CAN UPPER-LEVEL SO$_2$ BE MONITORED USING THE GOES SOUNDER?

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1. Introduction

During outbreaks of volcanic activity, plumes of SO$_2$, along with other gases and ash, are frequently expelled from the erupting volcanoes. Detection of these SO$_2$ plumes can be accomplished via the MODerate Infrared Sensor (MODIS) and Atmospheric InfraRed Sounder (AIRS) remote sensing instruments. The advantages of these two sensors are (1) the selection of the suite of bands available for sensing the surface and atmosphere is compatible with detecting SO$_2$, (2) high

Fig. 1. A picture of Soufriere Hills volcano, shortly after the initial eruption on 02:30 UTC, 13 July 2003.

spatial resolution of the MODIS and the high spectral resolution of the AIRS, and (3) the potential coverage for these two platforms is

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global, as both platforms are aboard polar orbiting satellites. The primary disadvantage of remotely sensed information derived from the MODIS and AIRS is the poor temporal resolution outside of the polar regions (two to four times per day for a given location).

The Geostationary Operational Environmental Satellite (GOES) –12, on the other hand does not have the extensive suite of InfraRed (IR) bands contained on either the MODIS or the AIRS sensors. In addition the bands chosen for the GOES Sounder were not selected for remote sensing of volcanic eruptions and specifically for detecting SO$_2$, nor are the spatial resolution and the geographical coverage comparable to the polar orbiters. But, one advantage of the GOES series of satellites over the MODIS and AIRS is its ability to provide high temporal information. For the Sounder the temporal refresh rate can be as high as once per hour, while for the Imager it can be every 15/30 minutes under routine operations.

On 12 July 2003 a series of volcanic eruptions began at the Soufriere Hills volcano located on the island of Montserrat in the eastern Caribbean. Over a three-day period four eruptions took place. The first eruption was triggered by a major dome collapse followed by pyroclastic flows, as shown in Fig. 1 (Montserrat Volcano Observatory 2003). According to the Washington Volcanic Ash Advisory Center (W-VAAC) volcanic ash from these eruptions was dispersed throughout the

Table 1. Band numbers and central wavelengths for GOES-12 Imager and Sounder.

GOES-12 Imager Band	Central Wavelength (µm)
1	0.65
2	3.9
3	6.48
4	10.7
6	13.3

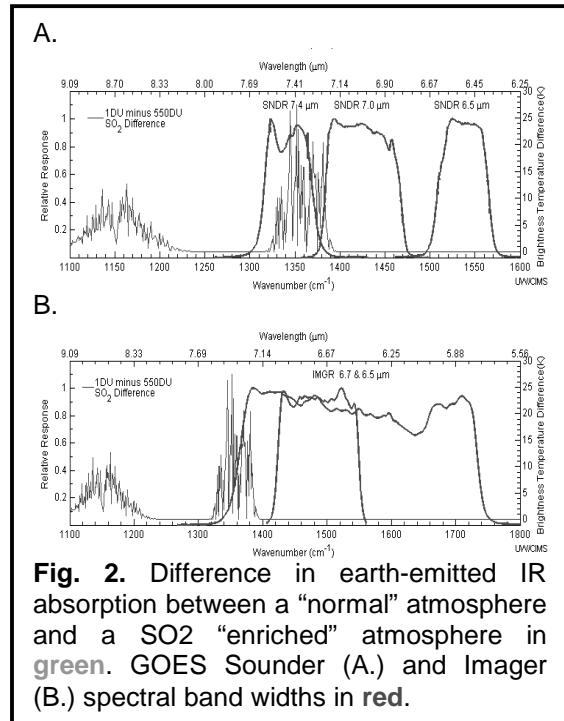| Sounder Band	Central Wavelength (µm)
1	14.71
2	14.37
3	14.06
4	13.64
5	13.37
6	12.66
7	12.02
8	11.03
9	9.71
10	7.43
11	7.02
12	6.51
13	4.57
14	4.52
15	4.46
16	4.13
17	3.98
18	3.74

region at heights ranging from 8 to 16 km. Sulfur Dioxide plumes were also detected by various instruments, including the MODIS, AIRS, and Total Ozone Mapping System (TOMS).

For this particular volcanic case the GOES IR information was investigated with respect to two questions. First, can the IR information from either the Sounder or Imager instrument provide useful radiance information for detecting SO_2? Second, once an SO_2 plume has been identified, can the high temporal resolution of the GOES be utilized to delineate the evolution of the plume? Therefore, the goal of this paper is to show that the GOES, and specifically the GOES Sounder, can be used to detect upper level SO_2. This will be shown by providing background information on the GOES Sounder instrument and

demonstrating that it does, in fact, remotely sense SO_2 for one particular band that is very close to a SO_2 absorption feature. This will be discussed in the following section. A close examination of the Soufriere Hills Volcano eruption will be detailed in section three. A summary of our findings and prospects for the future will be outlined in the final section.

2. Background

The recent Geostationary Operational Environmental Satellites (GOES) series (operationally known as "8 through 12") were first launched in 1995 (Menzel and Purdom 1994). The GOES platform contains two earth remote sensors, the Imager and the Sounder. Each instrument is comprised of a suite of infrared sensors and one visible sensor (the imager: four infrared bands; the sounder: 18 infrared bands). The Imager sensor is designed for high resolution (generally 4 km and 15/30 min. spatial and temporal resolution, respectively) and primarily qualitative

Fig. 2. Difference in earth-emitted IR absorption between a "normal" atmosphere and a SO2 "enriched" atmosphere in **green**. GOES Sounder (A.) and Imager (B.) spectral band widths in **red**.

imagery. In contrast, the Sounder is intended for quantitative purposes (10 km. Spatial resolution and once per hour temporal coverage). Table 1 briefly outlines the central wavelengths for both the Imager and the Sounder.

GOES–12 Sounder Bands 1 through 5 are long-wave CO_2 absorption bands, primarily used for the retrieval of atmospheric temperature and height and effective amount of clouds. These first five bands are sensitive to different layers of the atmosphere. Bands 6, 7, & 8 are "window" bands, although Bands 6 & 7 are additionally sensitive to low level moisture. The fourth mid-range band, Band 9, is sensitive to ozone. Bands 10 through 12 are sensitive to atmospheric water vapor at different levels in the troposphere. Band 10 is sensitive to water vapor at a higher level than Band 11, and Band 11 is higher than Band 12. Finally, Bands 13 through 18 are short wave IR bands and are primarily sensitive to temperature and are used in the quantitative determination of atmospheric temperature. This final group of bands is primarily used during the night due to their sensitivity to solar radiation. Band 19 is a visible band used for cloud detection.

The application of the bands on the GOES–12 Imager is as follows. Band 1, visible band, is used for cloud detection and tracking purposes. Band 2, short wave window band, is used for skin temperature calculations during the night and, along with Band 4, is useful in differentiating between ice and water clouds, and fire detection and characterization. Band 3, the water vapor band, is important in helping to delineate moist and dry regions of the troposphere, and Band 4, the long wave window band, is used to identify cloudy regions and in helping to define skin temperature in clear areas. Finally, the GOES-12 Imager Band 6, CO_2 absorption band, is primarily used in helping to define the cloud top height and effective cloud amount (Jung et al, 2004).

There are no existing bands on board the Imager, which are close enough to be considered useful in detecting SO_2, although the broad "water vapor" band does acquire some of its signal from the SO_2 absorption feature near 7.3 µm (Fig 2B).

An absorption spectra for SO_2 is shown in Figure. 2. There are two absorption regions. A strong absorption region is centered around 7.3 µm. A second, weaker, absorption region is located around 8.7 µm. Of all the bands on both the Sounder and the Imager, Band 10 of the GOES Sounder (7.46 µm central wavelength, Table 1) comes the closest to

being located within a SO_2 absorption band. An example of this is shown in Figure 2A. Given the proximity of Band 10 to the "7.3 µm" for extreme events it should be possible to detect SO_2 plumes resulting from volcanic eruptions, provided the plumes are within the geographical coverage of the GOES-12 Sounder.

A technique for displaying a potential SO_2 plume is by generating a "band difference" image based on the 7.46 µm (sensitive to Sulfur Dioxide) and a CO_2 absorption band (Band 5, 13.3 µm and not sensitive to SO_2). In this case Band 5 is chosen because the weighting function (i.e. the region or vertical layer of the atmosphere these spectral bands are most sensitive to changes) for both bands peak around the same region of the atmosphere. Therefore, the resulting derived image will in theory have subtracted the effects of the background temperature and more effectively portray the SO_2 plume. Of course the effects due to Water Vapor are not removed, as one would expect given a technique utilizing a full retrieval of SO_2.
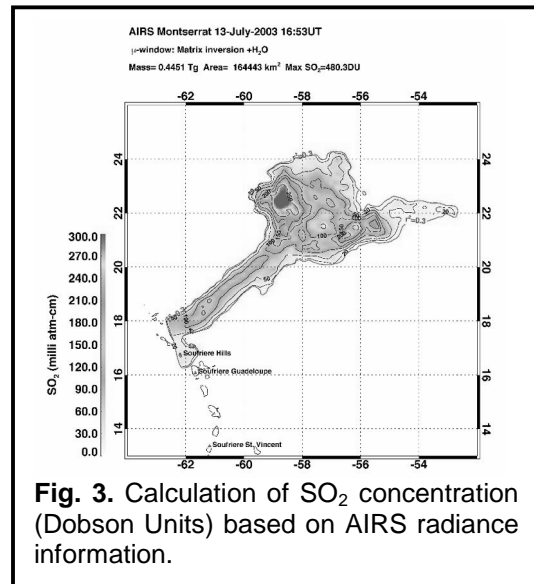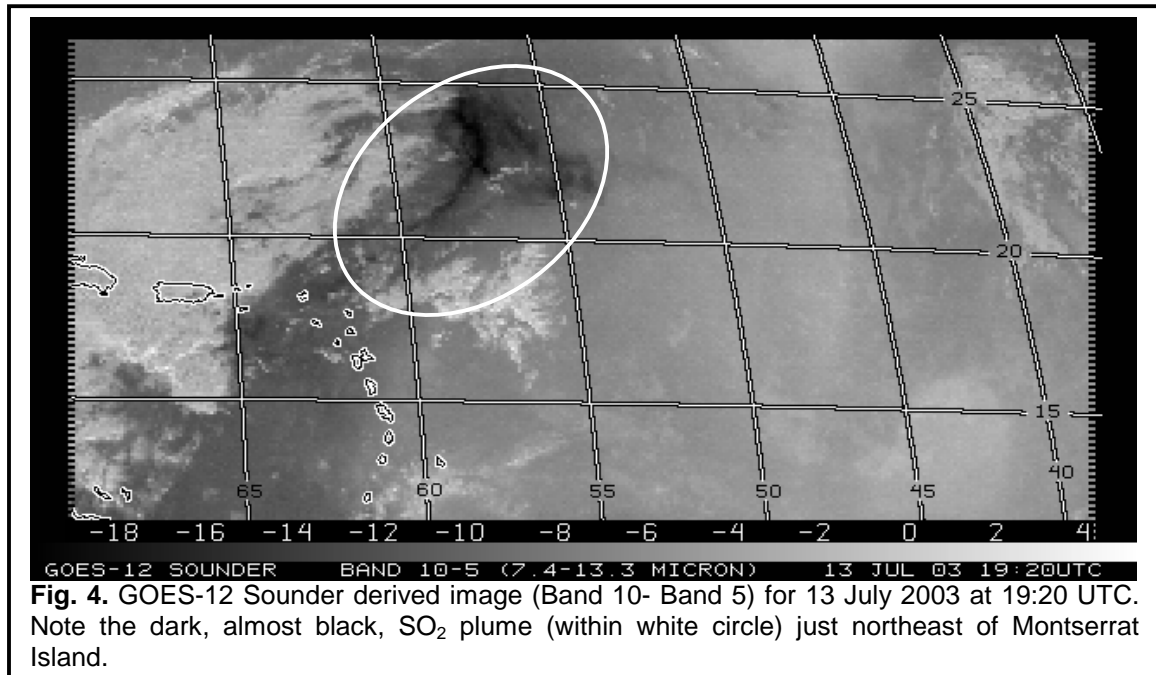

Fig. 3. Calculation of SO_2 concentration (Dobson Units) based on AIRS radiance information.

An example is shown in Fig. 4. The derived image is from 19:20 UTC on 13 July 2003, less than three hours after the quantitatively derived analysis of Figure 3. This GOES Sounder example also shows that the SO_2 plume has a unique signature and can therefore be used to identify plumes not having a priori information. In the derived image the black signature is the SO_2 plume. The white portion of image is cloud and the

gray area is clear sky. Note the similarity of the SO_2 plume in the GOES-12 Sounder derived image and the quantitatively retrieved information in Figure 3 (Prata et al, 2003).

Fig. 4. GOES-12 Sounder derived image (Band 10- Band 5) for 13 July 2003 at 19:20 UTC. Note the dark, almost black, SO_2 plume (within white circle) just northeast of Montserrat Island.
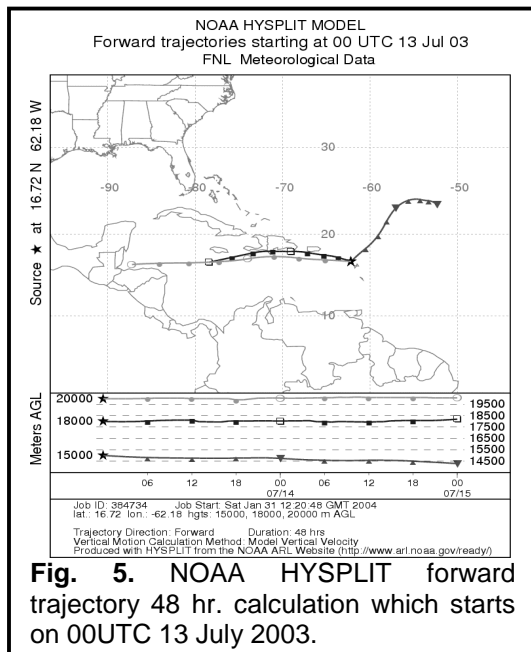
3. Case Study

The first eruption of the Soufriere Hills Volcano, Montserrat occurred late in the evening of 12 July 2003 (around 0230 UTC, 13 July 2003), triggered by a major collapse of the lava dome (Ellrod and Schreiner 2004). This major eruption spewed an ash cloud over 15 km high based on an IR estimate by the Washington VAAC. Over the course of the next three days, three more eruptions took place, but none of them were as dramatic as the initial explosion. A calculation of SO_2 concentration (Dobson Units) based on AIRS radiance information (Fig. 3) from 13 July at 1653 UTC shows a plume extending toward the northeast from Montserrat Island. A corresponding derived image based on the Band 10 minus Band 5 brightness temperature data for 1920 UTC on 13 July is shown in Figure 4.

Using a trajectory model, NOAA HYSPLIT Model, forward trajectories were calculated starting at 00 UTC 13 July 2003. Input into the model is the Global Forecast System (GFS). Trajectories were calculated for three different levels, 15,000 ft (4.8 km.), 18,000 ft (5.5 km.), and 20,000 ft (6.0 km.). The trajectories are shown in Figure 5. The trajectories show that at the two higher levels parcels of air would be moving in a more or less westward direction. But at the 4.8 km. level a parcel began moving to the northeast and by 00 UTC on 14 July the motion was in a more eastward direction. This upper level trajectory is confirmed by looking at a loop of the derived imagery focusing on this volcanic event. Such a loop is shown in Figure 6.

This series of images at six hourly intervals begins at 01:20 UTC on 13 July 2003 (just prior to the major eruption of Soufriere Hills Volcano) and extends until 19:20 UTC on 15 July 2003. The volcano erupted at approximately 02:30 UTC on 13 July. The second image of the loop shows an overall darkening of cloud and its immediate surroundings just northeast of Montserrat Island. This is significant in the determination that an eruption occurred, since Imager IR techniques did not identify the presence of volcanic ash at this time. By 13:20 UTC the plume has fully emerged and is beginning to move northeast of the island and away from the cloud deck, which is

moving over Puerto Rico and Santo Domingo along the eastern edge of the displayed area. From 13:20 UTC on 13 July until 01:20 UTC on 14 July the SO_2 plume is distinctly seen in the derived image and can be seen to trace out a northeastward track. By 01:20 UTC (14 July) the initial plume (note area within the white circle) is located between 50W and 55W and north of 20N.

Fig. 5. NOAA HYSPLIT forward trajectory 48 hr. calculation which starts on 00UTC 13 July 2003.

Beyond this time period the "signature" of the SO_2 plume is diffuse at best. From 07:20 UTC on 14 July through 19:20 UTC on the same day there are still remnants of the SO_2 "vapor trail." The diffuse plume (between 40W and 50W and north of 20N) is also faintly detectable. By 07:20 UTC on 15 July 2003 and beyond the SO_2 signature plume is not noticeably detectable via the derived difference image of the GOES Sounder. Of course it is possible that a full SO_2 retrieval (as opposed to a channel difference) might better detect the plume.
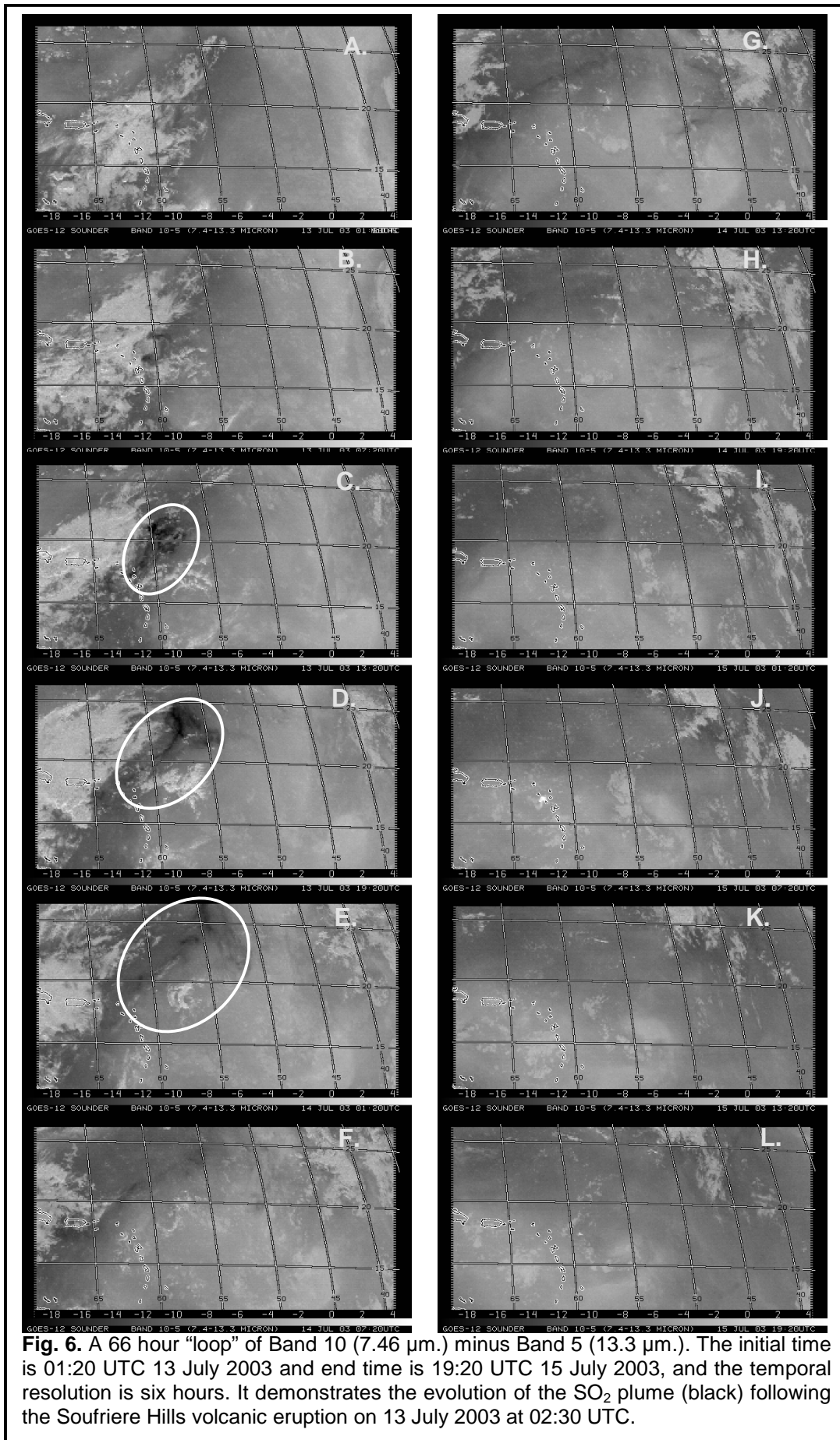
There were three additional volcanic eruptions on Montserrat Island that occurred within the time of the loop displayed in Figure 6. One occurred shortly after midnight local time (~06:00 UTC) on 14 July 2003. Another eruption took place on 15 July 2003 at approximately 05:30 UTC.

Signatures for both eruptions can be seen on the 07:20 UTC (14 July 2003) and 07:20 UTC (15 July 2003) images. But for both cases no detectable SO_2 was observed. This may be due to at least two factors. First, the ash cloud may be higher than the SO_2, itself. Since Band 10 (7.46 µm.) is also sensitive to water vapor, the observation would "saturate out" or be opaque to anything beneath the cloud. Second, whatever SO_2 that may have been expelled during these two eruptions was below the detectable tolerances of the GOES Sounder Band 10. This certainly is possible given the relatively coarse resolution (10 km at the satellite sub point) and due to the spectral width of the band is offset of the absorption band of SO_2.

4. Summary & Future Work

The GOES Sounder can be used to identify plumes of SO_2 as a result of volcanic eruptions. Although Band 10 (7.46 µm) was originally designed for the detection of middle and upper level water vapor, the spectral width of this particular band is coincident with an absorption spike characteristic of Sulfur Dioxide. The spatial resolution of the GOES Sounder is coarser than the MODIS and AIRS, but, because of its geostationary orbit, the GOES is capable of providing high temporal resolution. Of course more cases should be investigated. This will allow for a more complete and thorough examination of the evolution of a SO_2 plume episode.

Of greater interest is that with the introduction of the next series of geostationary platforms, GOES-R and beyond, the detection and identification of SO_2 resulting from volcanic eruptions will take a quantum step forward. This next generation of GOES will have improved spatial resolution characteristics for both an Imager and Sounder instrument. In addition, the suite of bands will be increased exponentially for the Sounder and bands for the Imager will be designed for the detection of SO_2, as opposed to the serendipitous band selection on the current GOES remote sensing instruments.

Fig. 6. A 66 hour "loop" of Band 10 (7.46 μm.) minus Band 5 (13.3 μm.). The initial time is 01:20 UTC 13 July 2003 and end time is 19:20 UTC 15 July 2003, and the temporal resolution is six hours. It demonstrates the evolution of the SO_2 plume (black) following the Soufriere Hills volcanic eruption on 13 July 2003 at 02:30 UTC.

5. Acknowledgements

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