EOS IDS Volcanology Team
Data Product Document
Product # 3288

Volcanic SO_2 Alert

Version 3

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Preface

This document describes plans to monitor Moderate Resolution Imaging Spectroradiometer (MODIS) Level 0 data in near-real time to detect large amounts of volcanic SO_2 in the upper troposphere and lower stratosphere. When SO_2 alerts are triggered at the MODIS Science Computing Facility (SCF) during Level 0 to Level 1A processing, data files will be sent to the Jet Propulsion Laboratory (JPL) for additional processing to create the products described in this document. The SO_2 alert products will be archived either in the EROS Data Center Distributed Active Archive Center (EDC DAAC) or in a Volcanology Interdisciplinary Science (IDS) SCF.

1. Introduction

1.1 Algorithm and Product Identification

The Earth Observing System (EOS) product number is 3288, and the label is "Volcanic SO2 Alert." An SO_2 alert detection algorithm and further processing will result in three closely-related products: alert data files (3288a), regional browse maps (3288b), and an alert description file (3288c). These products belong to the EOS IDS (Interdisciplinary Science) Volcanology Team, led by Peter Mouginis-Mark.

1.2 Algorithm Review

The alert detection algorithm is a simple check on thresholds for relationships between the DNs (digital numbers) of Level 0 MODIS data in four channels. This threshold check will be applied in near-real time at the MODIS SCF (Science Computing Facility) during Level 1A processing of all MODIS data. The time lag between data acquisition and Level 1A processing is currently unknown, but it will probably be between 10 to 50 hours, depending on downlink frequency and MODIS processing schedule. Any SO_2 alerts triggered will result in MODIS data files being sent to a Volcanology IDS SCF at JPL. The second part of the processing will be done at JPL to create the final products (alert location data files and maps), which will be archived in the EDC DAAC or in an IDS SCF. The alert is sensitive to high altitude (roughly 8 to 20 km) eruption clouds and is expected to ring on the order of zero to five times per year, but is not expected to ring false alerts.

1.3 Document Scope

This document describes the physical basis for the algorithm, implementation plan, required input, and output products.

1.4 Applicable Documents and Publications

Crisp, J. (1995, manuscript in prep.) Detection of volcanic SO_2 using the satellite infrared imaging radiometers HIRS2 and MODIS.

Flynn, L., 1995, Surface thermal alert, EOS IDS Volcanology Team Data Product Document for product 3290. This data product has many similarities with the SO_2 alert, especially the near-real time processing of Level 0 MODIS data.
Guenther, B., H. Montgomery, P. Abel, J. Barker, W. Barnes, P. Anuta, J. Baden, L. Carpenter, E. Knight, G. Godden, M. Hopkins, M. Jones, D. Knowles, S. Sinkfield, B. Veiga, N. Che, L. Goldberg, M. Maxwell, T. Zukowski, T. Pagano, N. Therrien, and J. Young, MODIS Level 1B Algorithm Theoretical Basis Document [MOD-02] (http://spso.gsfc.nasa.gov/atbd/modis/atbdmod01.html)
Realmuto, V.J., 1995, Volcanic SO_2 - High and moderate spatial resolution, EOS IDS Volcanology Team Data Product Document for product # 3289. Sulfur dioxide retrievals using mid-infrared data from the ASTER instrument.

2. Overview and Background Information

2.1 Experimental Objective

The purpose of this algorithm is to alert the EOS IDS Volcanology Team and others interested (such as volcanologists and air traffic controllers) to large eruption clouds. This may result in observations (remote sensing or field observations) being taken of transient eruption events that would have otherwise been missed. For instance, the EOS IDS Volcanology Team might react more quickly to request observations be made by ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), high-resolution MISR (Multi-angle Imaging Spectroradiometer), or TES (Tropospheric Emission Spectrometer). The results of the alert will also be useful for retrospective studies of SO_2 emission and conversion to aerosols.

The thresholds on the alert will be set so that there will be no (or very few) false alerts. For the MODIS channel configuration, an alert algorithm that does not trigger false alerts will also miss many eruption clouds. The desire is to have an automated alert that produces an unambiguous result. During the EOS mission, other alerts will be tested in a non-real-time fashion, and if a better approach is found, perhaps an improved version may be substituted a few years after the first launch, or when a new MODIS instrument is flown on another EOS platform.

2.2 Historical Perspective

Remote sensing of volcanic SO_2 has been done primarily at ultraviolet wavelengths from satellite using TOMS (Total Ozone Mapping Spectrometer) or from aircraft or on the ground using COSPEC (Correlation Spectrometer). Limited studies have also been done at thermal infrared wavelengths from aircraft using TIMS (Thermal Infrared Multispectral Scanner) and the NCAR (National Center for Atmospheric Research) Fourier Transform Spectrometer, and on the ground using Fourier Transform spectrometers. Another approach has been microwave measurement of SO_2 using the MLS (Microwave Limb Sounder) instrument aboard UARS (Upper Atmosphere Research Satellite). These other methods of SO_2 detection and measurement are summarized in Crisp (1995, in prep.). There currently are no global real-time SO_2 alert systems implemented for satellite sensors.

The currently active satellite instrument which is most similar to MODIS is HIRS2 (High Resolution Infrared Radiation Sounder/2). SO_2 absorption was noted in HIRS2 spectra of the El Chichon eruption cloud by Susskind (1982), and in eruption clouds from Mount St. Helens and Sierra Negra by Crisp (1995, in prep.). A study of HIRS2 data covering the 1978-1980 period was used to define an SO_2 detection alert algorithm (Crisp, 1995, in prep.), but no such algorithm has been implemented for real-time or retrospective processing of global HIRS2 data sets.

2.3 Instrument Characteristics

The first MODIS is scheduled for launch in 1998 on the AM-1 platform. The plan is to have a MODIS instrument on board all AM and PM EOS platforms, with launches every 3 to 4 years. With a duty cycle of 100%, throughout the EOS period, there should be one or two MODIS instruments in operation at any given time, each with a two-day repeat coverage of the globe. The AM-1 will have a descending 10:30 am equator crossing, and the PM-1 is planned to have an ascending 1:30 pm equator crossing. The MODIS swath dimensions are 2330 km cross track by 10 km along track at nadir.

The four MODIS channels which will be used in this algorithm have a spatial footprint of 1 km and these relevant characteristics (FWHM = full width half-maximum of the band, NEΔT = noise-equivalent delta-temperature):

Channel	Center (μm)	FWHM(μm)	NEΔT (K)
27	6.715	6.535 - 6.895	0.25
28	7.325	7.175 - 7.475	0.25
31	11.030	11.770 - 12.270	0.05
36	14.235	14.085 - 14.385	0.35

These four channels are not the same as the four required for the Surface Thermal Alert (Product 3290). Thus, a total of eight channels will have to be monitored during the Level 0 to Level 1A processing of the entire MODIS data stream. The two volcanology alert algorithms (SO_2 and thermal) are the only ones planned for operation in near-real time mode on MODIS Level 0 data.

3. Algorithm Description

3.1 Theoretical Description

3.1.1 Physics of the Problem

The alert is based on the strong absorption of SO_2 at 7.2 to 7.5 μm (Figure 1), which is precisely the location of MODIS Channel 28. Nonvolcanic background amounts of SO_2 are well below the detection limits of MODIS. Clouds below about 6 km altitude will be difficult to detect because of the low transmission of the atmosphere at these wavelengths. The physics is described in more detail in Crisp (1995, in prep.).

3.1.2 Mathematical Aspects of the Algorithm

An empirical study of HIRS2 data has determined a good set of threshold checks on brightness temperatures to detect SO_2 and avoid false SO_2 alerts (Crisp, 1995, in prep.). The results of the HIRS2 study, translated to similar MODIS channels, show that the most reliable alert is triggered when all four of these conditions are true (BT=brightness temperature):

BT_{28} minus $BT_{36} \leq 15$ K (I)

BT_{31} minus $BT_{27} < 10$ K (II)

BT_{31} minus $BT_{36} > 5$ K (III)

BT_{27} minus $BT_{28} > 0$ K (IV)

Thresholds I and IV are sensitive to the SO_2, whereas thresholds II and III are necessary to prevent upper tropospheric and stratospheric meteoric clouds from triggering false alerts.

3.1.3 Variance / Uncertainty Estimate

It is expected that no false alerts will be triggered by the algorithm. Thresholds will be set to accommodate any uncertainties in the DNs (which the MODIS team will be able to provide later). However, because of this, many eruptions will not be detected. If there is a shift in MODIS channel response function or adjustment to radiance calibration, the threshold settings (I-IV) on the alert may have to be adjusted slightly. Or, if the threshold settings for MODIS which were deduced from studies of HIRS2 and radiative transfer modelling are too sensitive, we may have to adjust the thresholds to eliminate false alerts.

This alert has been found to be very insensitive to a wide range of conditions: H_2SO_4 aerosols in the cloud with an optical depth of 0.3; andesite ash in the cloud with an optical depth of 0.2 or 0.6; water drops in the volcanic cloud; cirrus, altostratus, or nimbocumulus clouds below the volcanic cloud; two different surface reflectance types (ocean and basalt); instrument observation angle (20, 50, 70, or 80^o); surface temperature (273, 294, 334 K); a wide range of atmospheric vertical profiles of temperature, pressure, and humidity; and day versus night. The primary sensitivity of the alert is to the altitude of the eruption cloud and the SO_2 abundance. It does not detect SO_2 clouds at approximately 25-30 km altitude, because at these high altitudes, Channel 27 is colder than Channel 28 (failing threshold IV). Since eruptions this high are very rare (Simkin, 1994) and likely to be detected by other means (such as a TOMS instrument), this is not a serious issue. More serious is that the algorithm also does not detect SO_2 clouds in the 0-6 km altitude range, due to threshold (IV) not holding (the absorption by SO_2 does not occur at a cold enough elevation in the atmosphere to show up as a significant contrast with ambient). Column abundances of SO_2 detection limits for this alert are on the order of 0.1 to 0.2 atm cm (Crisp, 1995, in prep.), judging from both radiative transfer simulations and the combined observations of the Mount St. Helens cloud by HIRS2 and TOMS.

What has yet to be determined is:

(1) The effect of the difference in response functions between MODIS and HIRS2.

It is anticipated that these effects are negligible. The response functions are very similar (Figure 2). The MODIS team has provided us with preliminary estimates of the instrument response functions, but these are not the actual flight-hardware functions. When the MODIS response functions are known for the flight instrument, radiative transfer simulations can be done to assess the effect on the operation of the SO_2 alert, and the thresholds can be adjusted if necessary.
(2) The conversion factors between DN and brightness temperature so that the thresholds can be based on differences in DN rather than BT. This should be fairly straightforward, and requires assistance from the MODIS team.

Uncertainties in geolocation are unknown at this time (probably on the order of $\pm$ 5 or 10 km), but uncertainties (and geolocation formulas) will eventually be provided by the MODIS team.

3.2 Practical Considerations

The major practical considerations are the expected number of eruptions that will trigger the alert, the number of days each eruption will continue to trigger the alert, and the estimated number of pixels in a typical eruption cloud that will be triggered. A recent tabulation of eruption cloud heights in the interval 1975-1985 suggests that, on average, about five eruptions per year would have high enough eruption altitudes to be detected by this alert (Simkin, 1994; Simkin and Siebert, 1994). So far, a HIRS2 study (Crisp, 1995, in prep.) has only found the SO_2 alert to be triggered by large eruptions of size VEI 3 to 5 (Volcano Explosivity Index). Although VEI does not include SO_2 abundance in its formulation, it is still useful because of the dependence of VEI on cloud height and the well documented correlation between VEI and frequency of eruption (Simkin and Siebert, 1994). The VEI 3 eruption in 1979 of Sierra Negra in the Galapagos triggered the SO_2 alert for 67 HIRS2 pixels for one day. Because of the difference in spatial resolution, this same eruption cloud would have triggered the alert for about 125,000 MODIS pixels. The magnitude of the Sierra Negra eruption corresponds to a "1 on average per 4 months" type of eruption. The Mount St. Helens 1980 eruption, VEI 5, would have triggered roughly 50,000 to 300,000 MODIS pixels each day for about 3 days, and is a "1 on average per 12 years" type of eruption. Intermediate VEI 4 size eruptions occur on average once every 2 years. For a "typical" year, we estimate that the MODIS SO_2 alert would be triggered for about four VEI 3 or greater eruptions, one or two days each, amounting to a total of about 700,000 MODIS pixels. The uncertainty on this figure is enormous, but it provides a starting estimate. If there is an unusually large eruption, the total could rise to 2,000,000 pixels or higher over a several-day period.

Eruptions with a VEI of 0 to 2 would be unlikely to trigger the SO_2 alert because these eruptions generally have clouds that reach the 1 to 5 km altitude range. On average, there are about 25 VEI 2 eruptions per year (Simkin, 1993). Sulfur dioxide maps of these smaller eruption clouds could be made from ASTER observations, using the software algorithms of EOS Volcanology Product #3289. However, ASTER is operational only a small fraction of the time and the results would not be available in near-real time. Faster turn-around for detection of low-altitude clouds will only be possible using TOMS or Bands 4 and 5 of AVHRR, if an automated detection algorithm is implemented.

It is not known whether the expected high number of alerted pixels at infrequent intervals (1 to 3 times a year) will be too much for the MODIS Science Computing Facility to handle. This will have to be worked out in discussions between the IDS Volcanology Team and the MODIS Team. If it is too much of a burden, the algorithm at MODIS may have to include an automatic turn-off after a certain number of alerts (such as 10,000), for a certain amount of time (such as 24 hours). If a turn-off occurred, the JPL SCF would receive indication of this, and the alert products could be created later at JPL, using MODIS data archived in the GSFC DAAC. The initial alert would be received in near-real time and could be put into the EDC DAAC or Volcanology IDS team dat:a archive, but the complete alert data set and regional map would take longer (perhaps 1-2 days) to appear in the data archive.

The amount of data sent from the MODIS SCF to JPL for an alert would be approximately 23 bytes per pixel (date/time, lat/lon, 4 channel DNs), which would amount to a transfer of about 5 Mb per day to JPL for an eruption the size of Mount St. Helens. Currently it is unknown what additional data (such as calibration gain and offset) will be required to be sent from the MODIS SCF in order to convert the DN's to radiances.

The algorithm is expected to be operational at the start of the EOS mission, in 1998.

3.2.1 Numerical Computation Considerations

The SO_2 detection algorithm will be written in C, and be incorporated along with the thermal spike alert (EOS IDS Volcanology Product 3290) as part of the Level 0 to Level 1A processing at the MODIS SCF. The computational load is a minor fraction of the processing that produces Level 1A data. The algorithm is very simple, and there are no problems of numerical stability or round-off errors. Alert data will be sent to JPL rather than stored at the MODIS SCF. Storage of these data files sent from the MODIS SCF will easily be accommodated at JPL.

Algorithms for generating the alert data file and maps will be written using Fortran 77 and IDL (Interactive Data Language). The format of the final map products will be HDF-EOS (EOS subset of Hierarchical Data Format) or GIF. Regional maps will be custom made, whereas production of the annual global maps will be automated. The data files will be produced using Fortran 77 code. Since few eruptions are expected to trigger the alert, the computational load should be minimal.

3.2.2 Programming / Procedural Considerations

3.2.2.a Alert algorithm run on MODIS SCF

The SO_2 detection algorithm will be run at the same time as the thermal alert algorithm (EOS IDS product 3290 "Volcano Eruption Spike"). Data files will be automatically delivered by email to JPL when an alert is discovered at the MODIS SCF. MODIS SCF processing is expected to occur within about 10 to 50 hours of data collection. JPL processing and archival of the updated alert list file in EDC

DAAC should typically occur within less than 24 hours after that. No guarantee will be made by the MODIS team or EOS IDS Volcanology Team to create the alert products within a specified time interval.

3.2.2.b Data product generation at JPL SCF

After alert detection files are sent to JPL from the MODIS SCF, the geolocation will be done using MODIS-supplied formulas, and the SO_2 alert products will be created. Right after launch, these products will be created manually, so there may be a time-lag due to personnel being unavailable when an alert is triggered. Later, after real alerts have been generated, we will attempt to automate the creation and archiving of the data files.

3.2.3 Calibration and Validation

Results for the alert will be compared to other sources of information, such as Smithsonian Global Volcanism Network reports, weather satellite images, ASTER observations, or SO_2 maps from TOMS or MLS, to confirm that the alert is working properly. The results of these comparisons will be included in the data descriptive file (3.2.7.c), which will be continuously updated as new information is obtained.

3.2.4 Quality Control and Diagnostics

If false alerts are discovered, threshold settings will be adjusted to eliminate future false alerts. The version number of the algorithm will be changed and documented in the descriptive file 3.2.7.c. There will be no attempt to reprocess older MODIS Level 0 data if an alert algorithm is updated.

3.2.5 Exception Handling

If data are missing, it will simply not show up in the alert output products. Any parameters that are unknown will be filled in with an asterisk character. Manual checking will be done to make sure there is no gap (operational problems) in the MODIS data stream near the time of an alert, which could reduce the number of alert-triggered pixels. Such gaps will be noted in the descriptive file (3.2.7.c). The descriptive file will also note whether an eruption cloud was missed due to a temporal gap in MODIS data.

3.2.6 Data Dependencies (Input Data)

The input data needed for the alert detection algorithm run on the MODIS SCF are: MODIS Level 0 DNs for channels 27, 28, 31, and 36, along with location, date, and time. These very same data, but only for the pixels that trigger the alert, are the required input for the alert output products.

3.2.7 Output Products

Three types of products will be generated, listed below as items a through c. All three will be archived in the EDC DAAC. No computer code will be run at the DAAC; the DAAC will only be required to archive the data products which will be sent from an EOS IDS SCF at JPL. The current plan is to use cylindrical equidistant projections for the maps, and to store the maps as raster files in EOS-HDF format.

3.2.7.a Data files ***3288a***

The alert location data will be stored in HDF science data tables using the HDF Vdata interface. Each file will contain the SO_2 alert data for a particular MODIS orbit or batch of received MODIS data, usually within less than 24 hours after the data is received at JPL from the MODIS SCF. At first, these files will be created manually, but if the alert is found to be working in a reasonable fashion, then later this process will be automated.

Each pixel that triggers an alert will require 24 bytes of storage space in the output data file as shown:

Parameter (Units)	Range	Format	Bytes
Year (last 2 digits)	98:13	unsigned integer	1
Julian Day	1:365	unsigned integer	2
Time (hr+min) UT	0000:2459	unsigned integer	2
Latitude (deg)	-90.000:90.000	floating point	4
Longitude (deg)	-180.000:180.000	floating point	4
DN channel 27	1:4096	unsigned integer	2
DN channel 28	1:4096	unsigned integer	2
DN channel 31	1:4096	unsigned integer	2
DN channel 36	1:4096	unsigned integer	2
Software Version	0:255	unsigned integer	1
Reserved for Possible Use:			
Quality Indicator	0:255	unsigned integer	1
Alert Strength	0:255	unsigned integer	1
TOTAL DATA PER PIXEL IN OUTPUT DATA FILE :			24

Three parameters are reserved for possible use, one of which might be used as a quality indicator label if the MODIS data has any type of quality indicator. The second might be used to indicate the strength of the alert signal (how far the DN differences are above the thresholds for thresholds I and IV).

The current estimate is an average of about 700,000 pixel alerts per year, which would result in 17 Mb of output data. This could rise to as high as 100 Mb per year (or higher) if a very large eruption occurs, or could be as low as 0 Mb.

3.2.7.b Regional browse maps ***3288b***

Each day an alert goes off, a regional map showing SO_2 alert locations for that day will be generated, usually within 24 hours after the data is received at JPL from the MODIS SCF. There could be more than one map on a given day if there are multiple eruptions, if the eruption site is at a high latitude, or (after 2000) if both AM-1 and PM-1 detect SO_2 on the same day. Figure 3 shows an example of what this product will look like. The map title will indicate the average date and time (UTC) of the alerts in the image, and the total number of pixels triggered by the alert. Continental and US state boundaries, and latitude and longitude grid lines will be shown. The current estimate is roughly 7 maps per year, 0.5 Mb per map, for a total of 3.5 Mb per year. As noted before, for a year with highly unusual eruptive activity, there could be many more SO_2 maps per year, perhaps as many as 20, which would require 10 Mb.

3.2.7.c Results and algorithm documentation ***3288c***

An ASCII file (unformatted, straight ASCII text) will discuss the results of the alert and will document algorithm changes. The file will be updated and appended to, in as timely a fashion as possible. At the end of each calendar year, a new data file will be started. The file will include a description of the alert data file format and the algorithm versions. When possible, it will identify the probable origin (volcano name and location) of the eruption clouds detected, and any reported characteristics of that cloud. Large eruptions that did not trigger the alert will also be noted, along with their cloud characteristics, including cloud top temperature, base and top altitudes, SO_2 flux, SO_2 amounts, aerosol loading, characteristics of aerosols, instrument look angle, etc. The file size will be less than 2 Mb per year, and typically less than 0.1 Mb.

Expected Total Storage Required per Year (Mb) at the EDC DAAC:

	"typical year"	"unusually active year"
a) Alert Data File	17.	100.
b) Regional Browse Maps	3.5	10.0
c) Descriptive File	0.1	2.
TOTAL PER YEAR:	20.6	112.

4. Constraints, Limitations, and Assumptions

Currently there are no constraints on the algorithm. We know of no conditions that will trigger a false alert. However, there might be something other than a volcanic cloud which will trigger it, in which case, we will try to screen it out with a modification to the thresholds or a slight adjustment to the algorithm. This adjustment might be accommodated at the MODIS SCF or after the data is sent to the JPL SCF, it could be further screened. Any changes to the alert detection algorithm will result in a new software version number in the alert data file and a description of the change will be noted in the descriptive file product.

5. References

Crisp, J. (1995, manuscript in prep.) Detection of volcanic SO_2 using the satellite infrared imaging radiometers HIRS2 and MODIS.

Lauritson, L., Nelson, G.J., and Portco, F.W. (1979), Data extraction and calibration of TIROS-N/NOAA radiometers, *NOAA Tech. Memo.* NESS 107.

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Susskind, J. (1982), HIRS/MSU sounders, in *Radiative effects of the El Chichon volcanic eruption: preliminary results concerning remote sensing*, (Bandeen, W.R. and Fraser, R.S., Eds.), NASA Tech. Memo. 84959, pp.4-12 to 4-24.

6. Acknowledgements

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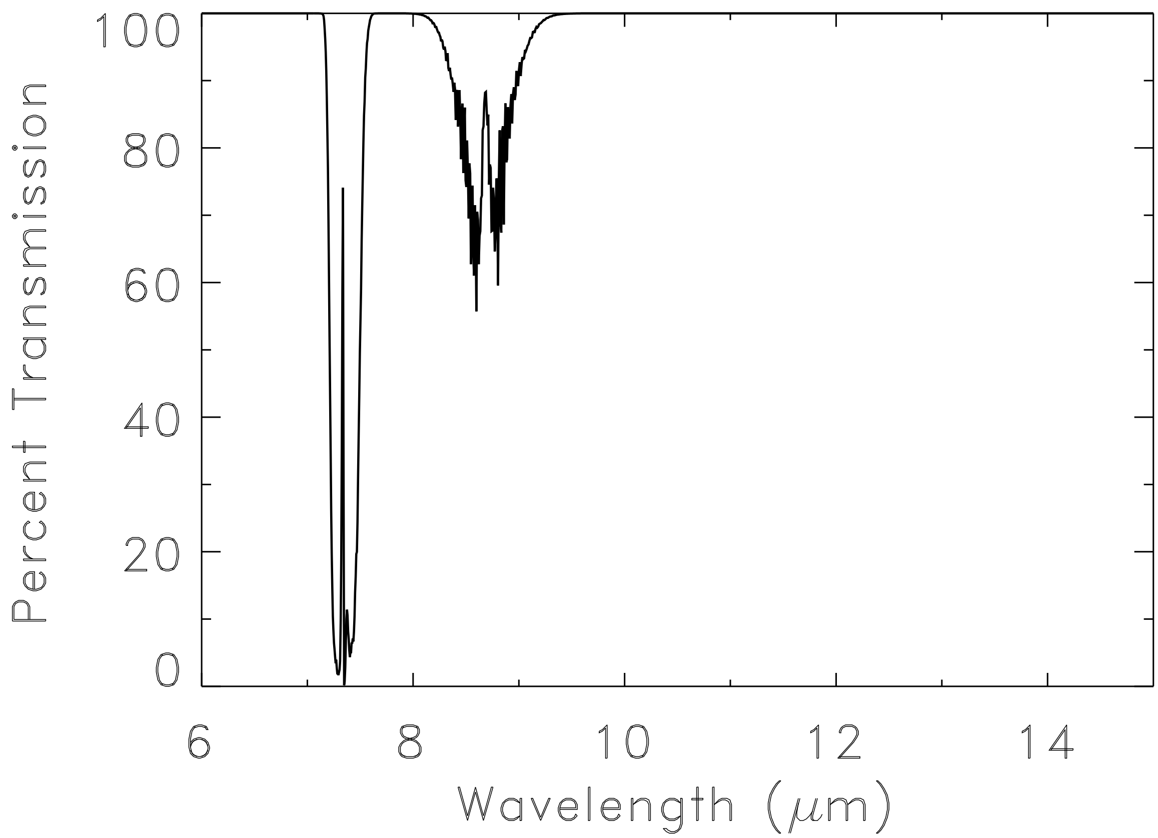

Figure 1. Nadir single-pass transmission through a cloud containing a column abundance of 0.25 atm cm SO_2, with a Gaussian vertical distribution peaked at 100 mb. This shows the strong absorption of SO_2 at 7.2-7.5 μm which affects MODIS channel 28, which has a half-width half-max bandwidth covering the same wavelength range, 7.2 to 7.5 μm.

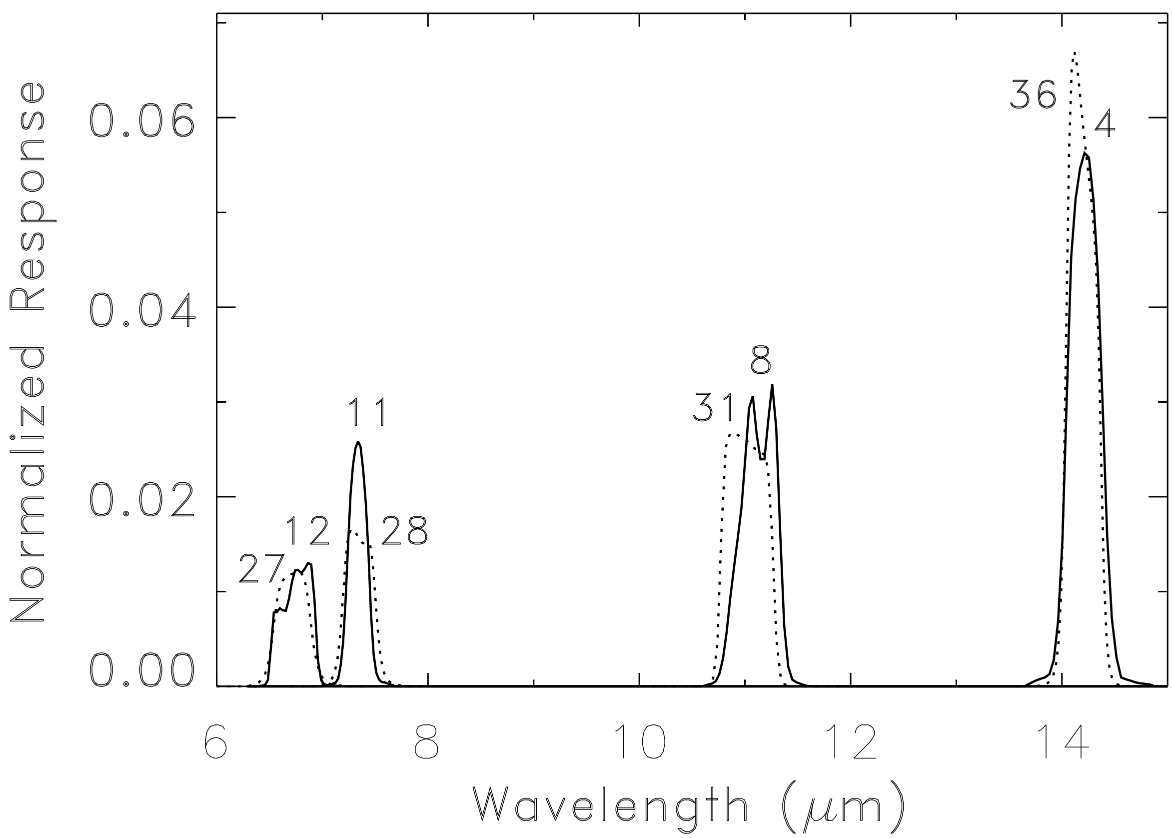

Figure 2. Response functions of the MODIS channels 27, 28, 31, and 36 (dotted curves) used in the SO_2 alert algorithm and the closely matched HIRS channels 4, 8, 11, and 12 (solid curves). HIRS2 functions are from Lauritson et al. (1979). MODIS functions are simulated preliminary estimates (not the definitive MODIS Spectral Data Set!) provided by Ed Knight, December 1994. Normalization is done for each channel by dividing the response at a given wavelength by the response integrated over wavenumber for that channel.

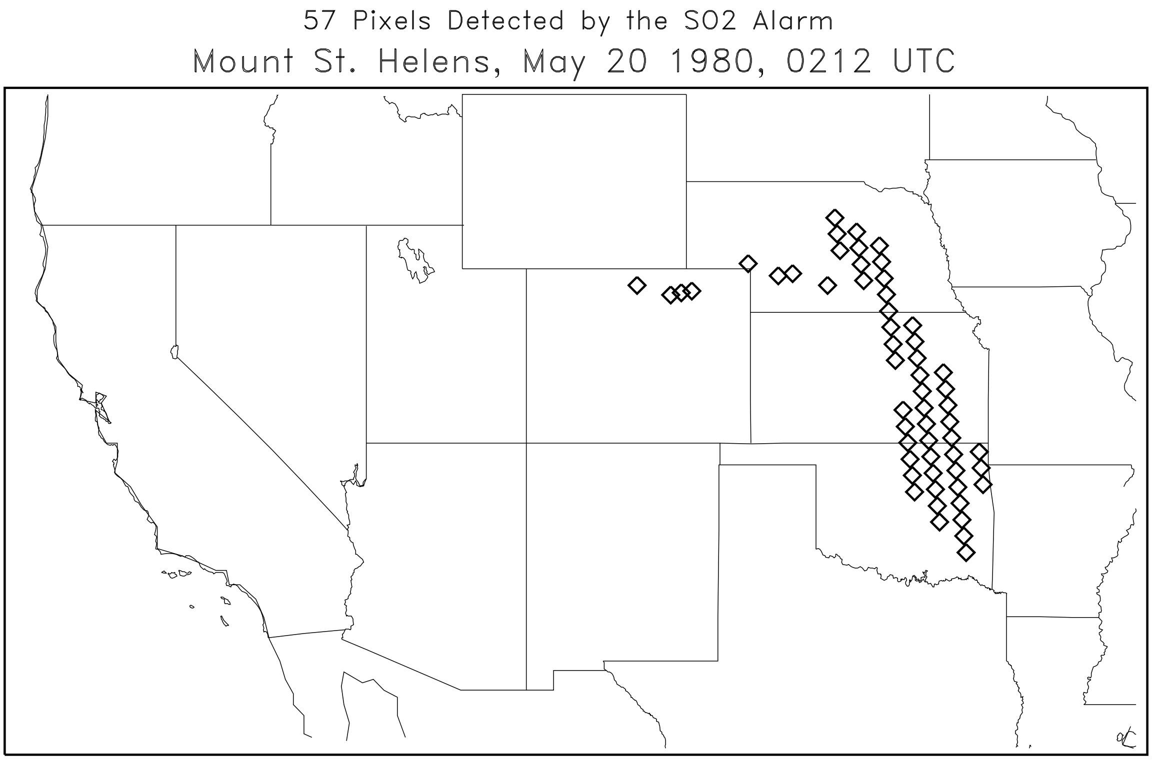

Figure 3. An example of a daily regional map of HIRS2 alert locations over the midwest United States. Each diamond symbol is a pixel for which the alert was triggered. HIRS2 pixel sizes range from 17 km diameter to 58.5 by 30 km. If an eruption cloud like this is observed by MODIS, the MODIS alert map will trigger many more pixels at the MODIS spatial resolution of 1 km. Either a smaller symbol size will be used for MODIS maps, or a zoom-in on location will be used for smaller eruption clouds.