Volcanic ash and SO_2 in the Kasatochi and Okmok eruptions: Interference and impact on quantitative retrievals

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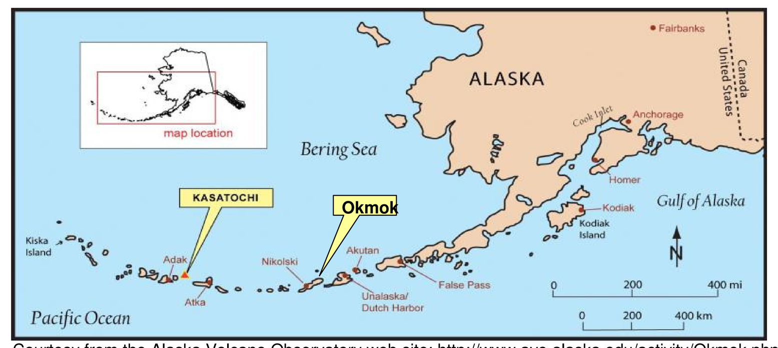
Ash and SO_2 were detected in the eruptions of Kasatochi and Okmok by infrared and UV sensors, including MODIS, AIRS and OMI. The simultaneous presence of ash and SO_2 in these clouds presents a problem for retrieving SO_2 column abundance because ash absorbs strongly near the 8.7 µm SO_2 absorption feature. This leads to a overestimation of the MODIS SO_2 abundance, unless the effects of ash are taken into account. Here, we use a new radiative transfer scheme to correct for the effects of ash on SO_2 retrieval at 8.7 µm and also account for the effects of ash on SO_2 retrieval at 7.3 µm, although this is much less severe, as we will demonstrate. The retrievals provide an improved quantitative description of the ash and SO_2 in volcanic eruptive clouds and will assist in developing warnings for aviation. A comparison between MODIS retrievals and contemporaneous OMI SO_2 retrievals and AIRS ash and SO_2 retrievals has been also presented.

Kasatochi

Between August 7 and August 8, 2008, three explosive eruptions occurred at the Kasatochi Volcano in the Aleutian Islands of Alaska. The thick plume of ash and sulfur dioxide released by the volcano reached an height of at least 11 Km. In the days that followed the eruption, different satellite instruments tracked a dense cloud that contained both sulfur dioxide and ash. The eruption produced one of the largest volcanic sulfur dioxide clouds observed since Chile's Hudson volcano erupted in August 1991.



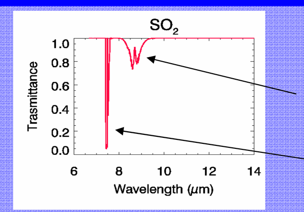
Courtesy from the Alaska Volcano Observatory web site: http://www.avo.alaska.edu/activity/Okmok.php

Okmok

The Okmok Volcano, also located within the Aleutian Island Chain, erupted on July 12, 2008 at approximately 11:43 a.m. local time, according to the Alaska Volcano Observatory. The eruption plume reached heights ranging initially from 9 to 11 Km and moved in a direction that was east to southeast of the volcano. Also in this case different satellite instruments detected and tracked the eruption plume for several days.

MODIS Retrievals and Ash correction procedure

SO_2 and Ash retrievals



The SO_2 columnar abundance is computed using a χ^2 procedure [*Realmuto et al., 1994*]:

$$\chi^2_{cs} = \sum_{i=1}^{n} \left[\frac{\underbrace{R_{s,i}}_{\text{Sensor radiance}} - \underbrace{R_{m,i}(c_s, 0, 0)}_{\text{Simulated radiance}}}{R_{s,i}} \right]^2 w_i$$

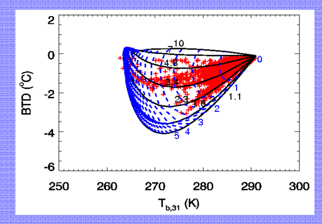
The ash detection is based on Brightness Temperature Difference algorithm applied on **11** and **12 µm** channels [*Prata, 1989*].

BTD= T_b(11µm)-T_b(12µm)

BTD < 0 volcanic ash

BTD > 0 meteo clouds

The retrieval is based on computing the simulated inverted arches curves "BTD-T_b(11µm)" varying the AOT and the particles effective radius [*Wen and Rose, 1994*]



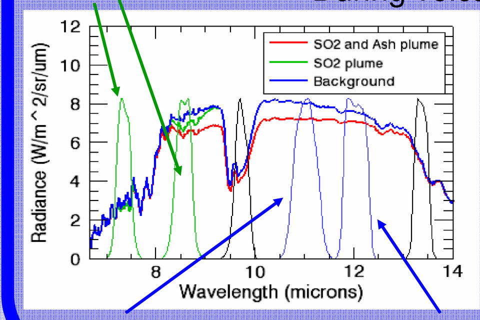
The **TOA simulated Radiances (R_m)**, needed for SO_2 and Ash retrievals, have been computed using MODTRAN 4 RTM

$$R_{m,i}(c_s, AOT, R_{eff})$$

- **21 values of c_s (0 to10 g/m², step 0.5 g/m²)**
- **11 values of AOT (0 to 5, step 0.5)**
- **8 values of R_{eff} (0.4 to 10 µm, constant step in a logarithmic scale)**

Ash correction procedure for SO_2 retrieval

MODIS slit functions used for SO_2 retrievals



MODIS slit functions for Ash retrieval

Why the ash correction?

During volcanic eruptions, SO_2 and ash are emitted simultaneously.

The plume ash particles reduce the top of atmosphere radiance in the entire TIR spectral range. The net effect is a significant SO_2 overestimation in particular when the 8.7 µm channel is used for the retrieval.

Procedure

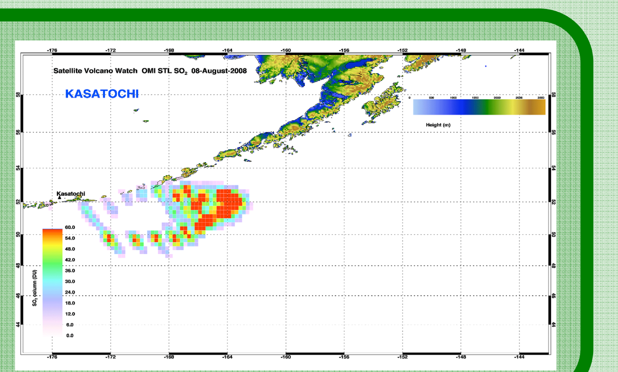
For each image pixel, containing both SO_2 and Ash, the least square fit procedure is applied with a simulated radiance interpolated using the AOT and the effective radius of the pixel itself.

$$\chi^2_{cs} = \sum_{i=1}^{n} \left[\frac{R_{s,i} - R_{m,i}(c_s, AOT_k, R_{eff,k})}{R_{s,i}} \right]^2 w_i$$

Kasatochi

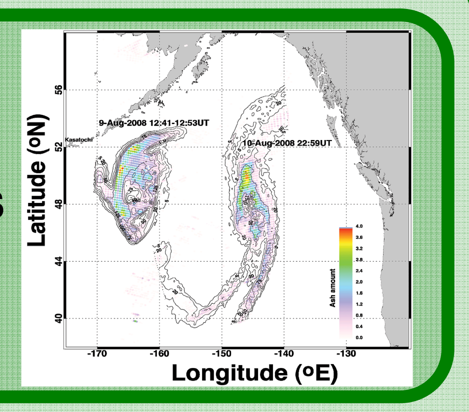
OMI SO_2

OMI SO_2 retrievals on 8 August 2008



AIRS SO_2

Contours of SO_2 and pixels where ash has been detected in AIRS data on 9 and 10 August, 2008



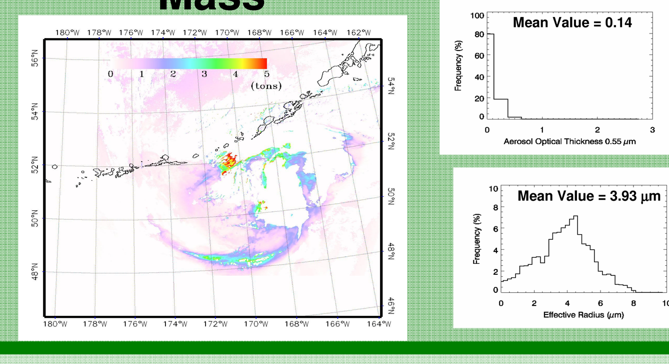
08 August 2008, 23:05 UTC

MODIS Ash

Mass

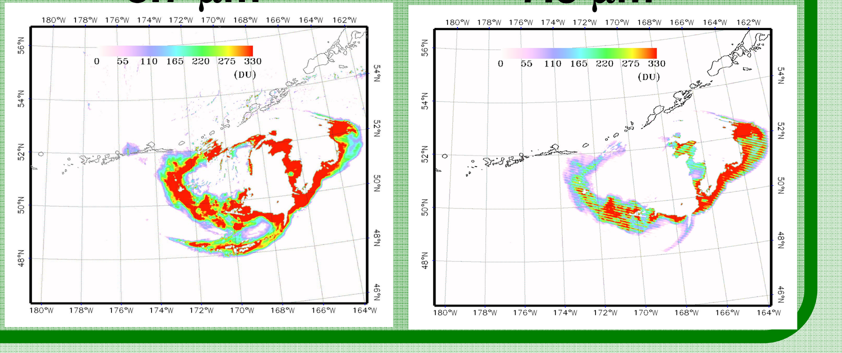
AOT (0.55 µm)

Effective Radius



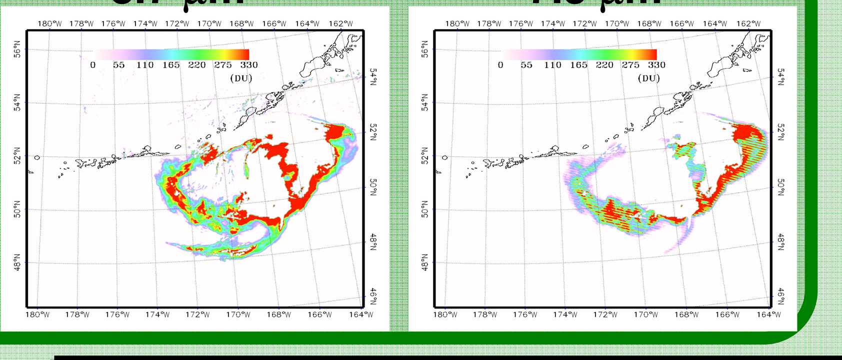
MODIS SO_2 Before Correction

8.7 µm **7.3 µm**



MODIS SO_2 After Correction

8.7 µm **7.3 µm**



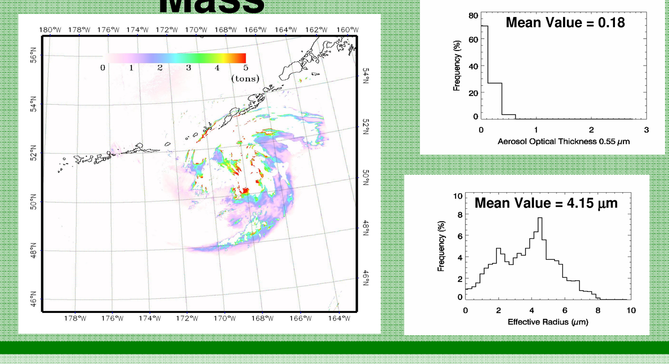
09 August 2008, 00:50 UTC

MODIS Ash

Mass

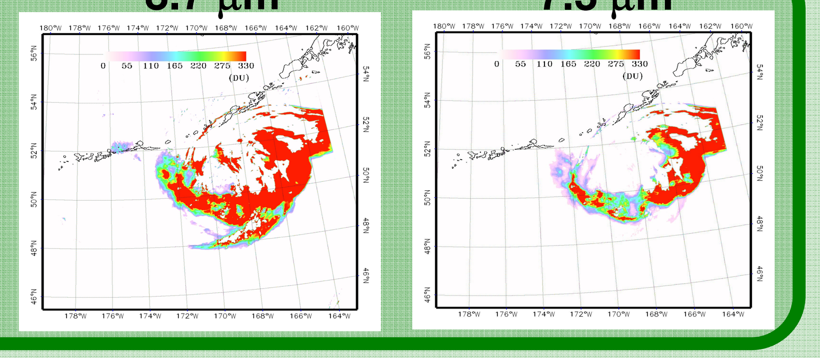
AOT (0.55 µm)

Effective Radius



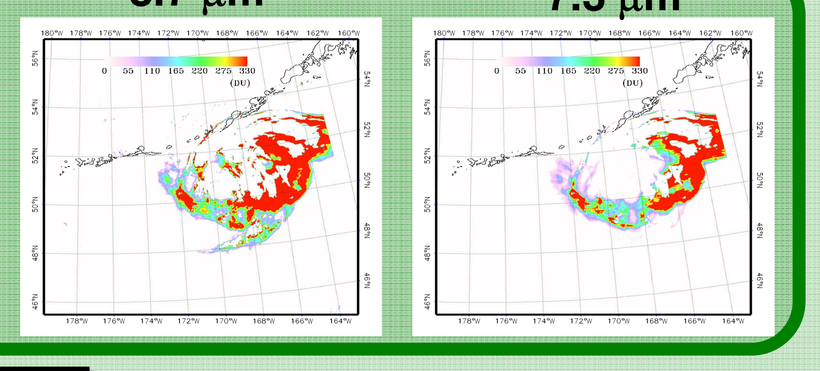
MODIS SO_2 Before Correction

8.7 µm **7.3 µm**



MODIS SO_2 After Correction

8.7 µm **7.3 µm**



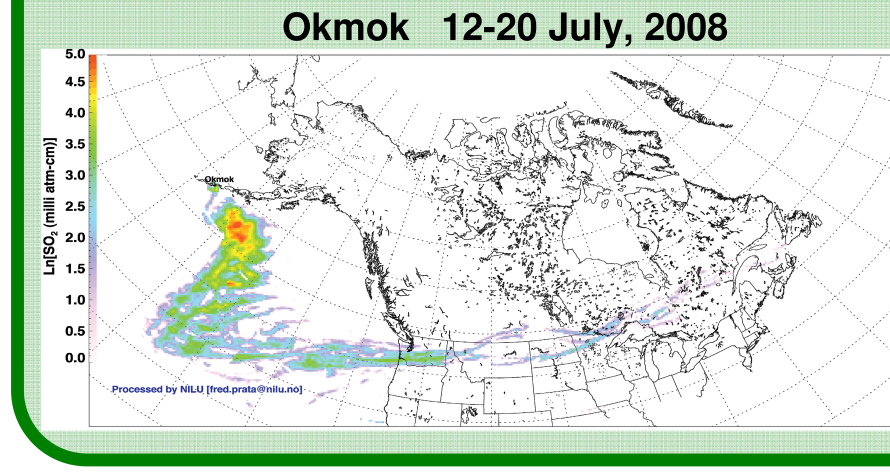
SO_2 mass (Tg)	OMI	AIRS[1]	MODIS (7.3 µm)	MODIS Correct. (7.3 µm)	MODIS (8.7 µm)	MODIS Correct. (8.7 µm)
8 August 2008	0.98	0.41	1.01	0.95	1.53	1.24
9 August 2008	0.88	0.62	1.02	0.95	1.70	1.36

Ash mass (Tg)	MODIS
8 August 2008	0.17
9 August 2008	0.16

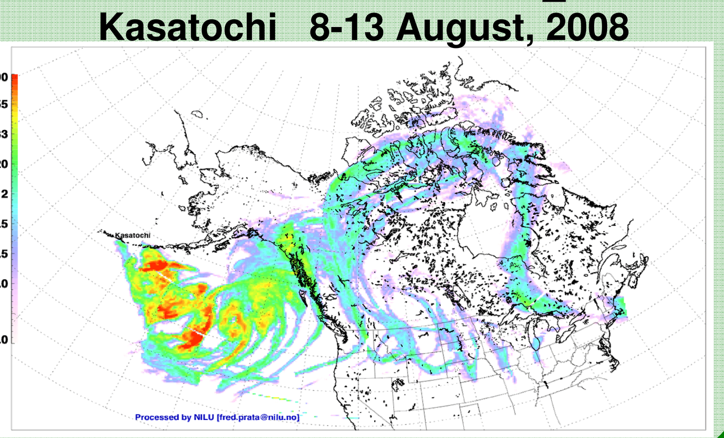
[1]Note that AIRS measures SO_2 in the upper troposphere/lower stratosphere and usually underestimates the total column if significant SO_2 lies in the lower troposphere.

AIRS 7.3 µm Cumulative retrievals of SO_2

Okmok 12-20 July, 2008

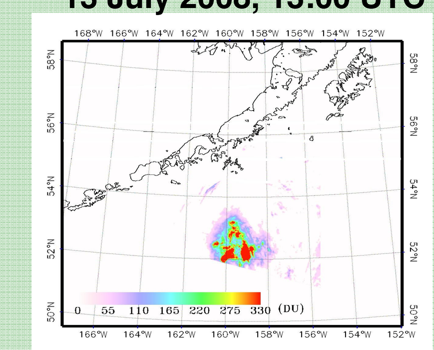


Kasatochi 8-13 August, 2008

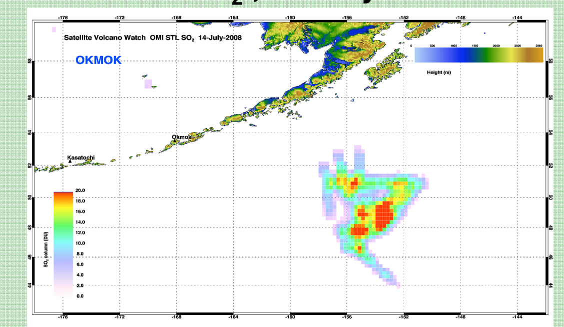


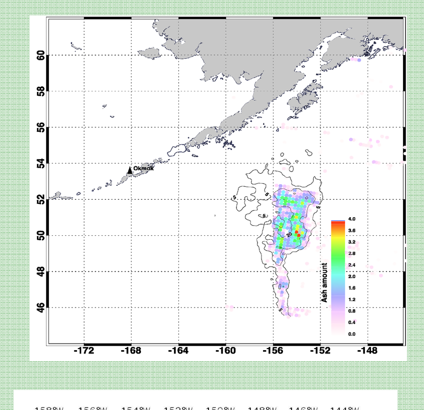
Okmok

MODIS SO_2 (7.3µm)
13 July 2008, 13:00 UTC

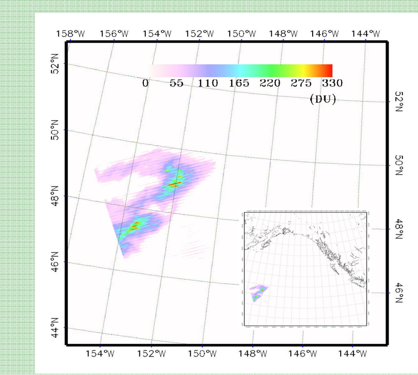


OMI SO_2 , 14 July 2008





AIRS SO_2 (contours) and ash (coloured dots) 14 July 2008



MODIS SO_2 (7.3µm) 15 July 2008 07:05 UTC

SO_2 mass (Tg)	OMI	AIRS	MODIS (7.3 µm)
13 July 2008	0.16	0.09	0.17
14 July 2008		0.07	X
15 July 2008		0.07	0.16

Conclusions

- Ash and SO_2 were detected in both Okmok and Kasatochi eruptions by AIRS.
- Ash and SO_2 (using both 7.3 and 8.7 µm channels) were detected by MODIS for Kasatochi eruption. For Okmok the SO_2 is retrieved only at 7.3 µm because the irregular atmospheric clouds under the plume prevents the definition of the background temperature (a key input parameter for the SO_2 retrieval at 8.7 µm).
- The ash correction for SO_2 MODIS retrieval on Kasatochi results meaningful for 8.7 µm and negligible for 7.3 µm as expected.
- The ash and SO_2 were collocated and travelled together.
- The SO_2 retrievals from the different instruments and for both eruptions show a good agreement.
- The AIRS concavity algorithm could be used to define the ash type. This information can be used to improve the MODTRAN simulations and therefore the MODIS ash and SO_2 retrievals.

References

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Gangale, G., Prata, A. J., and L. Clarisse, On the infrared signature of volcanic ash, *Submitted to Geophys. Res. Lett.*, 2008.

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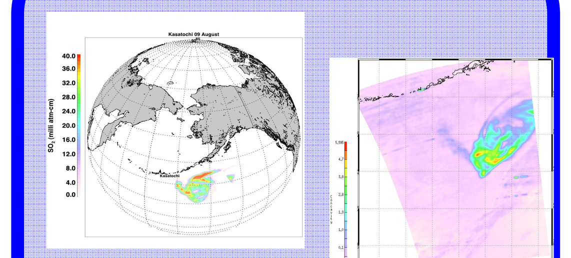
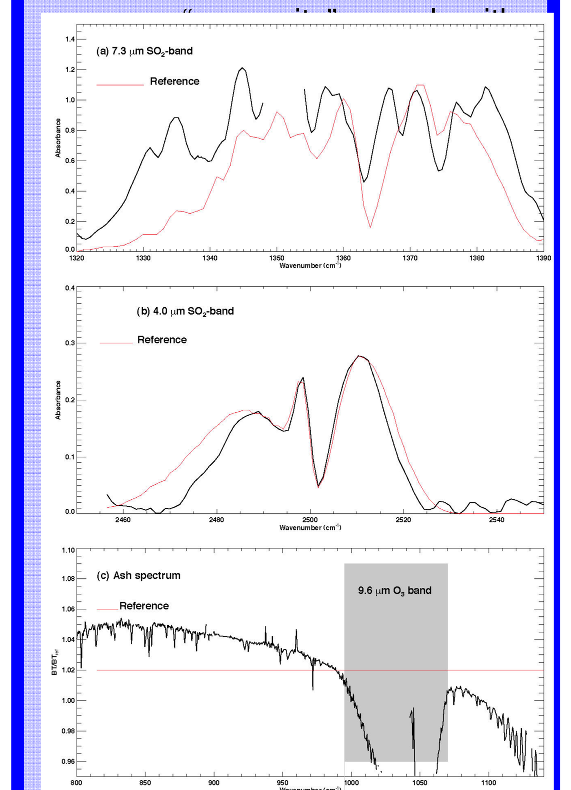
Realmuto, V.J., Abrams M.J., Buongiorno M.F., Pieri D.C., The use of multispectral thermal infrared image data to estimate the sulfur dioxide flux from volcanoes: a case study from Mount Etna, Sicily, July 29, 1986. *J. Geophys. Res.* **99** (B1), 481– 488, 1994.

Wen, S. and Rose W., Retrieval of sizes and total masses of particles in volcanic aerosol clouds using AVHRR bands 4 and 5. *J. Geophys. Res.*, **99**(D3), 5421–5431, 1994.



SO_2 & Ash from AIRS

SO_2 gas and volcanic ash are erupted from volcanoes and can enter the atmosphere to reach heights that make them a hazard to aircraft. Several satellite-borne instruments are capable of detecting both substances. SO_2 is more readily identified and quantified than ash, but it is less hazardous to jet aircraft. In the likely case that the ash and SO_2 are collocated and travel together, a sensible strategy is to identify SO_2 and use it as a surrogate to locate airspace likely to be affected by ash. Our work shows that in the first few days after the eruptions of Kasatochi and Okmok, the ash and SO_2 were collocated and continued to travel together. Data from the AIRS instrument (http://airs.jpl.nasa.gov) have been used to unambiguously indentify ash and SO_2. The SO_2 is detected at two absorption regions centred near 4 µm and 7.3 µm, while the ash is detected using the



The top panel shows the measured absorbance spectrum (black line) compared with a reference spectrum of SO_2. The middle panel shows the absorbance spectra for the 4.0 µm SO_2 band. The bottom panel shows the variation of the ratio of brightness temperature spectra of a pixel within the cloud to a reference pixel outside the cloud. The slope of these spectra with wavelength is characteristic of volcanic ash.