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Using the GOES Sounder to monitor upper level SO_2 from volcanic eruptions

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[1] This study explores the sensitivity of the Geostationary Operational Environmental Satellite (GOES) Sounder observations to atmospheric loadings of SO_2.from volcanic eruptions. The GOES Sounder offers a more rapid refresh rate than similar instruments on board polar-orbiting satellites, such as the High-Resolution Infrared Radiation Sounder (HIRS) carried on the NOAA and MetOp spacecraft. One of the GOES Sounder's 19 channels is in an SO_2 absorption band. Simulations demonstrate that this channel, centered at approximately 7.4 mm, when combined with other channels, can detect the presence of large amounts of SO_2 (e.g., greater than 50 DU) in the upper atmosphere (e.g., above 8 km). The GOES Sounder can also provide upper limits of the amount of upper level SO_2, provided the atmospheric altitude of the SO_2 is known. The sensitivity is demonstrated on two volcanic eruptions of the Soufrière Hills Volcano on the island of Montserrat. Through use of the GOES Sounder measurements, the advection and rapid spreading of the plume are easily observed. Efforts to fully characterize the plume size and transport are hampered by the limited spatial coverage of the current GOES Sounder.

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1. Introduction

[2] This paper describes techniques that are being developed for determining the location and mass loadings of volcanic plumes of sulfur dioxide (SO_2) using Geostationary Operational Environmental Satellite (GOES) Sounder observations. The ultimate purpose of this research is to provide satellite observations to support operational procedures for the avoidance of hazardous volcanic plumes by aircraft using existing and future satellite systems. Detection of SO_2 can also be useful in monitoring ash clouds when SO_2 is released along with ash during a volcanic eruption [*Realmuto*, 2000]. While SO_2 and ash plumes do not always follow the same post eruption trajectories [*Seftor et al.*, 1997], monitoring SO_2 clouds does provide insight for locating possible regions of volcanic ash. Explosive eruptions with SO_2 plumes also have short-term impacts on monitoring climate signatures. Oxidation of sulfur dioxide yields sulfate aerosol particles that reflect sunlight back into space, reducing the energy gains of earth. Monitoring of SO_2 volcanic emissions is therefore useful for climate studies.

[3] Several satellite systems have been used to detect and monitor SO_2 in the atmosphere. The ultraviolet Total Ozone Mapping Spectrometer (TOMS) and the Ozone Monitoring Instrument (OMI) instruments provide a long-term quantitative data record of volcanic SO_2 production [*Carn et al.*, 2003]. Spectral signature methods applied to the High-Resolution Infrared Radiation Sounder (HIRS), using measurements at 7.3, 8.5, 11, and 12 mm, have been successful in detecting volcanic plumes [e.g., *Baran et al.*, 1993; *Ackerman and Strabala*, 1994; *Ackerman*, 1997; *Yu and Rose*, 2000; *Prata et al.*, 2003]. The NASA's Moderate resolution Imaging Spectrometer (MODIS), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Thermal Infrared Multispectral Scanner (TIMS) have all been used to provide insight in the problem of volcanic SO_2 plume detection [e.g., *Corradini et al.*, 2003; *Watson et al.*, 2004; *Realmuto et al.*, 1997]. High spectral resolution observations from the Atmospheric Infrared Sounder (AIRS) on the EOS Aqua platform are also very capable in studying SO_2 plumes from volcanoes [e.g., *Carn et al.*, 2005; *Prata and Bernardo*, 2007]. These instruments are all on polar orbiting satellites. *Rose and Mayberry* [2000] made use of the 30 min temporal sampling of the GOES imager to study the eruption of Soufrière Hills in 1997–1999. *Prata et al.* [2007] and *Prata and Kerkmann* [2007] have recently demonstrated the value of geostationary platforms for monitoring volcanic plumes using the Meteosat Second Generation (MSG), Spin Enhanced Visible and Infrared Imager (SEVIRI). This paper exploits the

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Table 1. Central Wavelengths of the 19 Bands on the GOES-12 Sounder

Sounder Band	Central Wavelength, mm
1	14.71
2	14.37
3	14.06
4	13.64
5	13.37
6	12.66
7	12.02
8	11.02
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
19	0.65

temporal advantage of observing volcanic plumes from the GOES Sounder.

2. GOES Sounder

[4] The GOES-8 through GOES-12 Sounders [*Menzel and Purdom*, 1994; *Menzel et al.*, 1998] measure emitted radiation in 18 thermal infrared (IR) bands and reflected solar radiation in one visible band (Table 1). GOES-12 Sounder bands 1 through 5 are long-wave CO_2 absorption bands, primarily used for the retrieval of atmospheric temperature and effective amount of clouds. These first five bands have weighting function peaks in different layers of the atmosphere. Bands 6, 7, and 8 are atmospheric "window" bands, although bands 6 and 7 are additionally sensitive to low-level moisture. The fourth midrange 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 at a higher level than band 11, and band 11 at a higher level than band 12. Finally, bands 13 through 18 are short-wave IR bands that are mainly temperature-sensitive, and hence are used in the quantitative determination of atmospheric temperature profile. This final group of bands is used mostly at night because of their sensitivity to reflected solar radiation. Band 19 is a visible band used for cloud detection.

[5] The GOES Sounder detectors have an Instantaneous Geometric Field Of View (IGFOV) of approximately 242 microradians, or 8.7 km at the subsatellite point (e.g., 0° and 75°W for the eastern GOES satellite); however, the IGFOV spacing (sampling) at the subsatellite point is only every 10 km (280 microradians), so the Sounder is generally considered to have a "nominal resolution" of 10 km. The signal is quantized and the 13 bit data transmitted to the GOES receiving facilities. The Sounder is primarily used to retrieve atmospheric profiles of temperature and moisture (and the corresponding atmospheric stability parameters), total column ozone, surface skin temperature and cloud top pressure. Several of the GOES Sounder bands are also used for depicting midlevel atmospheric flow. The bands chosen for the GOES Sounder were not specifically selected for remote sensing of volcanic eruptions and for detecting SO_2, nor are the spatial resolution and the geographical coverage of GOES comparable to those of the polar orbiters. But, an advantage of the geostationary satellites is the ability to provide high temporal resolution information. The GOES Sounder provides hourly coverage over the continental United States (CONUS), although coverage over the Caribbean is less, approximately every 3 h. To maximize its signal-to-noise ratio, the GOES Sounder dwells on each pixel much longer than the GOES Imager. The downside of this longer dwell time is that the Sounder covers much less geographic region in a given amount of time. This fact, coupled with the requirement of the GOES Sounder to supply hourly images over the CONUS region to augment hourly cloud observations, means that the ability of the Sounder to scan regions outside the CONUS is limited. Each hour the GOES Sounder scans the CONUS region, taking approximately 40 min. For GOES-East, the remaining 20 min are left to scan other non-CONUS regions. Currently this means covering the Caribbean region one third of the time and the Gulf of Mexico the remaining two thirds of the time.

[6] Sulfur dioxide has a strong spectral absorption region centered near 7.4 μm, and a second, weaker, absorption region located near 8.7 μm. Band 10 of the GOES Sounder (7.43 μm central wavelength; Table 1) lies within an SO_2 absorption band as demonstrated in Figure 1. The proximity of band 10 to the 7.4 μm SO_2 absorption feature suggests that the Sounder may be useful for detecting volcanic eruptions with large amounts of SO_2. We explore this capability.

[7] Figure 2 shows example images of GOES-12 Sounder brightness temperature difference between $BT_{7.4}$ and $BT_{13.4}$ over the Caribbean region on 13 and 14 July 2003. As will be explained later, differencing the 7.4 μm and 13.4 μm bands can identify SO_2 plumes. The SO_2 plume from the eruption of the Soufrière Hills Volcano on the island of Montserrat is apparent in these images (circled region). Located at 16.72°N, 62.18°W at 915 m (~3,000 ft), this volcano results from the subduction of the Atlantic plate under the Caribbean plate. The volcano became active in 1995 and has continued to erupt since then. On 12 July 2003 a series of volcanic eruptions began at the Soufrière Hills volcano; over a 3-d period four eruptions took place, with ash clouds reaching up to 12 km. In this example, large negative brightness temperature differences of $BT_{7.4}$-$BT_{13.4}$ indicate the presence of the volcanic plume.

3. GOES Sounder Simulations

3.1. SO_2 Plume Detection and Total Loadings Retrieval Methods

[8] Algorithms to detect the presence of volcanic ash plumes have been developed and applied to real-time observations. For example, several aerosol remote sensing techniques have been developed using measurements from the Advanced Very High Resolution Radiometer (AVHRR) [e.g., *Prata*, 1989; *Barton et al.*, 1992; *Rose et al.*, 2000; *Pavolonis et al.*, 2006]. The volcanic ash plumes often generate negative brightness temperature differences between BT_{11} and BT_{12} and *Prata* [1989] has demonstrated the detection of volcanic aerosols using two infrared

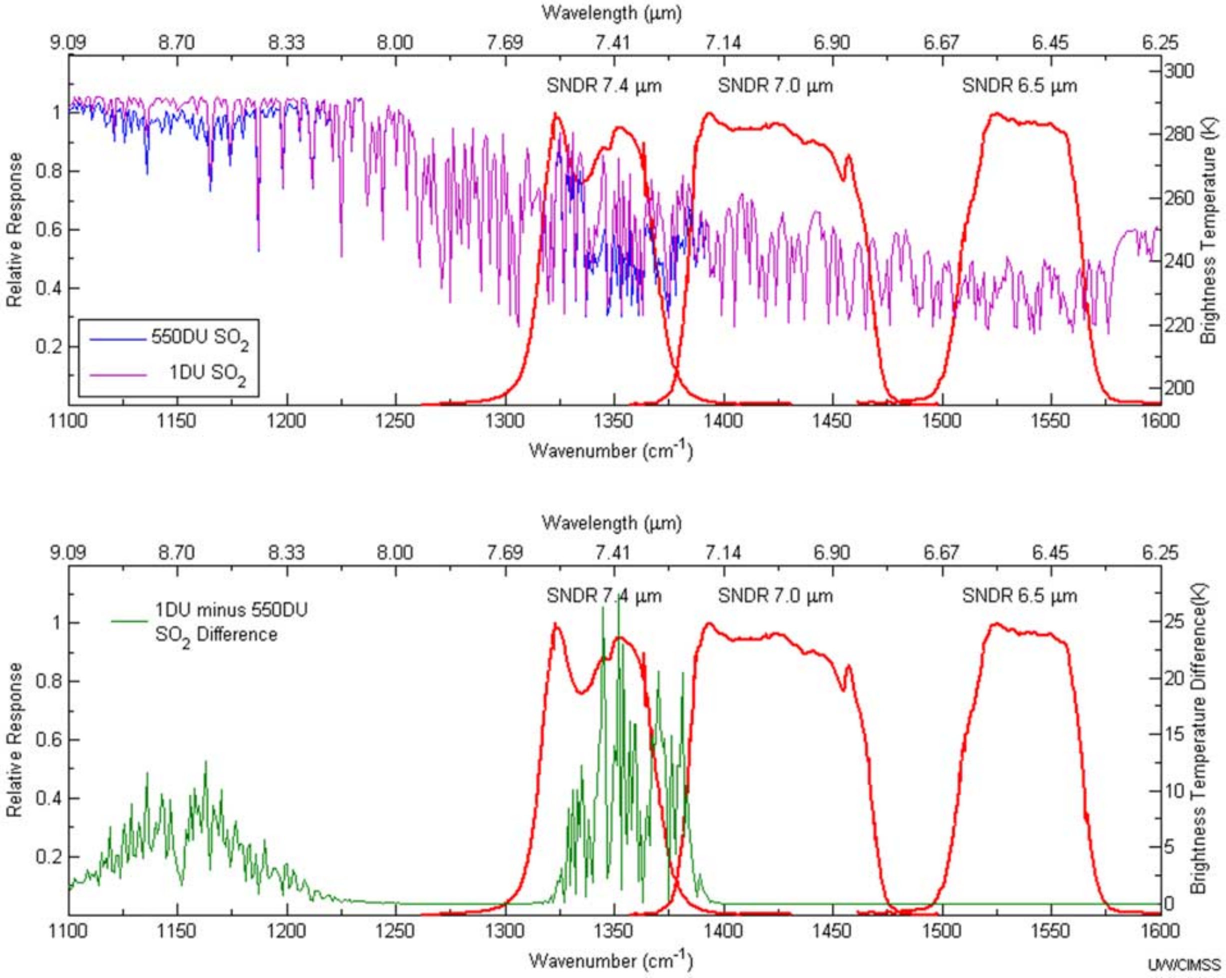

Figure 1. (top) The purple and blue lines represent theoretical simulations of brightness temperatures (right axis) over the 11 to 1600 cm^{-1} wave number (wavelength in microns is on the top axis) for an atmosphere with 1 and 550 DU of SO_2. The red line represents the GOES Sounder spectral response function (left axis) of bands 10, 11, and 12 over the same wave number range. (bottom) The green line represents the difference in the earth-emitted infrared brightness temperature (right axis) between an atmosphere with a total SO_2 load of 1 DU and a SO_2 "enriched" atmosphere with 550 DU as a function of wave number (wavelengths in mm are given at the top of the figure). The red lines represent the spectral response function of the same GOES channels as in Figure 1 (top).

channels. *Ackerman and Strabala* [1994] applied observations at 8.6, 11 and 12 μm from the HIRS instrument to study the Mt. Pinatubo stratospheric aerosol H_2SO_4. *Pavolonis et al.* [2006] supplemented the infrared reverse absorption technique with visible and near-infrared information to allow for nonnegative brightness temperature differences associated with ash clouds in moist environments. *Prata et al.* [2007] used the European operational satellite SEVIRI, with three channels sensitive to SO_2 (4, 7.3 and 8.6 μm), AIRS and OMI to study the transport of a volcanic SO_2 plume from an eruption on Montserrat.

[9] In this study, SO_2 plume detection is based on a "band difference" method, the brightness temperature difference between 7.4 μm band (sensitive to SO_2) and a CO_2 absorption band (band 5, 13.4 μm that is not sensitive to SO_2). The 13.4 mm band is chosen because the weighting functions (i.e., the vertical profiles of sensitivity to atmospheric changes) for both bands peak at roughly the same altitude.

[10] To study the capability, simulations of the GOES-12 Sounder observations were performed with the line-by-line LBLRTM [*Clough and Iacono*, 1995] version 8.4 and the spectroscopic database HITRAN [*Rothman et al.*, 1992] version 2000 (with AER update 1.1). Inputs consisted of temperature and water vapor profiles from either radiosonde observations or GOES retrievals. Sulfur dioxide profiles were constructed by inserting the gas in large concentrations at a number of different atmospheric levels, with total amounts ranging from 10 to 640 Dobson Units (DU). The very high spectral resolution information produced by LBLRTM was reduced to 0.1 cm^{-1} by boxcar averaging. The resulting data were then convolved with the GOES-12 band 10 spectral response function to produce transmittances with which to simulate radiances.

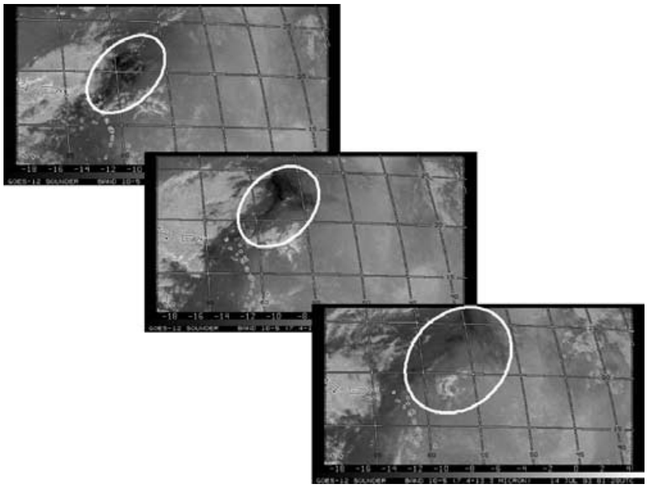

Figure 2. The GOES Sounder image of the brightness temperature difference for 2003 on (top) 13 July 1320 UTC, (middle) 13 July 1920 UTC, and (bottom) 14 July 0120 UTC. The ellipse indicates the SO_2 plume generated by the eruption of the Soufrière Hills Volcano on the island of Montserrat.

[11] Figure 3 shows a simulation of the GOES-12 Sounder observations in the presence of a SO_2 volcanic plume. The sensitivity is demonstrated by plotting $BT_{7.4}$-$BT_{13.4}$ versus SO_2 total column amount in Dobson Units (DU or milli-atm-cm) for four different plume altitudes: 3, 6, 12, and 16 km. The temperature and moisture profiles for this simulation are from the radiosonde observations of Gaudeloupe, French West Indies (16.27°N, 61.53°W) at 1200 UTC on 13 July 2003. The Sounder channels have very little sensitivity to the presence of low-level SO_2 plumes, because of the water vapor absorption in the 7.4 mm band. The simulations do show sensitivity to higher-altitude plumes, provided the SO_2 column loading is greater than about 50 DU.

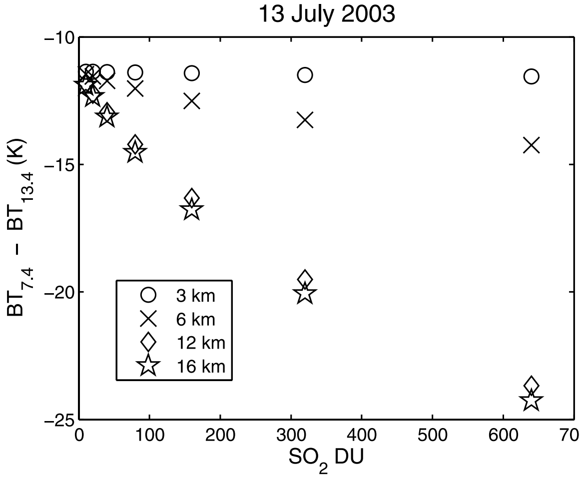

Figure 3. Simulated GOES-12 Sounder brightness temperature difference between the 7.4 and 13.4 mm bands as a function of column SO_2 amounts (DU) for four different plume altitudes. The temperature and moisture profiles are from Gaudeloupe, French West Indies (16.27°N, 61.53°W), at 1200 UTC on 13 July 2003.

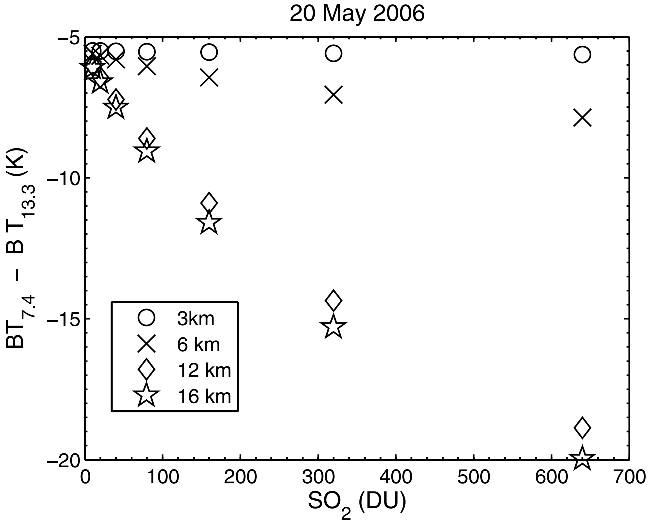

Figure 4. Simulated GOES-12 Sounder brightness temperature difference between the 7.4 and 13.4 mm bands as a function of column SO_2 amounts (DU) for four different plume altitudes. The temperature and moisture profiles are from Gaudeloupe, French West Indies (16.27°N, 61.53°W), at 1200 UTC on 20 May 2006.

[12] Of course the $BT_{7.4}$-$BT_{13.43}$ difference is also a function of the atmospheric temperature and moisture profile. This is demonstrated in Figure 4, which is the same as Figure 3 except for a radiosonde launch at 1200 UTC on 20 May 2006. Thus, as is the case with all IR retrieval approaches, knowledge of the clear-sky background signal

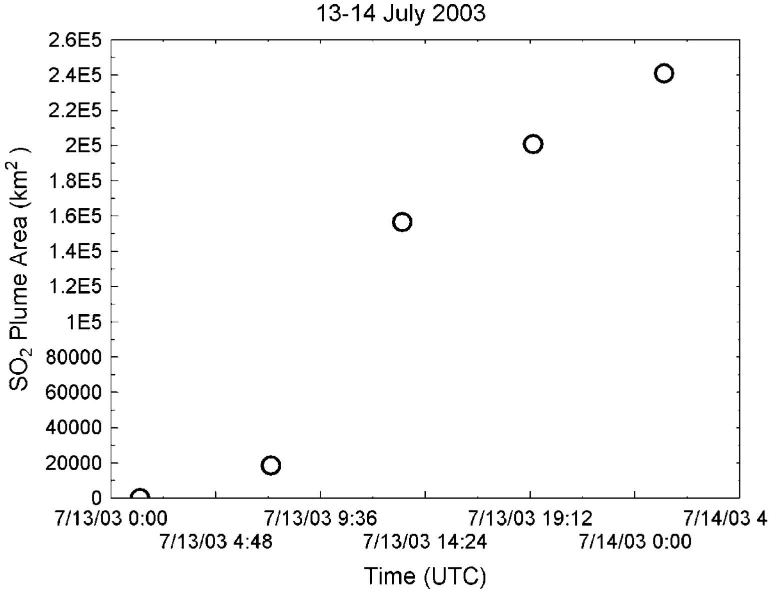

Figure 5. GOES Sounder estimated SO_2 plume area coverage of the 13–14 July 2003 eruption as a function of time. The circles represent the area at a given time of the SO_2 plume, when the plume lies totally with the geographic regions sampled by the GOES Sounder.

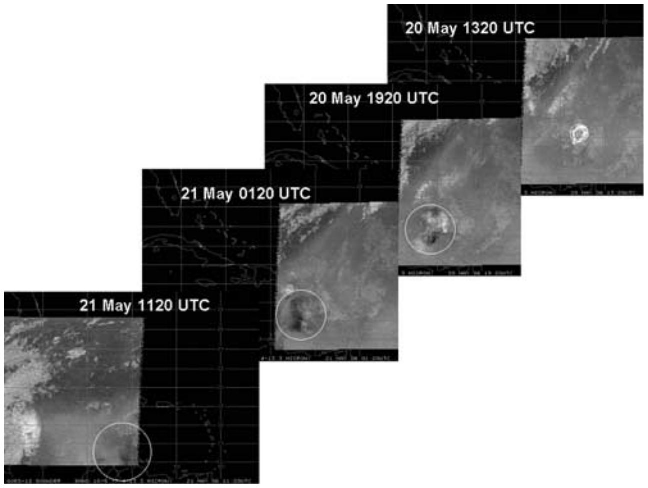

Figure 6. GOES Sounder image of brightness temperature difference ($BT_{7.4}$-$BT_{13.4}$) for four time periods on 20 and 21 May. The ellipse indicates the ash and SO_2 plumes generated by the 2006 eruption of the Soufrière Hills Volcano on the island of Montserrat.

is important for accurate retrievals. That signal can be derived from simulations or from the GOES-12 measurements under cloud free conditions. Such a "clear sky brightness temperature" is routinely determined by NOAA operations.

[13] Therefore, the signal of the SO_2 in the GOES Sounder is determined by the atmospheric temperature and moisture profile, the amount of SO_2 and its vertical location in the atmosphere. With only one channel sensitive to the SO_2 plume, the GOES Sounder can detect the location of the plume, but the height of the plume must be assumed or acquired from additional information.

3.2. Case Studies

[14] We demonstrate the GOES Sounder capability through two case studies; both are eruptions of the Soufrière Hills Volcano on the island of Montserrat. The first took place during mid-July 2003 (see Figure 2) and the second event started at about 1100 local time on 20 May 2006 when an eruption sent a plume of ash and volcanic gases approximately 17 km (55,000 feet) into the atmosphere.

[15] The SO_2 plume in July is identified in the analysis of $BT_{7.4}$-$BT_{13.4}$ image (see Figure 1). Comparison with clear sky scenes indicates a detection threshold for the SO_2 plume was defined as $-10 \leq BT_{7.4}\text{-}BT_{13.4} \leq -5$, and the area computed from the flagged pixels. Figure 5 shows the rapid expansion of the eruption. The GOES Sounder first detects the plume on 13 July 2003 at 0720 UTC. By 0120 UTC on 14 July, the plume size has expanded in a near linear fashion to over 240,000 km^2. On 13 July at 1320 and 1920 UTC, the GOES Sounder analysis estimates a plume size of 156,600 and 200,800 km^2, respectively. This is consistent with the 164,443 km^2 area of the plume on 13 July 1633 UTC from AIRS by *Prata and Bernardo* [2007]. After 14 July, the plume either moved out of the range of the GOES Sounder or is shielded by cloud.

[16] The second case study is the eruption on 20–22 May 2006 with a major lava dome collapse. At approximately 1140 UTC, an explosion resulted in an ash cloud ejected to nearly 17 km. A large area and rapidly expanding ash plume is seen in the 1320 UTC Sounder image analysis (Figure 6). At this time, the ash plume shields the presence of the SO_2 and so is not observed by the Sounder. The plume drifts westward and by 21 May 0120 UTC the plume is moving out of the region sampled by the GOES Sounder. Figure 7

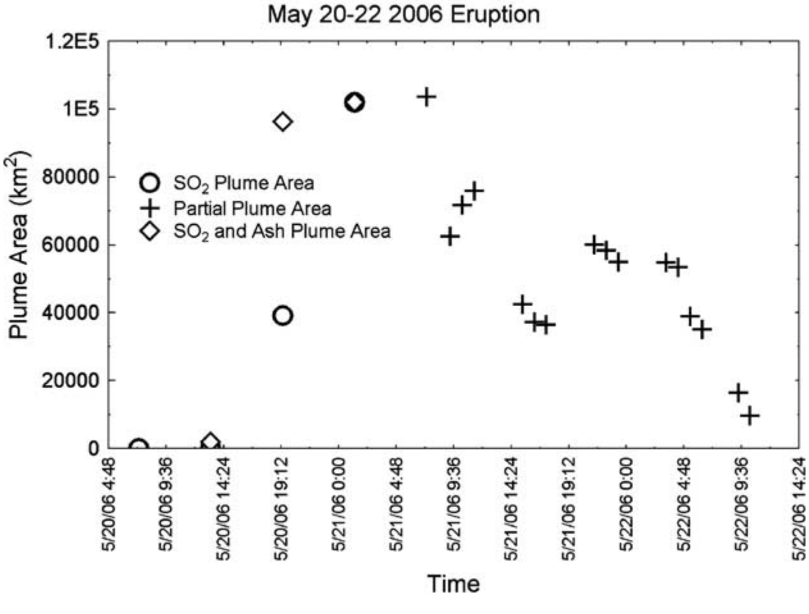

Figure 7. GOES Sounder estimated SO_2 plume area coverage of the 20–22 May 2006 eruption as a function of time. The circles represent the area at a given time of the SO_2 plume, when the plume lies totally within the geographic regions sampled by the GOES Sounder. The diamonds indicate the area covered by both SO_2 plume and ash cloud.

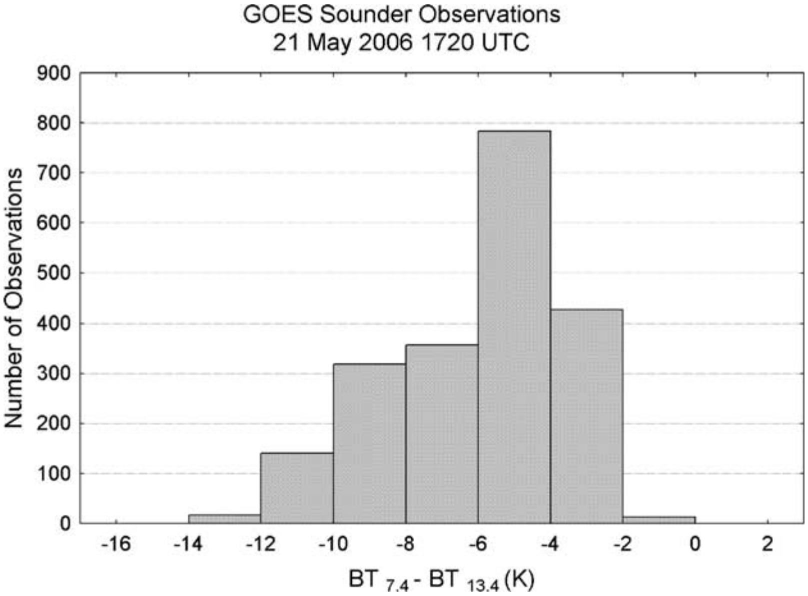

Figure 8. Histogram of the observed $BT_{7.4}$-$BT_{13.4}$ on 21 May 2006 at 1720 UTC.

shows the estimated SO_2 plume area from the GOES Sounder, defined as $-10 \leq BT_{7.4}\text{-}BT_{13.4} \leq -2$. By 21 May the area of the plume has expanded to 102,000 km^2. The partial image of the plume on 21 May 0720 UTC is 103,600 km^2. Because of the sounder scan coverage, only part of the plume could be monitored for certain time periods. On 20 May 1700–1840 UTC OMI analysis indicates an area of 202,457 km^2. This is approximately 5 times the area estimated by the Sounder identified SO_2 plume at 1920 UTC of 39,100 km^2. The OMI is more sensitive to the presence of SO_2, so it is expected that the OMI would estimate a larger coverage. In addition, the volcanic ash cloud shields the GOES Sounder SO_2 estimate. If both the ash and SO_2 plume are included in the GOES estimates, then the area covered by the volcanic plume is 96,300 km^2, about half the size of the OMI estimate.

[17] Figure 8 is a histogram of the $BT_{7.4}$-$BT_{13.4}$ difference for the SO_2 plume region on 21 May 2007 at 1720 UTC. As seen previously, the differences are a function of the SO_2 plume height and amount. Without an estimate of the altitude, the GOES cannot estimate the gases loading. This ambiguity, which is due to having only one channel sensitive to the absorber in question, should be alleviated with the advent of sensors that have additional bands that respond to changes in SO_2 for the GOES-R Advanced Baseline Imager (ABI). This plume was estimated to reach 20 km [e.g., *Prata et al.*, 2007]. The histogram indicates few observations of $BT_{7.4}$-$BT_{13.4}$ less than -12K. If the altitude of the plume is estimated, the GOES observations may place an upper limit on the loading of SO_2. Simulations were performed using the retrieved temperature and moisture profile in the vicinity of the SO_2 plume region. In the "plume free" case, the observed band 10 brightness temperature was 269.92 K, and the calculated was 269.47 K, providing confidence in the simulation procedure. The observations were simulated assuming SO_2 concentrations ranging from 40 to 640 DU imbedded in an altitude between 19 and 21 km and 18–20 km. The simulations would indicate that the SO_2 total loading would have to be less than approximately 150 DU. The AIRS estimates of total SO_2 for this eruption on 20 and 21 May range from 10 to approximately 100 DU [*Prata et al.*, 2007]. The GOES Sounder upper limit is a bit high, suggesting its greatest value is in tracking the movement of the plume.

4. Summary

[18] Plumes of SO_2, along with other gases and ash, can be expelled from erupting volcanoes. Detection of these SO_2 plumes is important for both aviation safety and monitoring of climatic effects. The capability of the GOES Sounder to provide information on these eruptions is explored in this paper.

[19] The GOES Sounder observations can delineate SO_2 atmospheric loading that results from a volcanic eruption. The brightness temperature difference between 7.3 μm and 13.3 μm bands is associated with SO_2 presence and loading. The 7.3 μm band radiance based SO_2 retrieval is sensitive to SO_2 height, relative to the altitude of water vapor contained in the atmosphere. Simulations indicate that the plumes lower than 3 km will not be detected, in agreement with *Prata and Kerkmann* [2007].

[20] This study demonstrates the advantages and disadvantages of using the current GOES Sound to track SO2 plumes from volcanoes. The temporal resolution of the Sounder delineates the evolution of the plume. While the current GOES Sounder has shown the ability to track and monitor upper level SO_2 amounts from volcanic activity, its spatial resolution, timeliness and coverage rate limits the information that can be depicted relative to the spatial and temporal information provided by geostationary imagers. Estimates of the area coverage of the 20–22 May 2006 and July 2003 eruptions of from Soufrière Hills volcano on Montserrat are generally smaller than that retrieved using instruments more sensitive to the presence of SO_2. Estimating the total loading of SO_2 requires a good estimate of the vertical distribution of the plume, so that the GOES Sounder

can only provide an estimate of the upper bounds of upper tropospheric SO_2 amounts, only if the altitude of the plume is known.

[21] These limitations will be reduced with the advent of the Advanced Baseline Imager (ABI) in the GOES-R era. The ABI will improve the monitoring of upper level SO_2 [*Schmit et al.*, 2005], because of the additional spectral bands, improved spatial resolution and improved temporal resolution. For example, one of the ABI water vapor bands has been shifted to better monitor upper level SO_2. In addition, the ABI will carry the 8.5 mm band, similar to SEVIRI. While the ABI is a great improvement over the current GOES Sounder, the spectral sensitivity to a large SO_2 event by a high spectral resolution sounder (e.g., AIRS) is approximately twice that of a broadband imager, such as the ABI.

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