Analysis of MODIS Images from the Nov 03-05 Eruption of Reventador

Comparison of Retrieval Methods, Plume Characteristics, and Data Results from the Nov 04, 2002 Reventador Plume

Abstract

Since late-1999 and mid-2002, MODIS detectors aboard the Terra and Aqua EOS satellites have circled the globe, recording several hundred images each day. Six of the bands that MODIS records are tuned closely with the absorption wavelengths of volcanic ash and SO_2, specifically bands 27-32. The sizeable eruption of Reventador Volcano, Ecuador, during November of 2002 provided an excellent opportunity to test several retrieval methods for estimating SO_2 content of large eruptive plumes. Due to significant prolonged activity, the plume reached a height of 16.8 km asl and a length of over 450 km. Reventador displayed continuous high levels of activity over a period of three days which began on the morning of November 03 and culminated Nov 05; exhalations of ash and gas continued for several weeks, but were insignificant in comparison to the main eruptive event. For the purpose of this project, two MODIS images from Nov 04 were analyzed and compared to other collected data. While the plumes are obvious in the images, a number of difficulties in running the retrievals, mostly associated with opacity of the plume, prohibited the reliable calculation of mass SO_2 and raises the question of reliability in using the MODIS instruments for large eruptions in general.

Introduction

The eruption of Reventador, Ecuador, during early November of 2002 provided one of the first good opportunities to look at a large eruption through the MODIS instruments aboard the Terra and Aqua EOS satellites. This unique opportunity enabled us to observe the eruptive plume through several different wavelengths and combinations thereof, as well as analyze the SO_2 content through several different retrieval methods. The eruption persisted for three days, from Nov 03 through 05, but only data from Nov 04 were analyzed for this project. The reasons for this are as follows. (a) The plume from the Nov 03 image is underdeveloped; that is, the image shows an eruption column with a large umbrella region, but the plume has not traveled far from its source. (b) The location of volcanic clouds in the Nov 05 eruption is questionable, though more intensive analysis of the images would probably reveal them rather plainly. (c) There was simply not enough time during the course of this project to analyze more than a single day's data. (d) Nov 04's images show all or nearly all regions of interest and display elongated and obvious plumes. The other plumes, though not "ideal," are certainly worth looking at and a future analysis of these images could prove to be a worthwhile endeavor.

Reventador is a remote andesitic-basalt volcano that is located roughly 80 km east of Quito. The volcano is very inaccessible due to the surrounding dense vegetation of the western Amazon basin, it's location east of the crest of the Andes, and the presence of thick perennial cloud cover which hides it from view of most Earth-observing satellites.[1,2]

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[1] University of North Dakota's Volcano World website, Reventador page, http://volcano.und.nodak.edu/vwdocs/volc_images/img_reventador.html

Table 1: % Composition of Reventador Lavas

	Pre-Caldera	Post-Caldera
Plagioclase	30-36	30-36
Clinopyroxene	1.1-2.6	3.6-10.1
Orthopyroxene	1.5-4.3	0-3.4
Olivine	Trace	0.2-3.3
Hornblende	1.3-2.1	0-0.6
Iron Oxides	2.4-8.1	2.4-8.1
Silica	57-65	51-59
	1976 Ash	***Nov 2002, Ash***
SiO_2	57.44	58.70
TiO_2	0.79	0.74
Al_2O_3	18.26	17.55
Fe_2O_3	2.38	6.75
FeO	4.24	-
MgO	3.59	3.00
CaO	6.74	6.05
Na_2O	4.14	4.40
K_2O	1.97	2.13
MnO	0.12	0.11
H_2O	0.12	0.33
P_2O_5	-	0.38

Nov 2002 data from IGEPN[3], rest from Hall[4]

Reventador rises 1300m above the caldera floor on which it resides. The caldera, itself, is 3 km wide and displays numerous lava flows and ash deposits which correspond with past eruptions of Reventador. The volcano is also located in a rather odd place, being part of the volcanic chain Cordillera Real, but far east of this chain's axis.

Due to the inaccessibility of Reventador, its official discovery did not occur until 1928 (although the volcano was known to exist from historical ashfalls). Since its discovery, Reventador has had four separate eruptive phases: one in 1944, 1960, 1973, and 1976[5]. Table 1 contains data on the composition of magma and ash collected from Reventador and shows the change and variability of magma composition over time. Moreover, Reventador displays a range of eruptive styles with mostly explosive activity in 1944 and 1960, and mostly effusive activity in 1973 (1976's eruption displayed both styles of eruption in nearly equal magnitudes).

On the morning of November 03, 2002, the volcano awoke with little noticed warning. At 10:00am, UTC, Reventador produced a column of ash to an estimated height of 3 km. The main eruptive phase began around 2 pm, with pyroclastic flows forming along with further growth of the eruptive column. This state of activity continues with ash reaching the coastline at 10pm UTC. On Nov 04, with the eruption still in full swing, the Terra EOS passes overhead at 3:35am and 3:55pm.[6] The main eruptive phase of Reventador appears to have ended early Nov 05, though the exact timing may depend on the definition of "main phase." Smaller exhalations of ash and gas were recorded for several weeks following the eruption. IGEPN provides a small amount of data on gasses from the eruption as well as the composition of the ash, which can be viewed in table 1. Fluorine was measured at a concentration of 33 ppm, Chlorine was measured at 527 ppm, and SO_2 was observed at a concentration of 2162 ppm, during the eruption on November 03, 2002.

The magnitude of this eruption, the size of the plume, the impact on Ecuador, and its recent occurrence all made this eruption an appetizing event to study. Images from the

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[2] GVP/USGS Weekly Volcanic Activity Report for Nov 27- Dec 03
[3] Instituto Geofisico – Escuela Politecnica Nacional website, Ceniza page, http://www.igepn.edu.ec/vulcanologia/reventador/ceniza.htm
[4] *El Reventador, Ecuador; an active volcano in the northern Andes*, Minard Hall, Politecnica vol 5, no. 2
[5] Instituto Geofisico – Escuela Politecnica Nacional website, Historia page, http://www.igepn.edu.ec/vulcanologia/reventador/actividad/historia.htm
[6] Simon Carn, personal communication

Terra EOS overpasses at 0335 and 1555 UTC, Nov 04, were used for the reasons outlined earlier, as well as a TOMS image from 1632 UTC of the same day. There have been few eruptions since the launching of the first MODIS instruments whose magnitudes have rivaled this recent event. This allows us to, for the first time, look at how MODIS performs in observing large plumes and how associated algorithms perform in deriving mass SO_2 from this data. The objectives of this study include: observing the behavior and physical dimensions of the Nov 04 Reventador plumes; comparing the results of several different SO_2 retrievals, including data from both TOMS and MODIS; analyzing the reliability of these retrievals and noting any significant problems that arise in quantifying SO_2 mass; qualitatively analyzing the feasibility of applying these methods of data reduction to other plumes and more urgent situations. This paper will first deal with a description of the methods used in retrieving the data and processing it. It will secondly discuss the characteristics of the raw images and thirdly describe what was done in analyzing them quantitatively. Finally, this paper will cover problems encountered in the processing, analysis, and interpretation of the data as well as look to the future application of these techniques to similar eruptions elsewhere.

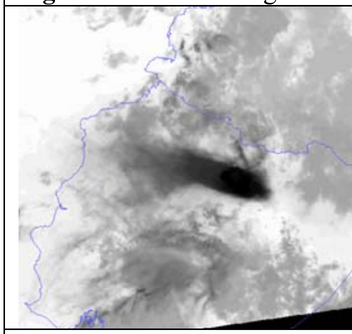
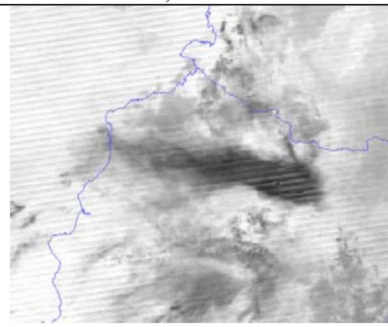
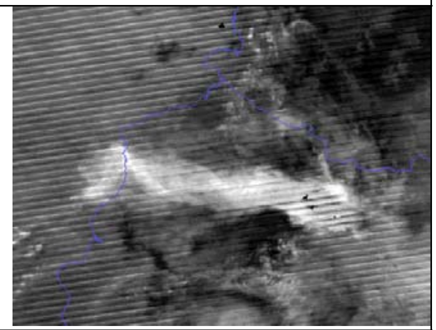
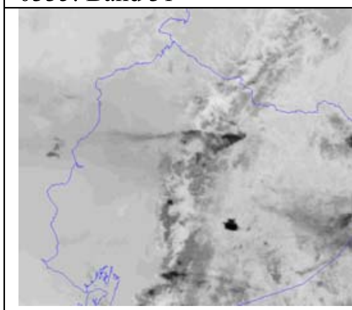
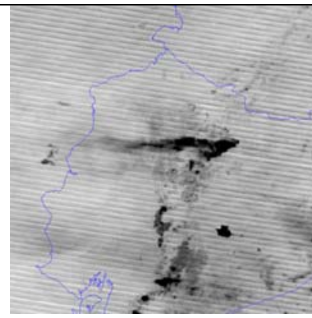
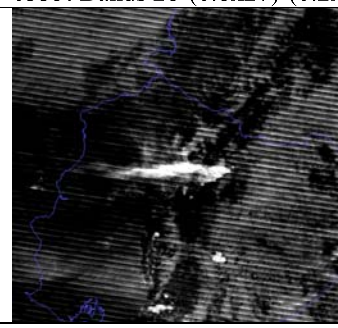
Methods

Upon receiving news of the eruption of Reventador, nine MODIS images were collected from the GSFC DAAC [7] based on requirements that they be within the time frame of the main event and that they cover an area possibly containing the plume. This number was narrowed down to five due to the lack of a plume in some images. From these, as mentioned earlier, two images from Nov 04 were selected to be analyzed. The data were collected via ftp and came in an hdf format, which could be read by the program ENVI 3.4. After creating latitude and longitude files, the data were processed to create a large text file and envi file, which were then processed to create a tdf file. In Terrascan, a master file was created and used with the tdf file to create a grid file, which could be read by the program. With all of this completed, the images could now be looked at and manipulated by Terrascan in bands 27-32. A number of algorithms were performed on the images to best find and measure the dimensions of the plumes, of which the following worked best: band 31, band 28 minus band 27, and band 28 - (0.8 x band 27) – (0.2 x band 31). Band 27 displays infrared data of wavelength 6.7μ and is useful for detecting ash; band 28 measures a wavelength of 7.3μ and detects SO_2, H_2O, and SO_4; band 31 measures a wavelength of 11μ and detects ash, ice, and SO_4. The algorithms listed above were designed to remove the effects of ash from the image in order to see the presence of SO_2 within the plume. These images can be found in figure 1 (the images from the final algorithm are color-reversed).

After viewing the images and measuring dimensions of the plumes, the retrievals were begun. First, an 8.6μ retrieval was run through the "map_so2" program of the IDE software. Before this could be started, an atmospheric profile for the location needed to be found and was collected from a University of Wyoming weather website[8]. The nearest

[7] Goddard Space Flight Center Distributed Active Archive Center, http://acdisx.gsfc.nasa.gov/data/parameter/nofrills.html
[8] http://weather.uwyo.edu/upperair/sounding.html

Figure 1: MODIS Images from 0335 and 1555, Nov 04

		
0335: Band 31	0335: Bands 28-27	0335: Bands 28-(0.8x27)-(0.2x31)
		
1555: Band 31	1555: Bands 28-27	1555: Bands 28-(0.8x27)-(0.2x31)

reliable profile that that was found was for Bogotá, Colombia, which is several hundred miles away. Next, the bad datum points were removed and trends for dew point, temperature, and pressure were analyzed from the data to interpolate values for the elevation thousand marks (5k meters, 6k meters, etc…); after completing this, the data was edited to a format that the program could read and changed to a .atm extension. Next, the envi files that had been created earlier were opened in ENVI 3.4 and modified to RGB files displaying bands 28, 31, and 32. Once this was done, the envi files were again processed to create radiance files (IRAD) with bands 29-32. With all of the required files now created to perform the 8.6μ retrieval, the map_so2 program was run; the files were inputted and default parameters were adjusted to reflect the dimensions of the plume, measured from Terrascan. A background region was selected and analyzed to get a "background emissivity spectrum." This provided the background radiation against which the plume could be measured. Next, sections of the plumes were selected based on apparent background environment and opacity (opaque regions were initially ignored to avoid errant values caused by masking by ash). Once the retrieval had been run, the files were saved and SO_2 maps were viewed; a tonnage SO_2 calculation could be performed by the program with the simple clicking of a button. Once these data were recorded, the process was repeated against another background until all non-opaque regions of the plume had been analyzed; the retrieval was later performed for the entire plume against two backgrounds and omitting no sections.

With the 8.6μ retrieval now completed, the 7.3μ retrieval was begun. The atmospheric profile, again, was reformatted and, this time, changed to a text file. The retrieval, which is actually the product of several cooperating programs, produced a simple black-and-white map of SO_2. Tonnage SO_2 estimates could only be obtained with a large degree of difficulty and hassle; since, based on the characteristics of the images, the values were likely to be faulty, mass SO_2 was not calculated.

To compare these retrievals to a well-known and tested method, a TOMS image from Nov 04 was obtained and analyzed to get a map of the plume and tonnage SO_2 estimates. This was accomplished by contacting an individual who already had the image and by following a TOMS tutorial that was provided by Gregg Bluth.[9]

Data

There was a significant quantity of data that was derived from this study: first the plume's physical dimensions will be covered, followed by a discussion of the data from the 8.6μ and 7.3μ retrievals, and is concluded with a description of results from the TOMS analysis. The plumes, through Terrascan, were measured to find general size and bearing. The eruption at 0335, however, turned out to be unique because it actually produced two plumes moving in nearly opposite directions. At approximately 15.4 km asl, there was a dramatic wind shear that caused the plume to divide between the two zones; this allowed us to interpolate that the main plume, at a reported maximum height of 16.8 km, was 1.4 km thick. This plume was traveling WNW at 282.5 degrees, was approximately 411 km long, and covered an area of roughly 40652 km^2. The secondary plume was very faint, making it impossible to determine the size, though its direction of movement could still be determined to be ESE at 119 degrees. At 1555, the plume had changed somewhat: it was now bearing WSW at 258 degrees and there appeared to be no secondary plume at all. The plume in this image was 458 km long and 30659 km^2. This "shrinking" of the plume's area is likely the result of its fading against the background rather than some unexplained atmospheric constriction of the ash and SO_2. Figure 2 shows the VAAC ash advisory sketches from times near to that of the MODIS images. It is important to note that the raw MODIS image from 0335 is upside-down due to the orientation of the satellite at the time of capture. This is not seen from the Terrascan images, which were corrected for the effect.

Because the 8.6μ retrieval produced a mosaic of images, there were a number of problems encountered with getting total mass SO_2. First, the tonnage estimates only applied to the specific region that each retrieval targeted, but these were summed to get a number for the entire process. Despite overcoming this problem, there were others that could not be avoided. For one, there were holes in this "mosaic of data" which appeared due to imprecise placement of selection boxes that were analyzed from the image. Secondly, the interior of the plume, which appeared opaque, was not included and so there is likely a very significant amount of SO_2 missing from the retrieval. In figures 3 and 4, the SO_2 maps are shown and overlain on a Terrascan image of the same plumes to give an idea of the extent of measurements. Keeping in mind that the tonnage values are only an estimate of the amount of SO_2 within the selected regions shown in figure 3 and 4, total SO_2 at 0335 is 47.3 kt and at 1555 is 106.7kt. The data from the 1555 retrieval is thrown into further doubt by the large cloud at the left of the overlay. During the

[9] Gregg Bluth, http://www.geo.mtu.edu/~gbluth/Teaching/toms.tutorial.html

Figure 2: Sketches from the Washington VAAC for 0515 and 1645 Nov 04

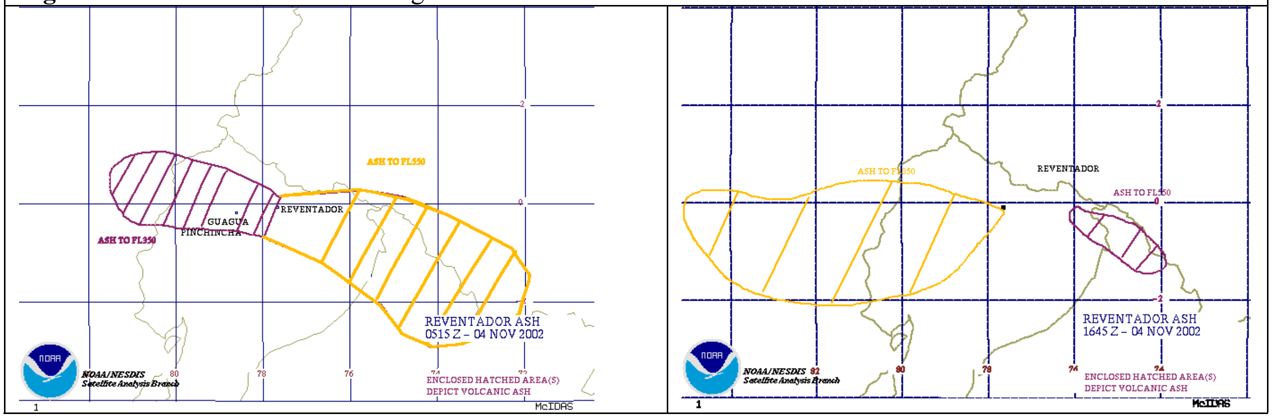


Figure 3: 8.6μ retrieval SO_2 maps from 0335

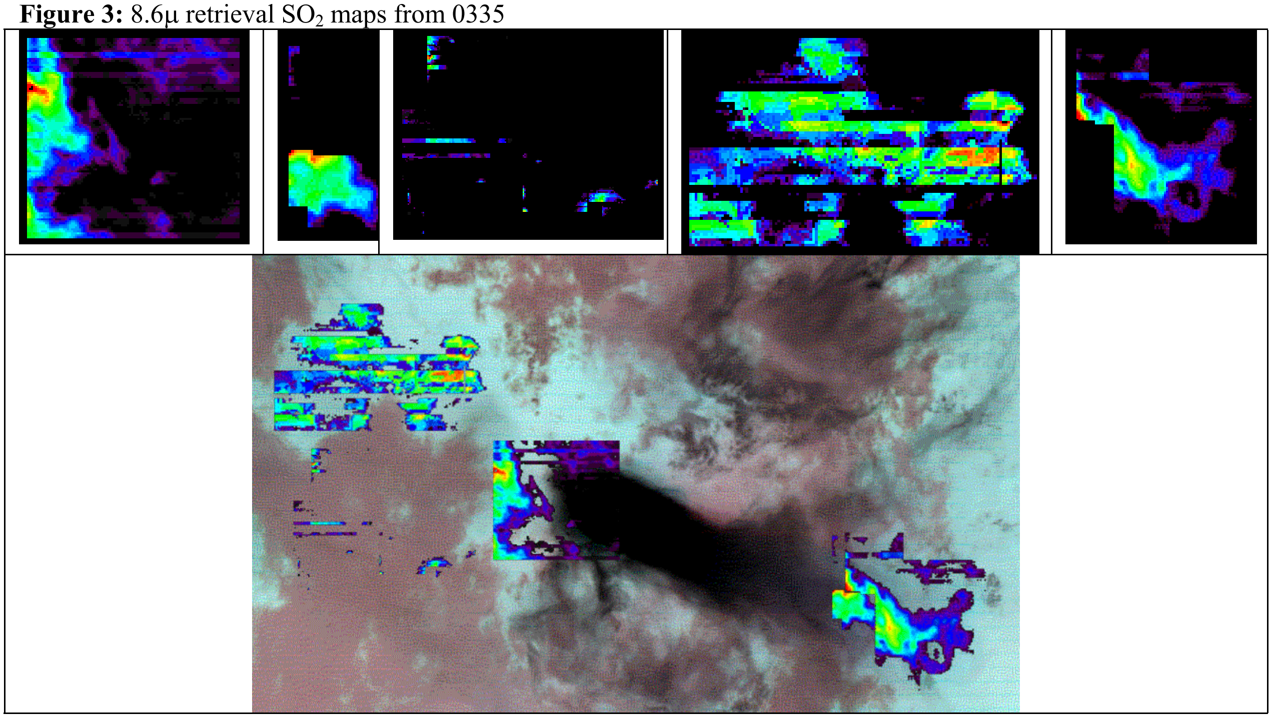


Figure 4: 8.6μ retrieval SO_2 maps from 1555

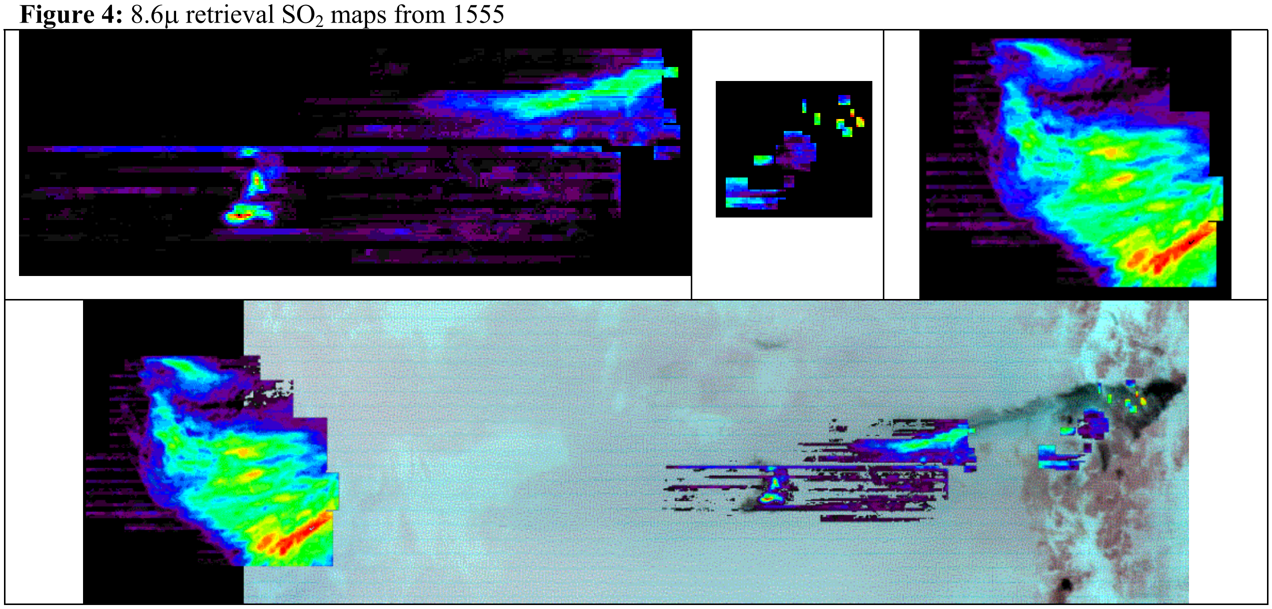


Figure 5: 8.6 μ retrieval SO_2 map (top) and temperature map (bottom) for 0335

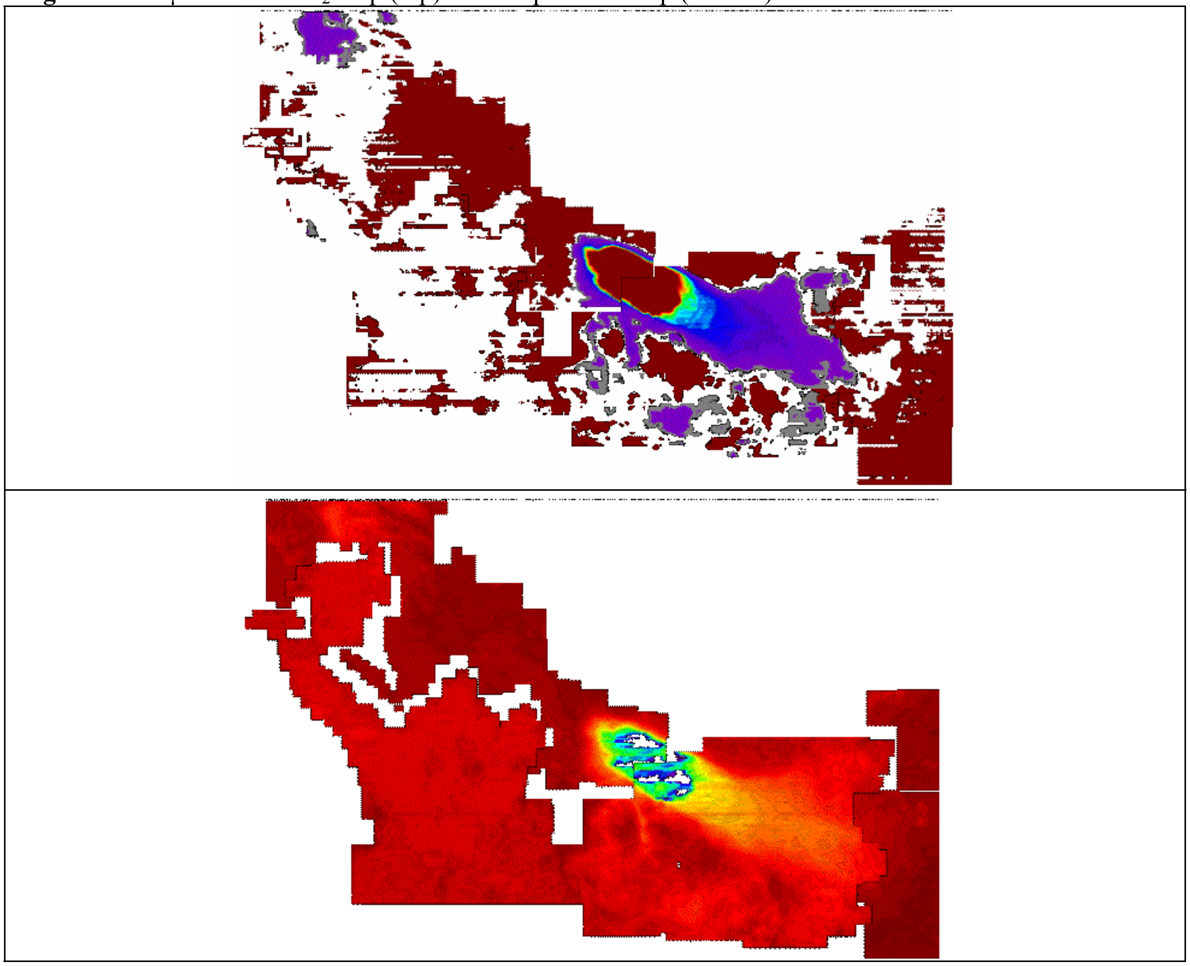
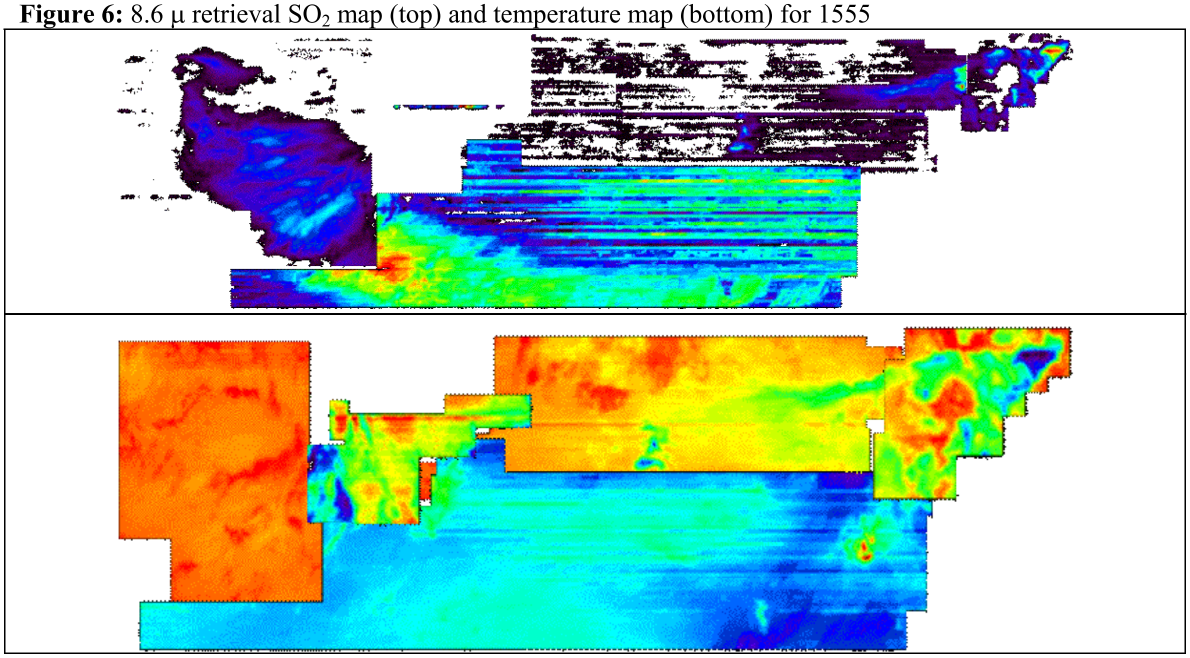


Figure 6: 8.6 μ retrieval SO_2 map (top) and temperature map (bottom) for 1555



retrieval, it was assumed that this was a separate volcanic cloud, from the previous day, that had drifted out to sea. From other images, this is not apparent at all and is likely a meteorological cloud. To compare the above data to a full map of the plume and region, I re-ran the retrieval over the entire plume. While tonnage SO_2 values were not calculated from the results, the images are given in Figures 5 and 6 which show maps of the SO_2 (top) and temperature profile (bottom).

There are several valuable points that can be taken from figures 5 and 6. (a) From all of the pictures, it should be obvious that piecing these "puzzle pieces" back together can be highly problematic. Due to human error in choosing portions of the image to analyze, problems involving overlap and missing sections appear. Moreover, basic software limitations can hinder the accurate placement of these "pieces" when producing a visual compilation of the data. (b) From the 1555 images, the importance of background becomes apparent (note the sudden change in color between the top and bottom sections of each image). Seemingly small variations in the background emissivity spectrum can cause large changes in the appearance of the retrieval images and will have a similar impact on the mass SO_2 calculations (though this assertion has not been quantified during the course of this project). (c) You can see from the SO_2 map of figure 5 that opaque plume regions simply do not show up against the background. Clearly, the interior of the plume (which shows up as background in the image) is not free of SO_2 though it does not appear; this casts the reliability of this retrieval into even deeper doubt. (d) Interference in the images becomes dramatic, with banding the dominant feature in some sections of the SO_2 map. This interference is likely to shift the tonnage SO_2 estimates and make them less reliable, though the actual quantitative impact of this interference was not calculated during this project. (e) When the data is analyzed in fragments, as was done during this study, you get fragmental results: a rather obvious statement, but an important one nonetheless. By looking at small sections of data, the big-picture can be easily missed. An example of such a problem was the initial assertion that the western portion of figure 4's overlay showed a portion of volcanic cloud that had separated from the rest of the plume overnight. When the entire region was imaged for SO_2 and temperature, a very different picture emerged: in the temperature map, the cloud barely shows up at all; from the SO_2 map, we can see that this cloud is not of volcanic origin at all, but from a band of westward moving meteorological clouds south of the eruption. If these large-scale images from figure 5 had not been looked at, a very wrong conclusion may have been drawn in the end (note that the SO_2 tonnage calculation included this section; it contributed 89.3 kt to the SO_2 total).

The 7.3μ retrieval was initially planned to be a quantitative analysis of the tonnage SO_2, however, problems concerning the execution of this retrieval limited it to a purely qualitative analysis. Images were far different from expected due to the parameters that were set for the program- these images can be seen in figures 7 and 8. In the SO_2 map from the 7.3μ retrieval of the 0335 plume, there is a near-perfect outline of the plume that was targeted. The vast majority of the main plume itself, in this image, is completely black (which indicates the complete absence of SO_2) while there are faint wisps of white leading to the upper-left corner (this would be the secondary plume). The most likely explanation for this lack of data in the cloud is that some sort of fool-proof

Figure 7: 7.3µ retrieval SO_2 map from the 0335 plume

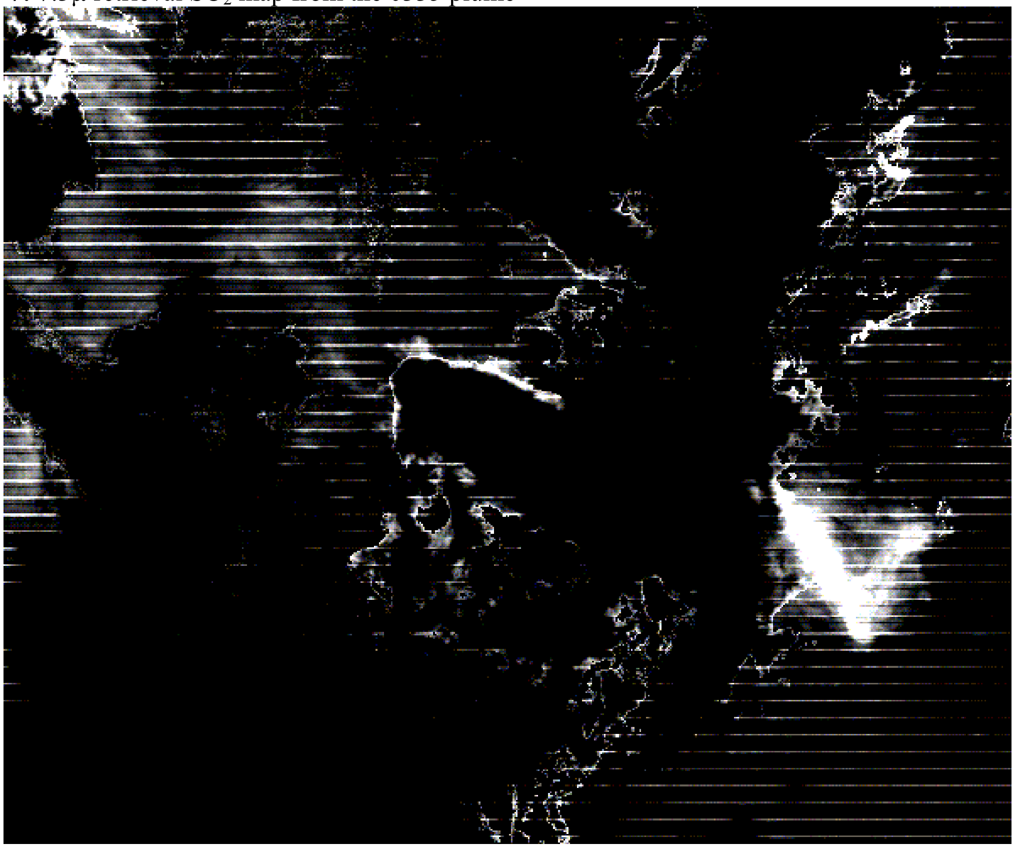
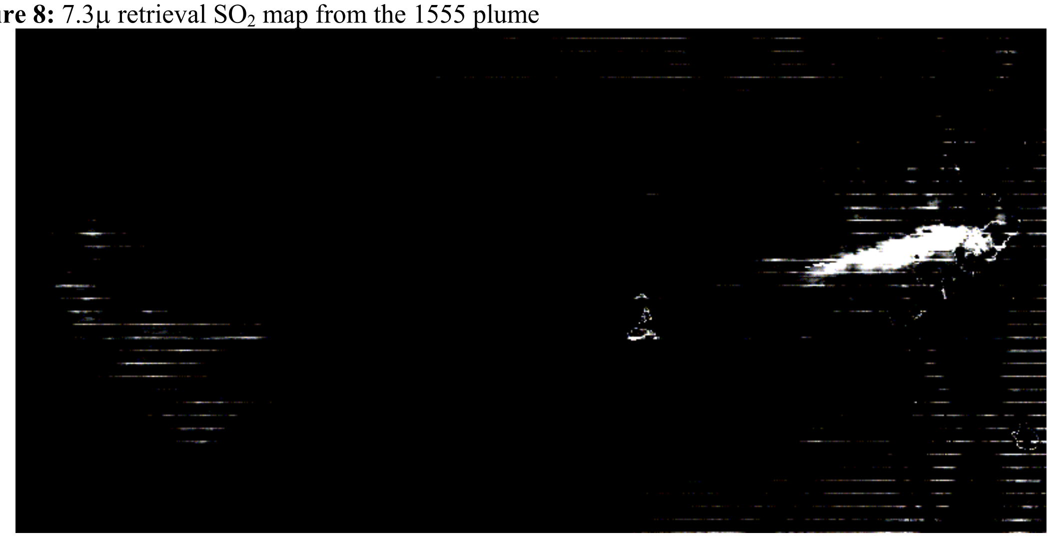


Figure 8: 7.3µ retrieval SO_2 map from the 1555 plume



mechanism triggered itself when extremely high values were recorded. The program converted these high-values to zero-values, assuming that the anomalies were produced by ash rather than SO_2. To a point, this assumption was probably valid, but it proved too difficult a chore to deactivate this feature in order to compare images. Thus, there is no way to accurately compare how effective and accurate this fail-safe is. There are two more notable features here that deserve pointing out. The first is the cloud outline at the left side of the image, which appears to intrude into the secondary plume. This cloud showed up clearly in red in the RGB image of figure 3. You may note the lack of data in this section that was produced from the 8.6μ retrieval; this is thought to have been caused by some sort of masking effect, which blocked out the SO_2. This assessment is supported by the similar masking effect seen in the 7.3μ retrieval from 0335- even through the interference bands. The second point worth noting is the large strip of zero-values that cuts diagonally through the image and plume. This strip begins at the upper-right and ends at the bottom-center; the reason for this strip of seemingly bad values is currently unknown. In the image from 1555 (figure 8), the plume is *much* smaller than what it is known to be from other images and retrievals. Moreover, banding plays a large role in the SO_2 map while the known meteorological cloud in the left section, though faint, does show up as SO_2.

A quantitative analysis of mass SO_2 was not performed for this retrieval due to the large number of pixels in each plume, which would make this task enormously time-consuming and impractical. Such an analysis would require selecting each pixel to process individually and then measuring the "brightness" and summing the values for the entire plume. Because of the amount of time this would have involved *and* the fact that both SO_2 maps were unreliable, the quantitative calculations were not performed.

TOMS data were collected for Nov 04 in order to compare SO_2 calculations between it and the 8.6μ retrieval. SO_2 estimations based on TOMS data have been made for years and is the most commonly used method of deriving mass SO_2 output from large eruptions. For this reason, a comparison of data and results between the new MODIS sensors and the seasoned TOMS satellite would be very helpful in gaining an idea of the accuracy of the 8.6μ retrieval (though TOMS is probably far from 100% accurate in measuring total SO_2, itself). The TOMS images were processed to get SO_2 and aerosol maps (figure 9). From the SO_2 map, the plume can be seen clearly moving westward out to sea. This plume can also be seen from the aerosol map; however, it is not as distinct due to fairly low measured values and high relative background reflectivity. Calculations were performed from the SO_2 map to get values for two methods: gridding and pixel. The gridding calculation gave a tonnage SO_2 estimate of 93.5 kt, while the pixel method resulted in an estimation of 108 kt. These numbers are much larger than the 0335 8.6μ retrieval results, but closer to the 1555 results; this would be great were the 8.6μ retrieval data not so highly questionable. A comparison of mass SO_2 estimates is provided in table 2.

Figure 9: TOMS Imagery for Nov 04, 2002. Top image shows SO_2 while the bottom displays aerosol

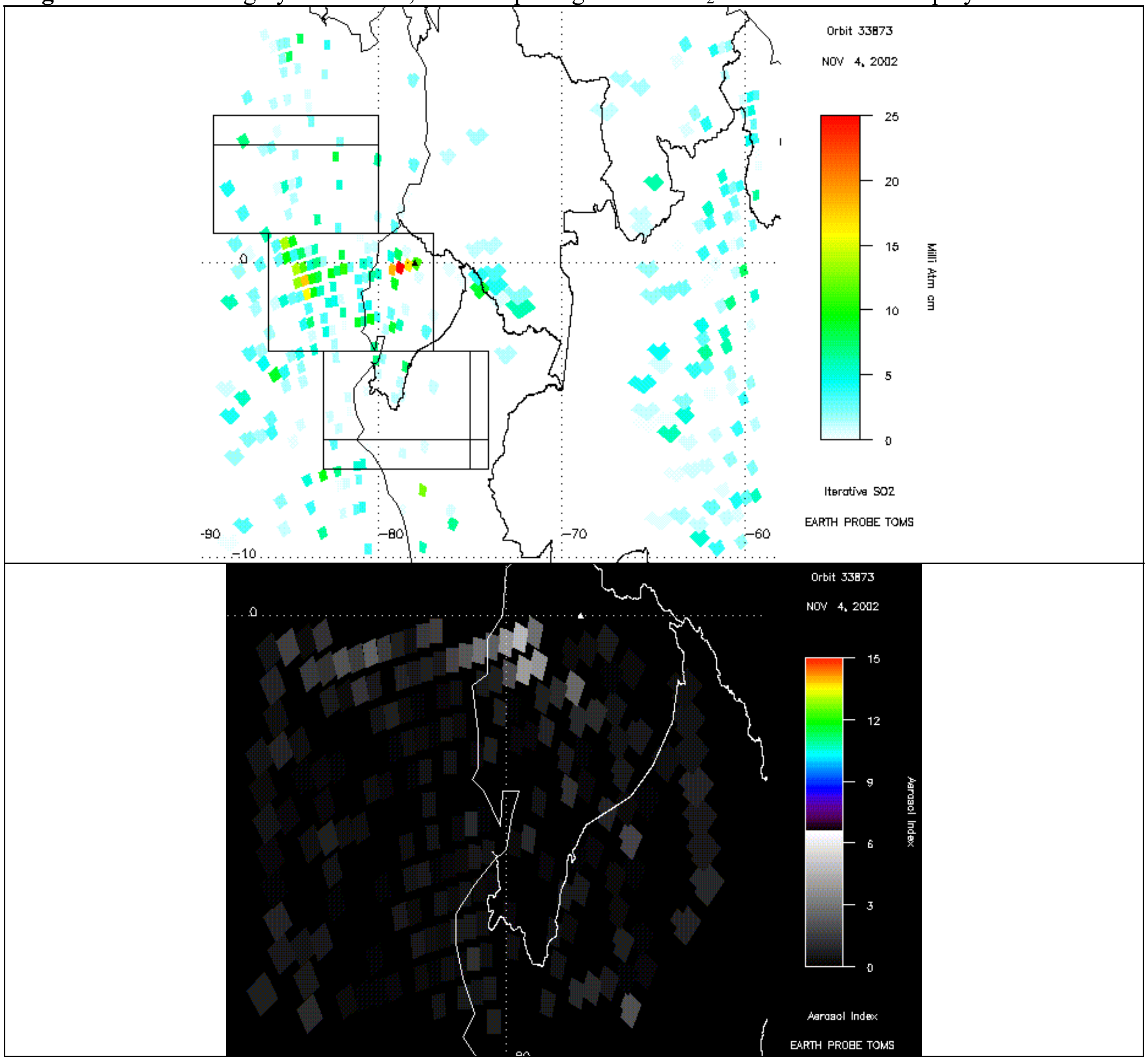


Table 2: **SO_2 data comparison**

Retrieval	***Mass SO_2 Calculations***
8.6µ, 0335, Nov 04	47328
8.6µ, 1555, Nov 04	106674
Gridded Calculation, TOMS, Nov 04	93500
Pixel Calculation, TOMS, Nov 04	108000

Analysis

From the data collected and produced during this study, it is impossible to say what the value of these new MODIS retrieval methods are in relation to smaller or even medium-sized eruptions (depending on the definition of "medium"). It may be that, for SO_2 dominant emissions or eruptions, these methods and algorithms work well for calculating the amount of SO_2 produced in an effusive event. However, for large eruptions such as Reventador on Nov 04, 2002 (and probably Nov 03 as well), the existing retrievals for MODIS images are inaccurate, awkward, and generally an inefficient use of time. Opaque sections of plume, which may contain more SO_2 than translucent sections, give bad values or none at all due to the masking of background infrared wavelengths by ash. This problem appears in both the 7.3μ and 8.6μ retrievals and is likely to be irresolvable simply due to the overwhelming influence of ash in the image. Attempts to change program parameters and disable fool-proofing mechanisms may result in the production of more, but potentially worse, data. Even in non-opaque regions, the influence of ash on the data cannot be completely known unless an SO_2-free region of plume, displaying the same concentration of ash, can be selected as a background spectrum for the analysis.

The selection of regions to analyze against a specific background emissivity spectrum in the 8.6μ retrieval is likely a handy tool for small plumes, but in large plumes where several background regions are traversed, the process becomes tedious and highly subject to error. Making poor choices in the selection of a background can result in dramatically shifted SO_2 values as well as color-mismatched tiles in a compilation image of data (as seen in figure 6). The process of selecting tiles to analyze is highly prone to human error as memory must be relied upon to determine the dimensions of the next region while attempting to minimize overlap and gaps in the data (both of which will create sizeable error in any SO_2 estimates). Areas in which the background change is gradual are impossible to accurately map without making a near-infinite number of background selections in the image. Creating a composite map, in some cases, may amplify the likelihood of misinterpreting data as was done with the mistaken meteorological cloud in the 1555 MODIS image. Moreover, some backgrounds appear to completely mask the SO_2 signal as seen in the red regions of figure 3's overlay.

Interference in the image may have a minor effect on smaller plumes (depending on the amount and location relative to the plume). For large plumes, however, interference can create numerous bands of bad data that cross the target plume. While this interference could reasonably be ignored for dark sections of the plume, fainter regions can be heavily influenced. In these areas, interference can become the dominant feature (see the SO_2 map in figure 6) and, if a large section of the plume is faint, it can potentially skew SO_2 values to the point at which they essentially become worthless.

Problems regarding the atmospheric profile can arise when there are no data available for locations near the eruption. Fortunately for this project, the profile from Bogotá appears to closely match the atmospheric conditions present around the plume in Ecuador. Holes in the data may also contribute to problems in the accuracy of the retrievals, though their effects are limited depending on how well the missing values are predicted. Finally, data on plume height and thickness may be difficult to obtain in some situations, which can cause significant problems in the accuracy of SO_2 retrieval numbers.

The 7.3μ retrieval, in its current form, is utterly useless in performing a quantitative analysis of mass SO_2 in a large plume. The size of the plume makes the selection of individual pixels for analysis impractical and extremely time-consuming. Very high SO_2 values are interpreted by the program to be anomalies caused by ash-masking and are assigned a value of zero; this, while probably correct, means that an accurate calculation of mass SO_2 cannot be performed. Removing this feature from the program simply allows the highly ash-contaminated values to appear and creates new error to replace the ones corrected for. Regardless of the effects, altering the program in such a way requires tedious amounts of code working. Moreover, the effects of interference in the images are even more dramatic than that seen in the 8.6μ retrieval maps. Sections of the images, which clearly should not detect SO_2 show values that are independent of the plume. If such regions appear close to or crossing a plume, further error may be introduced.

Performing these analyses, or even looking at the MODIS images, in any sort of short time frame is completely out of the question. Nearly every step in the process of generating and analyzing MODIS images is painfully slow (though, for many tasks, the speed depends on the quality of your computer's processor). First, MODIS images are not made available to the public until the day after they have been collected. The data must then be ordered; preparation of the data by the service will take at least several hours and sometimes several days. The notification comes via e-mail and transferring the data is no quick business either; the emissive-band MODIS images come in two sizes that I've seen: 100 and 300 megabytes (approximate values, real numbers are slightly higher). The large size of these images means that you need a fast internet connection, time, and enough memory to store these data. Converting these images to Terrascan-readable grid files can take over an hour and result in over 600 mb of data for each image. Collecting and fixing atmospheric profiles is no quick task and can take a very long time if you don't know where to find this type of data or are not accustomed to rapidly predicting missing values. The retrievals are time-consuming as well: the 8.6μ retrieval images required 7-9hrs each while the times for the 7.3μ retrieval ranged from 12 minutes to 2 hours (they were performed on three different computers- the 12 minute time was achieved on a new fiber-optics driven server).

A person can expect to realistically spend several days or several weeks getting this data collected and analyzed. For a large eruption, with the programs mentioned in this paper, we can anticipate quantitative data to be largely worthless. While this process may hold great promise for smaller eruptions with little ash, there appear to be irreconcilable problems regarding opacity of the plumes due to ash-masking. This problem is likely to be prevalent in all measurements involving infrared emission; thus, for accurate future estimations of SO_2 content in large volcanic plumes, new wavelengths for data collection must be investigated.

References

Atmospheric Soundings webpage, University of Wyoming, http://weather.uwyo.edu/upperair/sounding.html

El Reventador, Ecuador; an active volcano in the northern Andes, Minard Hall, Politecnica vol 5, no. 2

Goddard Space Flight Center Distributed Active Archive Center, http://acdisx.gsfc.nasa.gov/data/parameter/nofrills.html

GVP/USGS Weekly Volcanic Activity Report for Nov 27- Dec 03

Instituto Geofisico – Escuela Politecnica Nacional website, Ceniza and Historia pages http://www.igepn.edu.ec/vulcanologia/reventador/ceniza.htm, http://www.igepn.edu.ec/vulcanologia/reventador/actividad/historia.htm

Simon Carn, e-mail notification

Volcano World website, Reventador page, University of North Dakota, http://volcano.und.nodak.edu/vwdocs/volc_images/img_reventador.html

2001 Volcanic Clouds Workshop webpage, Gregg Bluth (Michigan Technological University), http://www.geo.mtu.edu/~gbluth/Teaching/toms.tutorial.html