT VOLCANIC ASH DETECTION IN THE GOES-12 ERA

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1. INTRODUCTION

The Geostationary Operational Environmental Satellite (GOES)-12 Imager, which was activated 1 April 2003, has been re-configured with the addition of a 13.3 μm Infrared (IR) spectral band, in place of the "split window" 12.0 μm band. This suite of spectral bands will remain in place until the GOES-R Advanced Baseline Imager (ABI) becomes operational circa 2013. The 12.0 μm band has been successfully used for volcanic ash detection from GOES for nearly ten years, since it first became available on GOES-8 in 1995. The "Two-Band Split Window (TBSW)" technique, as it is often referred as, has its heritage dating back to the late 1980's when it was applied to data from the Advanced very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting spacecraft (e.g. Prata 1989; Holasek and Rose 1991). The unavailability of this channel has resulted in some concern about the impact of this change on short term warnings and forecasts for aviation operations over North and South America. Since the implementation of GOES-12, several weak to moderate volcanic eruptions have been observed by the new Imager, the most significant of which occurred at the Soufriere Hills Volcano, on the island of Montserrat in the eastern Caribbean during 12-15 July 2003. Ash clouds resulting from a series of four eruptions were dispersed throughout the Eastern Caribbean at altitudes as high as 16 km. As a result, numerous advisories were issued by the Washington Volcanic Ash Advisory Center. This paper will discuss the use of GOES-12 data to detect and track these events, and how data from the lower resolution GOES Sounder can be used to complement products obtained from the Imager.

2. CHANGES TO THE GOES IMAGER

Plans to add an additional longwave Infrared (IR) channel at 13.3μm to GOES Imagers, as well as to improve the resolution of the 6.7μm water vapor channel, were devised back in the early 1990's in order to provide more accurate height assignment of thin cirrus cloud tracers by means of a CO_2 analysis technique (COAT). More accurate cloud heights would lead to improved satellite-derived winds that are assimilated into numerical prediction models. A major improvement was then anticipated in the prediction of tropical cyclone motion, a major forecast problem for North America and Central America. Although the original plan was to maintain all of the existing channels, budget restrictions led to the elimination of Band 5 (12μm), effective with the GOES-M (12) through P (15) spacecraft. The resulting GOES Imager configuration is summarized in Table 1.

TABLE 1.
GOES Imager Spectral Bands

	GOES 8-11		**GOES M-P**	
Band	Wave-length (μm)	Res. (km)	Wave-length (μm)	Res. (km)
1	0.6	1	0.6	1
2	3.9	4	3.9	4
3	6.7	8	**6.5**	**4**
4	10.7	4	10.7	4
5	12.0	4	**-**	**-**
6	-	-	**13.3**	**8**

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3. PREDICTED IMPACT OF 12μm INFRARED BAND LOSS

Prior to the GOES-12 launch, a study was conducted to estimate possible impacts on volcanic ash detection without the 12 μm IR channel (Band 5 in Table 1) (Ellrod 2004). The study used data from the GOES Imager and Sounder, and other instruments such as the Moderate resolution Imaging Spectroradiometer (MODIS) available on the National Aeronautics and Space Administration's (NASA) experimental Earth Observing System (EOS) spacecraft. For the GOES data, principal component analysis (PCA) images were obtained using software developed by Hillger (1996). PCA techniques sort multi-spectral data to determine combinations that display the most redundant information in the first images, followed by increasingly unique information with higher numbered images. The latter images explain progressively less variance between image channels.

PCA images in the study were produced that included and/or excluded the 12 μm and 13.3 μm IR bands for several case studies to simulate capabilities for the GOES-8-11 and GOES-M+ series Imagers. In addition to subjective evaluation of the best PCA images, an objective parameter was devised to estimate overestimation of ash cloud extent due to false detection. The study concluded that some degradation of volcanic ash detection capability would be likely, mainly a result of (1) falsely identifying various meteorological cloud types and surface features as volcanic ash, and (2) under-detection of very thin ash. However, it was felt that significant ash clouds could still be effectively detected and tracked, albeit with more uncertainty. A study by Hillger and Clark (2002) led to similar conclusions. It was also determined that the new 13.3 μm band could be useful in discriminating high level ash from cirrus clouds.

A few reasons why the loss of this channel may not be as serious as some expected is that there are situations where the TBSW technique fares poorly, due to: (1) the excessive thickness of the eruption cloud (which often contains copious water and large ejected particles) within a few hours after the eruption, (2) a lack of temperature contrast between the airborne ash and underlying surface, and (3) ambient atmospheric moisture that can mask low level ash clouds (e.g. Simpson et al 2000). Despite these shortcomings, the TBSW technique is effective in many cases, and has become an international benchmark for volcanic ash detection.

In order to mitigate the loss of Band 5 it was recommended that (1) all existing bands on the GOES M-P Imagers be utilized (except possibly Band 3 water vapor which normally has little value), (2) products from the GOES Sounder (although limited in temporal and geographic coverage) be exploited since that instrument remains unchanged and has nineteen spectral bands, and (3) employ data from higher resolution instruments on polar orbiting spacecraft such as the NOAA AVHRR, and MODIS on NASA's Terra and Aqua. The remainder of this paper will show examples of how the GOES-12 Imager and Sounder are being used to detect potentially hazardous volcanic ash events.

4. GOES-12 VOLCANIC ASH ALGORITHM

The loss of the 12 μm IR channel on GOES-12 created the urgent need for a different approach to volcanic ash detection. Based partly on results of the impact studies previously described, a new algorithm was developed based on GOES Sounder and MODIS IR data (Ellrod and Im 2003), since those instruments possess the same channels as the GOES-12 Imager, though with different resolutions and spectral widths. The chosen method uses an arithmetic combination of Bands 2 (3.9 μm), 4 (11 μm) and 6 (13.3 μm) expressed as:

$$B = 5\,(DT) - 230 \qquad (1)$$

Where B is output brightness count, DT = ($T_2 - 1.5T_4 + 1.5T_6$), T_2 is brightness temperature (BT) (K) observed in Band 2 (3.9μm), T_4 is BT in Band 4 (10.7μm) and T_6 in BT in Band 6 (13.3μm). DT values between 230 and 300 are scaled to output brightness counts between 0 and 255. Values of B that are large relative to surrounding clouds and terrain represent volcanic ash. Thresholds for volcanic ash detection using this new approach have not yet been established due to the diurnal variation of T_2. Even in bright daytime scenes, however, the ash clouds stand out against the background if they are sufficiently dense. Figure 1 shows brightness count (B) values from Equation (1) versus Band 4 temperature (K) on 14 July 2003 at 0915 UTC (0515 Caribbean Standard Time (CST)) for several different types of features. The volcanic ash (red) is clearly distinguishable from the cirrus (black), mid-level clouds (green), and warm ocean (blue) at this time. Note that if only thermal IR data were used, the ash would be virtually indistinguishable from other clouds in the region due to similar brightness temperatures.

The GOES-12 volcanic ash product is generated routinely for several active volcanic regions in North and South America by both the NESDIS Office of Research and Applications, and the NESDIS Satellite Services Division and placed on their respective Web sites:

http://www.orbit.nesdis.noaa.gov/smcd/opdb/aviation/volc.html (ORA)

http://www.ssd.noaa.gov/VAAC/ (SSD)

5. OBSERVATIONS OF THE SOUFRIERE HILLS ERUPTIONS OF 12-15 JULY 2003

Several eruptions of Soufriere Hills Volcano on the island of Montserrat occurred 12-15 July 2003, and provided the first opportunity to test GOES-12 ash detection capability under “live” conditions. The first and strongest event during the night of 12-13 July 2003 was clearly seen in GOES Band 4 IR due to cold cloud top temperatures and high altitude of the eruption column (15.7 km according to the Washington Volcanic Ash Advisory Center (W-VAAC), although multi-spectral techniques were not effective due to extensive high cloudiness caused by a tropical easterly wave. Figure 2 is a sequence of IR images that shows the evolution of the cold clouds related to the eruption as they spread to the northeast. Confirmation that this was volcanic ash was obtained from a Total Ozone Mapping Spectrometer (TOMS) Aerosol Index later that day (image available from NASA Web site at: http://skye.gfsc.nasa.gov/archives.html

A second, weaker eruption occurred shortly after Midnight local time on 14 July 2003, resulting in a small ash cloud that reached 11.3 km based on the W-VAAC analysis. The ash cloud could be clearly tracked in a sequence of multi-spectral images as it drifted to the west and northwest. Figure 3 compares the GOES-12 three-band ash product described in equation 1 at 0715 UTC (panel A) with the same product based on the Sounder at 0720 UTC (panel B), and the TBSW image, also from the Sounder at 0720 UTC. The Imager product depicts the boundary of the ash cloud at least as well as the Sounder images, including the TBSW combination.

The last significant eruption in the series occurred early on the morning of 15 July 2003 and produced an ash cloud that reached an altitude of 14.7 km as it drifted to the west and southwest. The ash clouds could be tracked for a period of ten hours. Figure 4 is a comparison similar to Figure 3, showing that the GOES-12 Imager three-band composite was quite effective in discriminating the ash cloud from surrounding features.

6. OTHER GOES-12 CAPABILITIES

6.1 *Imager Cloud Top Height Estimates*

The addition of a 13.3 μm IR band allows evaluation of a CO_2 Analysis Technique (COAT) for the estimation of cloud top heights for semi-transparent clouds, including volcanic ash, in the GOES Cloud Top Pressure (CTP). Details on this technique are provided by Schreiner and Schmit 2001, and Schreiner et al 2002. The main assumptions are (1) cloud is opaque but infinitesimally thin (thus allowing application for semi-transparent clouds), and (2) emissivity is the same in both spectral ranges. The latter assumption, when applied to the 13.3 μm and 10.7 μm bands on GOES-12, is only valid when a volcanic cloud is partially composed of ice. For opaque clouds, an IR Window Technique is used, which matches the IR cloud top temperature with the appropriate height in upper air or numerical model temperature profiles.

Although the CTP derived from the Imager is not considered to be as accurate as one obtained from the Sounder due to fewer spectral bands in the 13-15 μm range, the advantage of the Imager product is more frequent observations to monitor rapidly changing conditions such as for major volcanic events. The Imager observes the eastern Caribbean every 30 minutes, the Sounder only once every six hours. Figure 5 shows the GOES cloud top analysis at 0845 UTC with the volcanic clouds encircled. Cloud top heights agreed with those provided by the W-

VAAC at 0545 UTC (Figure 6) which were obtained using an independent technique. The W-VAAC estimates the altitudes of volcanic ash clouds by matching trajectories derived from image animations with wind direction and speed obtained from nearby radiosondes, numerical prediction models, or satellite cloud drift. The cloud top height is the maximum altitude that best correlates with that wind.

6.2 *Sulfur Dioxide Detection from the Sounder*

The GOES Sounder has a nineteen channel filter wheel instrument whose main purpose is retrieval of temperature and moisture vertical profiles for selected regions of North America and adjacent oceanic areas. A detailed description of the GOES Sounder and various derived products is found in Menzel et al (1998). The Sounder aboard GOES-12 has remained unchanged from earlier spacecraft. Table 2 lists the Sounder infrared channels and associated spectral regions. Band 19 is a visible channel.

TABLE 2.
GOES Sounder Spectral Bands

GOES-12 Sounder band	Central wavelength (μm)
1	14.71
2	14.37
3	14.06
4	13.64
5	13.37
6	12.66
7	12.02
8	11.03
9	9.71
10	7.43
11	7.02
12	6.51
13	4.57
14	4.52
15	4.46
16	4.13
17	3.98
18	3.74

There are two spectral bands on the Sounder that are sensitive to absorption by SO_2: Band 10 centered near 7.4 μm, and Band 17 near 4.0 μm. Based on various studies, Band 10 is considered the better of the two. Since Band 10 is also sensitive to middle Tropospheric moisture, it is most effective in providing information on SO_2 that is in the upper Troposphere or lower Stratosphere where the effects of moisture are minimal. The use of Sounder data in determining quantitative retrievals of SO_2 content is described in Prata et al 2004.

For qualitative determination of the presence of SO_2, it may be simply adequate to produce images based on the difference of Band 10 and an additional band that has a peak response in the upper Troposphere and is not subject to moisture contamination such as Bands 9 (9.7 μm) and 5 (13.3 μm). An example is shown in Figure 7 for the Soufriere Hills event on 12 July 2004. The GOES Sounder image (left panel) is based on the Band 10 – Band 9 BTD at 1520 UTC, and is compared with a NASA TOMS SO_2 Index product (right panel) at approximately 1630 UTC. Lighter gray shades in the GOES image show regions where SO_2 concentration is largest. Despite the difference in valid times, there is good qualitative correlation between the two. The GOES product shows a strong signal for SO_2 to the west of Montserrat that was not observed by TOMS due to its location near the edge of the swath, and suggests the presence of SO_2 at mid-Tropospheric levels in the deep easterly flow.

Although SO_2 is not as hazardous to aircraft as volcanic ash, information on its presence could be used to (1) reduce the geographic extent of volcanic ash advisories and warnings, and (2) confirm the occurrence of an eruption in situations where cloudiness prevents positive identification based on multi-spectral IR techniques. An example of the latter application occurred on the night of 12-13 July 2003. Figure 8 is the Band 10 – 9 BTD product from the GOES Sounder at 0920 UTC shortly after the eruption, showing a signal for SO_2 just to the east of the eruption cloud.

6.3 *TBSW Images From the Sounder*

Since the Sounder still has a 12μm IR Band (Table 2), TBSW images can still be obtained, although at reduced resolution and frequency. Examples of these products and comparisons with those from the Imager were described by Ellrod (1998).

7. SUMMARY AND CONCLUSIONS

Data from the reconfigured GOES-12 Imager without a 12.0 μm IR band was able to adequately observe the eruption clouds from Soufriere Hills Volcano during the 12-15 July 2003 episode using multi-spectral IR techniques. The strongest event on 12 July 2003 was partially obscured by high level clouds, a common deficiency of IR techniques. Subsequent episodes were well-observed using multi-spectral products. Although conditions for two of the eruption events were considered ideal because of the uniformly warm ocean background scene and absence of cloudiness, it nevertheless suggests that GOES-12 and its successors can be used effectively to warn pilots of hazardous ash clouds in many situations. Further analyses of additional events are needed to confirm these findings. Other new capabilities from GOES-12 that could be utilized in the issuance of volcanic ash advisories are: (1) improved cloud top height estimates from the Imager and (2) sulfur dioxide (SO_2) detection using Sounder spectral band differences.

8. ACKNOWLEDGEMENTS

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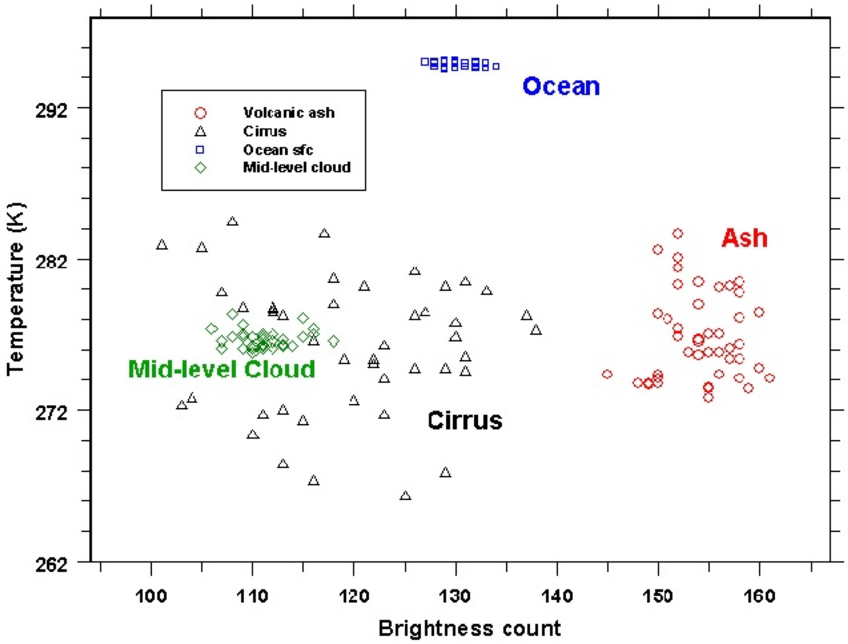

***Figure 1**. Brightness count from Equation 1 plotted versus Band 4 IR temperature (K) for a variety of cloud or surface types, including volcanic ash (red). Data collected from the 0915 UTC image time on 14 July 2003.*

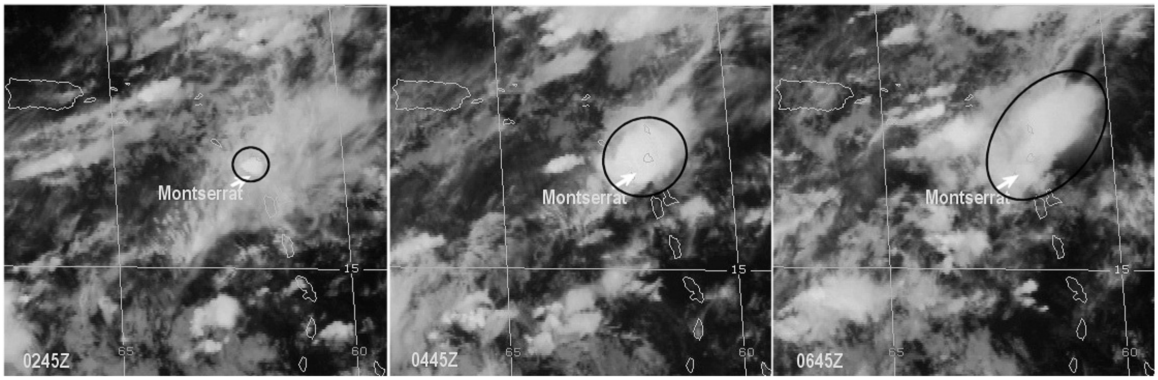

***Figure 2.** Sequence of Band 4 IR images at 0245 UTC, 0445 UTC, and 0645 UTC on 13 July 2003 showing expansion of eruption cloud (estimated to be within encircled area) from Soufriere Hills Volcano, Montserrat*.

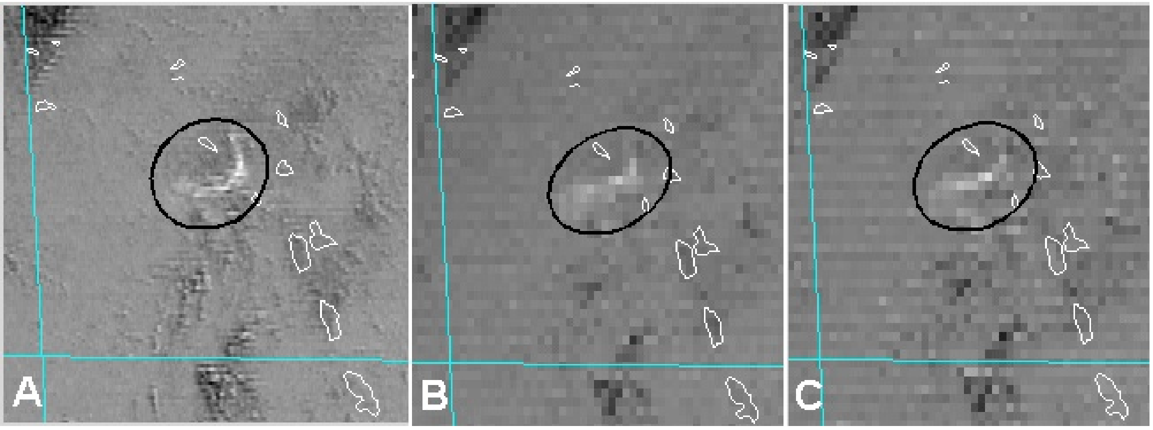

__Figure 3.__ Comparison of GOES-12 three-band IR image from Imager at 0715 UTC on 14 July 2003 (A) with the same image product from the Sounder valid at 0720 UTC (B). Panel C is a Two-Band Split Window image (based on 12.0μm and 11.0μm IR channels), also from the Sounder at 0720 UTC. Ash is shown by lighter gray shades within encircled areas. Black pixels represent cirrus clouds.

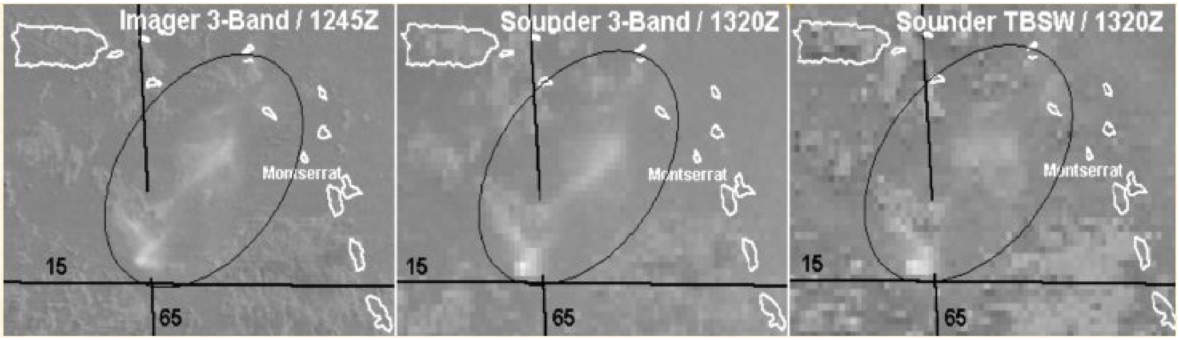

***Figure 4**. Volcanic ash product (based on the 3.9, 10.7 and 13.3 μm bands) from the GOES-12 Imager (left) at 1245 UTC compared with the same product from the Sounder at 1320 UTC (center), and a two-band split window (TBSW) based on the 12.0 and 11.0 μm channels from the Sounder, also at 1320 UTC (right).*

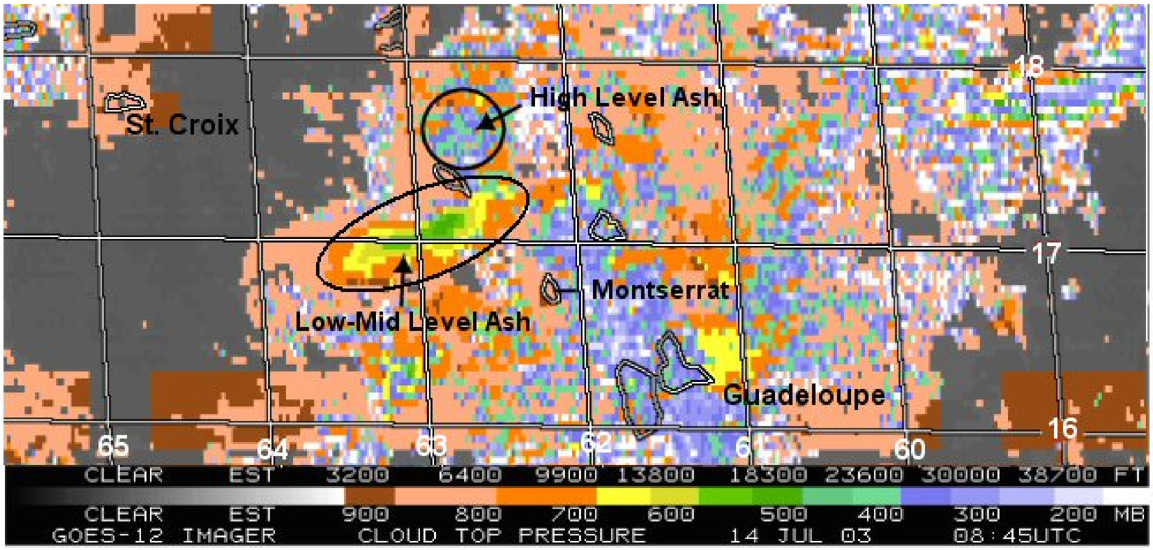

Figure 5. *Cloud top height product from the GOES Imager valid 0845 UTC, 14 July 2003. Cloud top scales are height (ft) and pressure (hPa). Ash cloud was bi-furcated, with mid-level ash moving to west-northwest, and higher level ash drifting north-northwest. Ash cloud heights are in good agreement with those from the VAAC (shown in Figure 6).*

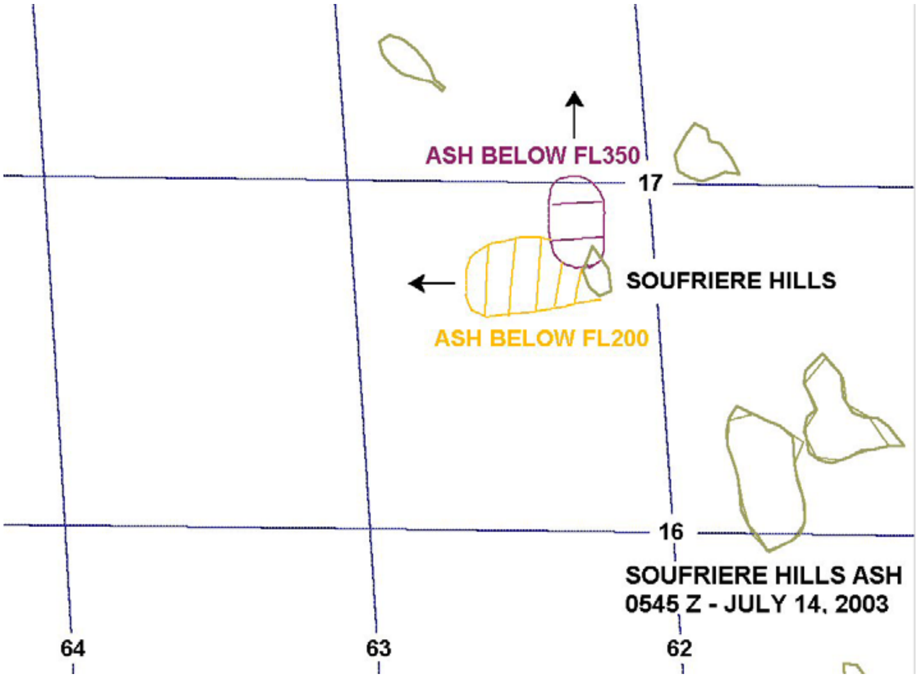

Figure 6. *Graphic from the Washington Volcanic Ash Advisory Center showing an analysis of volcanic ash cloud heights at 0545 UTC, 14 July 2003.*

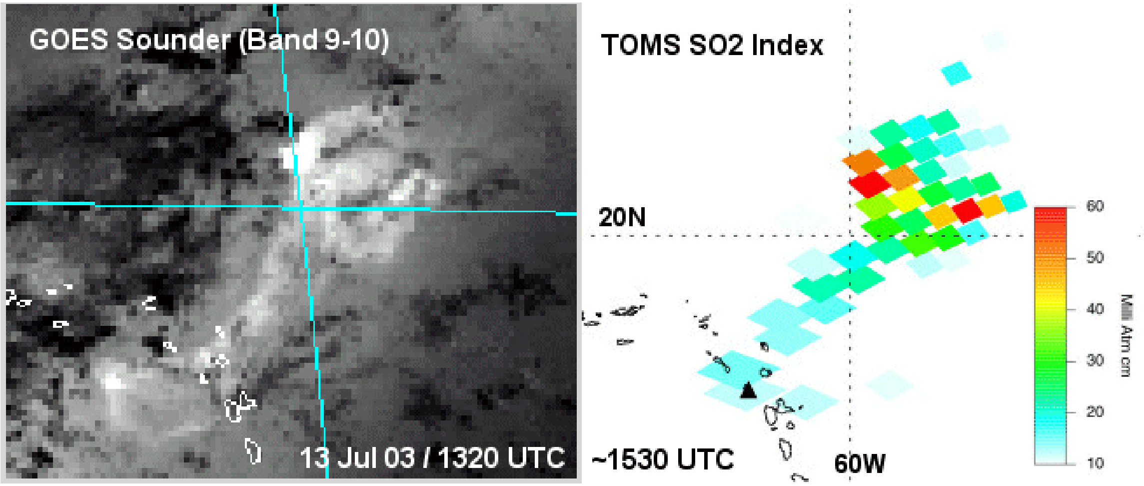

Figure 7. *Comparison of a Band 9 (9.7 μm) minus Band 10 (7.4 μm) image from the GOES-12 Sounder at 1320 UTC (left) versus the SO_2 Index product derived from UltraViolet channels on the NASA Total Ozone Mapping Spectrometer (TOMS – right).*

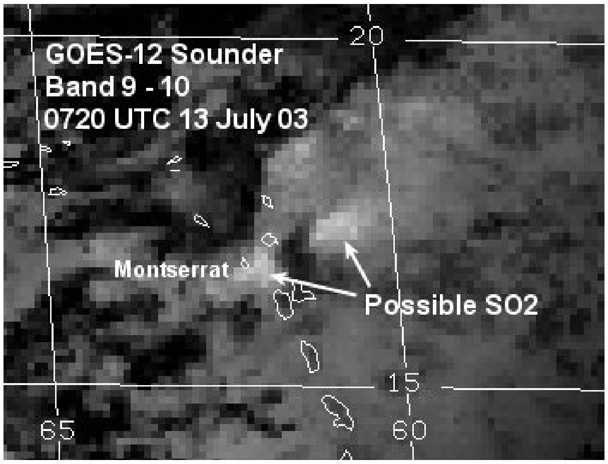

Figure 8. *GOES-12 Sounder Band 9 minus Band 10 at 0720 UTC on 13 July 2003 showing possible SO_2 signatures to the east and northeast of Montserrat. See Figure 2 for Band 4 IR from Imager at 0645 UTC.*