Advantageous GOES IR results for ash mapping at high latitudes: Cleveland eruptions 2001

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[1]   The February 2001 eruption of Cleveland Volcano, Alaska allowed for comparisons of volcanic ash detection using two-band thermal infrared (10–12 μm) remote sensing from MODIS, AVHRR, and GOES 10. Results show that high latitude GOES volcanic cloud sensing the range of about 50 to 65°N is significantly enhanced. For the Cleveland volcanic clouds the MODIS and AVHRR data have zenith angles 6–65 degrees and the GOES has zenith angles that are around 70 degrees. The enhancements are explained by distortion in the satellite view of the cloud's lateral extent because the satellite zenith angles result in a "side-looking" aspect and longer path lengths through the volcanic cloud. The shape of the cloud with respect to the GOES look angle also influences the results. The MODIS and AVHRR data give consistent retrievals of the ash cloud evolution over time and are good corrections for the GOES data. **Citation:** Gu, Y., W. I. Rose, D. J. Schneider, G. J. S. Bluth, and I. M. Watson (2005), Advantageous GOES IR results for ash mapping at high latitudes: Cleveland eruptions 2001, *Geophys. Res. Lett.*, *32*, L02305, doi:10.1029/2004GL021651.

1. Introduction

[2]   Current meteorological satellites are very useful for the observation of volcanic ash by using the split window algorithm in the thermal infrared (~10–12 μm wavelength) [*Prata*, 1989; *Rose and Schneider*, 1996; *Davies and Rose*, 1998; *Rose and Mayberry*, 2000; *Yu and Rose*, 2000]. Such data are available on meteorological satellites (GOES and AVHRR) and also on MODIS. GOES 10 (Geostationary Operational Environmental Satellites) two-band IR channels we used here are bands 4 and 5 (centered at 10.7 and 12 μm) which have a spatial resolution of about 4 km at nadir. The advantage of the GOES 10 data is that the temporal resolution is very high (~30 minutes), which allows retrieval of smaller or short-lived volcanic clouds and helps remove uncertainty in detection [*Rose and Mayberry*, 2000]. MODIS (Moderate Resolution Imaging Spectroradiometer) was launched in December 1999 aboard the Terra satellite. It has high spatial resolution (1 km at nadir) and large numbers of channels (36 channels, wavelength range from 645 nm to 14.2 μm) that allow scientists to detect, track, and measure the volcanic clouds more effectively. Channel 31 and 32 (centered at 11.03 and 12.02 μm) are used to retrieve the volcanic ash based on the work of *Prata* [1989] and *Wen and Rose* [1994]. In order to fill the time gap of the MODIS images in this study, Advanced Very High Resolution Radiometer (AVHRR) band 4 and 5 (centered at 10.8 and 12.0 μm) are also used in the volcanic ash retrievals. For comparison purposes, GOES and MODIS data have been rebinned into 5×5 km^2 pixels.

[3]   Cleveland volcano, located at 52°49′N, 169°57′W, 1500 km southwest of Anchorage, had explosive volcanic eruptions on February 19, March 11 and March 19, 2001. *Simpson et al.* [2002] have reported on the detection of this cloud using GOES data. The February 2001 eruption allowed for comparisons of volcanic ash detection by using MODIS, AVHRR, and GOES 10 data. The algorithm for converting thermal infrared brightness temperature (BT) and brightness temperature differences (BTD) of two thermal infrared channels of AVHRR to retrieve the mass of volcanic ash was developed by *Wen and Rose* [1994]. In this paper, we performed retrievals on GOES 10, MODIS, and AVHRR images of volcanic clouds using *Wen and Rose*'s [1994] method. The data sets differ in spatial resolution and satellite zenith angle. The MODIS and AVHRR data have zenith angles between 6–65 degrees and the GOES 10 has zenith angles for the Cleveland volcanic clouds that are around 70 degrees. Because of the geometry, the rectified footprints of GOES 10 volcanic cloud areas are much larger than those of MODIS and the magnitude of the negative brightness temperature difference is also higher. The differences are explained by distortion in the viewing of the cloud's lateral extent because of the side-looking aspect and the longer path length through the volcanic cloud because of the high zenith angle.

2. Volcanic Clouds in GOES 10 and MODIS Images

[4]   AVHRR bands 4 minus band 5 BTD images are used in the *Wen and Rose* [1994] model to discern the volcanic clouds from meteorological clouds. Meteorological clouds usually have positive BTD [*Yamanouchi et al.*, 1987] and volcanic ash clouds have negative BTD [*Prata*, 1989; *Wen and Rose*, 1994]. Brightness temperature difference images from MODIS and GOES 10 for closely associated times during the Cleveland volcanic cloud episode are shown in Figure 1. The first MODIS image (Figure 1a) is at the edge of a swath, so it cuts off the western edge of the volcanic cloud. In the earlier stage of the volcanic cloud (for both GOES 10 and MODIS), the maximum BTD in the center of

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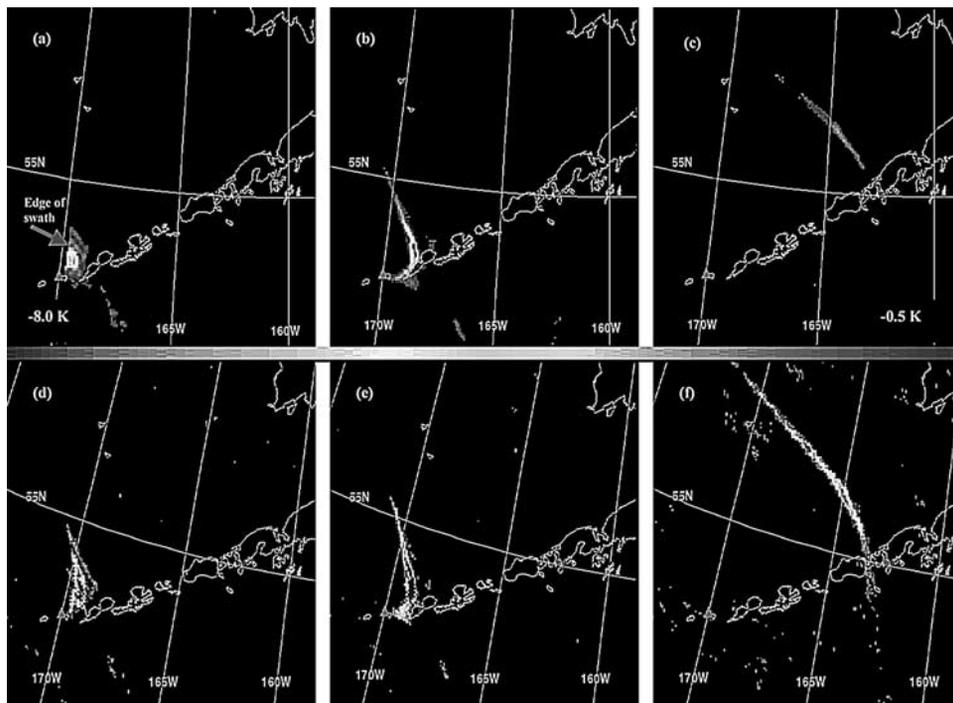
Figure 1. Brightness temperature difference (band4−band5) images from MODIS and GOES 10 for closely associated times during the Cleveland volcanic cloud episode. The red triangle represents Cleveland volcano. (a) 21:30 UT, February 19, 2001 MODIS image (b) 23:10 UT, February 19, 2001 MODIS image (c) 08:45 UT, February 20, 2001 MODIS image (d) 22:00 UT, February 19, 2001 GOES 10 image (e) 23:00 UT, February 19, 2001 GOES 10 image (f) 08:00 UT, February 20, 2001 GOES 10 image. For the comparison purposes, GOES and MODIS data have been rebinned into 5 × 5 km^2 pixels. See color version of this figure in the HTML.

the volcanic cloud is around −9 K, which represents a strong silicate ash cloud signal. Figure 1 indicates that the magnitude of the negative BTD for the GOES 10 images are 1 to 3 times higher than that in the MODIS images at the similar time. This may be because of the satellite zenith angle, which produces a longer path length through the volcanic cloud to the satellite (Figure 2a) and thus enhances the BTD (the ratio of the secants of the respective viewing angles of GOES and MODIS indicates the factor can be up to 3 times). The satellite zenith angle is the angle between the satellite and a line perpendicular to the earth's surface at the viewpoint. The zenith angle will influence brightness temperatures measured by the sensor. In addition, the cloud areas detected by GOES 10 shown in Figure 1 are 1−3 times larger than those detected by MODIS (see also Figure 3). We suggest that this difference is due to the larger zenith angle which will let satellite sees a larger area below any particular BTD cutoff value (Figure 2b). Figure 2 shows how the satellite zenith angle affects a simple shape (square) of cloud edge area (ash cloud is assumed in one thin homogeneous layer parallel to the surface) detection. The enlarged area detected by the satellite should be $\sqrt{1 + \left(\frac{h}{y}\right)^2}$ times larger than the true area. The final pair of comparisons (the February 20 images) in Figure 1 indicates that MODIS data have smaller BTD values (less −3.0 K) while GOES 10 have larger BTD values (−8.0 K). This latter pair shows the enhancement of GOES 10 best because the zenith angle of MODIS at that time is just 6 degrees. The
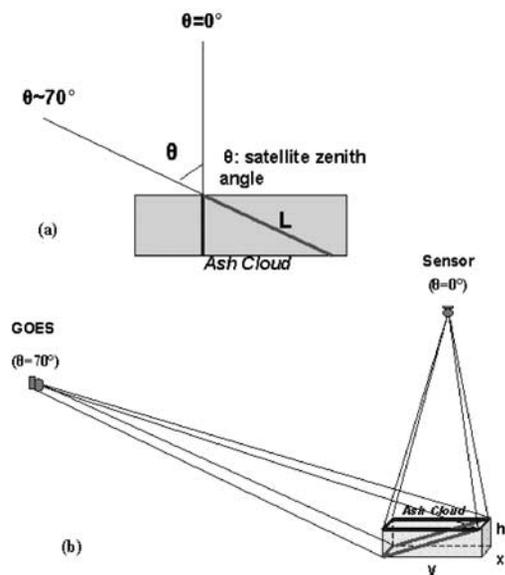
Figure 2. A large satellite zenith angle affects a simple shape (square) cloud detection (ash cloud is assumed in one thin homogeneous layer parallel to the surface). (a) Large satellite zenith angle causes longer path length L (red line) through the volcanic cloud. (b) Large satellite zenith angle affects the volcanic cloud edge area detection, h is the geometric thickness of the cloud, x and y represent the width and length of the cloud. The red square is the area detected by the GOES which is $\sqrt{1 + \left(\frac{h}{y}\right)^2}$ larger than the true (synoptic) area. See color version of this figure in the HTML.
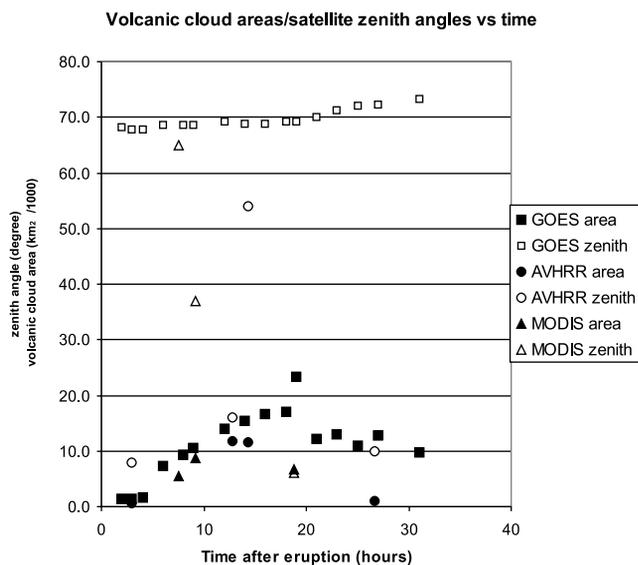
Figure 3. The satellite zenith angles/volcanic cloud areas versus time after eruption. See color version of this figure in the HTML.

volcanic cloud areas versus satellite zenith angles are shown in Figure 3.

3. Retrieval of Ash Masses Using Two Thermal Infrared Bands

[5] The mass of fine ash retrieved using the split window method is a small fraction ($<1-3\%$) of the total mass of ash erupted, because the largest amounts of the ash are coarse (>1 mm) and fall out very quickly (within 30 minutes following the eruption) [*Rose et al.*, 1995]. The BTD retrieval method assumes that the ash particle is within the Mie region (about $1-15$ μm diameter) [*Prata*, 1989]. Figure 4 shows retrieval maps of pixel mean mass of ash in volcanic cloud [after *Wen and Rose*, 1994] using the same six Cleveland images shown in Figure 1.
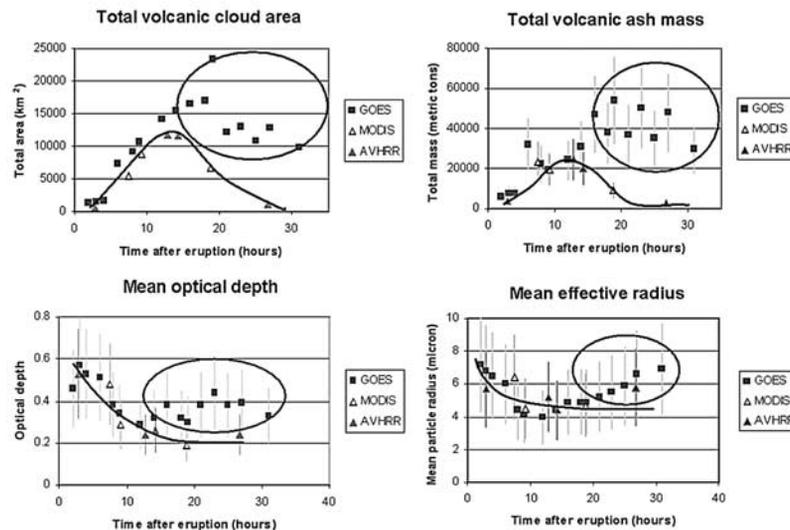
[6] The first pair of the GOES 10 and MODIS images (Figures 4a and 4d) is at the beginning of the eruption and there are only slight differences. The area of the ash cloud from the GOES 10 image is only slightly larger than MODIS image. The maximum pixel mean mass of the volcanic ash is nearly 400 metric tons per pixel (25 square kilometers). For the last pair compared in Figures 4c and 4f (19 hours after eruption), the total amount of ash in the volcanic cloud is ~3 times larger for GOES 10 image than the MODIS image. The area of cloud is also significantly larger. The third pair of images we compared shows a large degree of difference probably because of the significant zenith angle difference between MODIS ($\sim6°$) and GOES ($\sim70°$).

[7] The retrieval results for GOES 10, MODIS, and AVHRR data are listed in sequence in Table 1. The maximum mean effective radius of the ash listed in Table 1 is initially 7.2 μm and then decreases with time to 4.5 μm. The decrease of the mean retrieved radius is mainly due to the evolution of the cloud as the smaller particles have longer residence time. The highest optical depth values are also in the earliest GOES images. The maximum optical depth value then decreases to 0.29 after ten hours of eruption. All retrieval results from GOES 10, MODIS and AVHRR data [*Rose et al.*, 2000, 2001] are plotted against time in Figure 5. Because the particle size distribution and refractive index of Cleveland ash particles are known, the retrieval error is estimated to be $\sim40\%$ [*Wen and Rose*, 1994; *Gu et al.*, 2003]. The minimum optical depth for MODIS retrieval shown in Figure 5 is 0.19, after 19 hours of eruption. MODIS retrievals indicate that the optical depth of the volcanic cloud decreases with time, which is consistent with dilution of the volcanic cloud with time. We have plotted black lines which show expected trends of cloud evolution based on other volcanic cloud studies [*Rose et al.*, 2000]. Those trends are consistent with MODIS, AVHRR, and early GOES data for Cleveland, but differ from the later GOES results, whereas the retrieval results (cloud areas, total ash mass, and mean optical depth) from MODIS and AVHRR sensors are generally consistent throughout the observation period. The volcanic cloud areas, mean optical
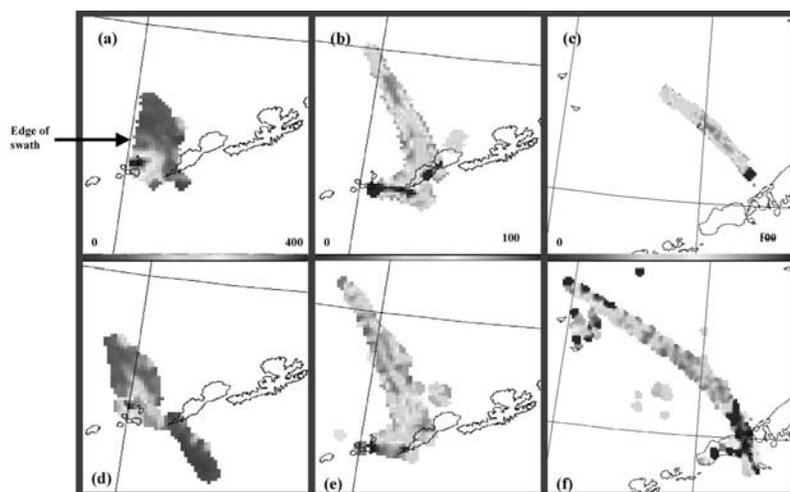
Figure 4. The retrieval maps of pixel mean mass (metric ton) of ash in volcanic cloud. (a) 21:30 UT, February 19, 2001 MODIS image (b) 23:10 UT, February 19, 2001 MODIS image (c) 08:45 UT, February 20, 2001 MODIS image (d) 22:00 UT, February 19, 2001 GOES 10 image (e) 23:00 UT, February 19, 2001 GOES 10 image (f) 08:00 UT, February 20, 2001 GOES 10 image. See color version of this figure in the HTML.

Table 1. The Retrieval Results for All the GOES 10, MODIS and AVHRR Images in the Time Sequence[a]

Sensor	GOES	AVHRR	GOES	GOES	GOES	MODIS	GOES	GOES	MODIS	GOES	AVHRR	GOES	AVHRR	GOES	GOES	MODIS	GOES	GOES	GOES	GOES	AVHRR	GOES	GOES
Date	02/19	**02/19**	02/19	02/19	02/19	**02/19**	02/19	02/19	**02/19**	02/20	**02/20**	02/20	**02/20**	02/20	02/20	**02/20**	02/20	02/20	02/20	02/20	**02/20**	02/20	02/20
Time	16:00	**16:53**	17:00	18:00	20:00	**21:30**	22:00	23:00	**23:10**	02:00	**02:46**	04:00	**04:20**	06:00	08:00	**08:45**	09:00	11:00	13:00	15:00	**16:41**	17:00	21:00
Zenith angle (degree)	68.2	**8.0**	67.9	67.9	68.6	**65.0**	68.6	68.6	**37.6**	69.2	**16.0**	68.9	**54.0**	68.9	69.3	**6.0**	69.3	70.0	71.3	72.0	**10.0**	72.3	73.4
Mean effective radius (μm)	7.2	**5.7**	6.8	6.5	6.0	**6.4**	4.4	4.1	**4.5**	4.0	**5.2**	4.4	**4.4**	4.9	4.9	**4.7**	4.9	5.2	5.5	5.9	**5.8**	6.6	6.9
Mean particle radius (μm)	2.4	**1.9**	2.3	2.2	2.0	**2.1**	1.5	1.4	**1.5**	1.3	**1.8**	1.5	**1.5**	1.6	1.6	**1.6**	1.7	1.7	1.8	2.0	**2.0**	2.2	2.3
Mean optical depth (unitless)	0.46	**0.53**	0.57	0.53	0.51	**0.48**	0.38	0.34	**0.29**	0.29	**0.24**	0.32	**0.26**	0.38	0.32	**0.19**	0.30	0.38	0.44	0.38	**0.24**	0.39	0.33
Total cloud area (km²)	1372	**675**	1425	1603	7300	**5572**	9250	10626	**8801**	14100	**11850**	15465	**11639**	16550	17025	**6734**	23291	12200	12975	10875	**1100**	12850	9800
mean mass/km² (Metric tons)	4.3	**5.4**	5.5	4.8	4.4	**4.2**	2.4	1.8	**2.2**	1.7	**2.1**	2.0	**1.7**	2.8	2.2	**2.0**	2.3	3.0	3.7	3.2	**2.6**	3.7	3.0
Total ash mass (Metric tons)	5872	**3628**	7809	7632	32030	**23472**	22326	19557	**19492**	24076	**24761**	30930	**20245**	46960	37658	**9112**	54034	36504	50261	34933	**2818**	48023	29461

[a]The retrieval results from MODIS are in bold fonts with outline, AVHRR are in bold fonts.

Figure 5. The retrieval results of total area of volcanic cloud, total mass of ash, mean optical depth, and mean effective radius are displayed versus time for GOES 10, MODIS, and AVHRR data. The eruption began at ~14:00 UTC (http://www.avo.alaska.edu/avo4/atlas/volc/cleve/cleveFeb2001/clevesatellite.htm). The values that are overestimated by GOES 10 data are circled. The expected trends of cloud evolution based on other volcanic cloud studies are plotted with black lines. Data are from Table 1. See color version of this figure in the HTML.

depth, mean particle radius, and total mass of ash of volcanic ash overestimated by GOES 10 data are circled. They occur after 15 hours of residence when volcanic cloud has an optical depth less than about 0.2 (MODIS value). Figure 5 demonstrates that though there are fewer MODIS (and AVHRR) images available in the Cleveland eruption, these data may give a more accurate measure of the ash cloud evolution.

[8] The GOES-10 11 μm brightness temperature images indicate the background meteorological clouds interfere with the volcanic cloud mainly before 2000 UTC on February 19 [*Simpson et al.*, 2002]. During most of the period for our retrieval, the atmospheric conditions are dry due to the relative small amounts of cloud cover and polar upper air condition. The total mass retrievals affected by meteorological conditions are less than 10% for Cleveland volcanic cloud if the atmospheric moisture correction method developed by *Yu et al.* [2002] is applied.
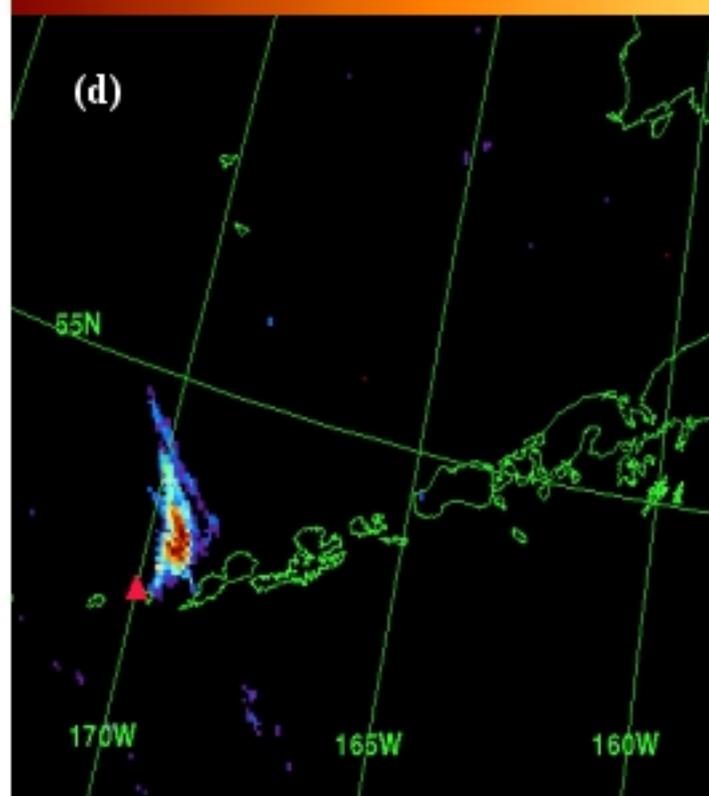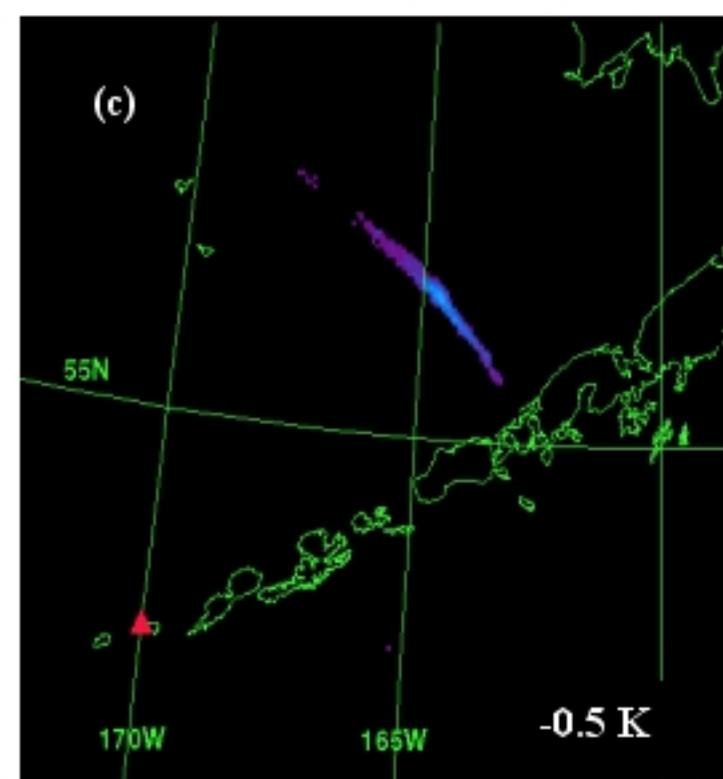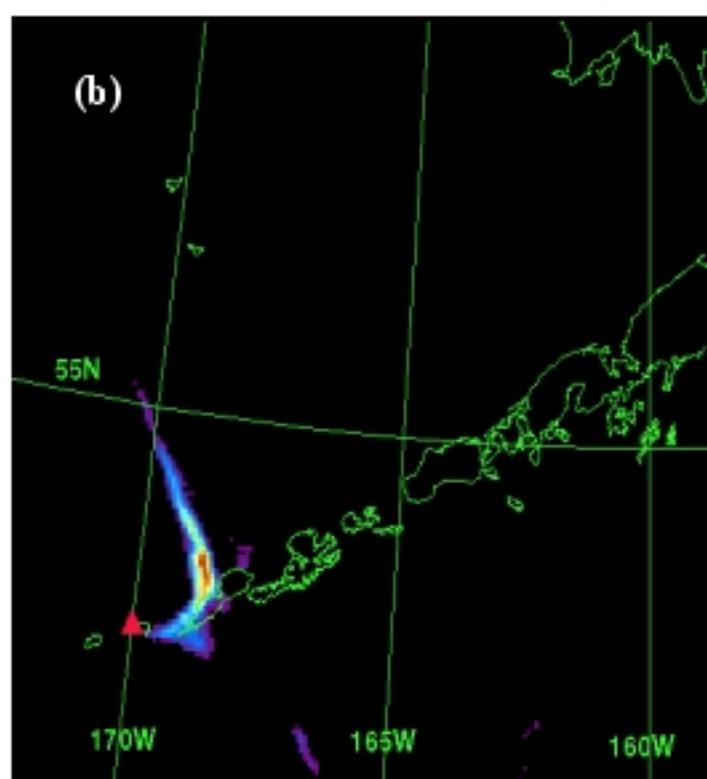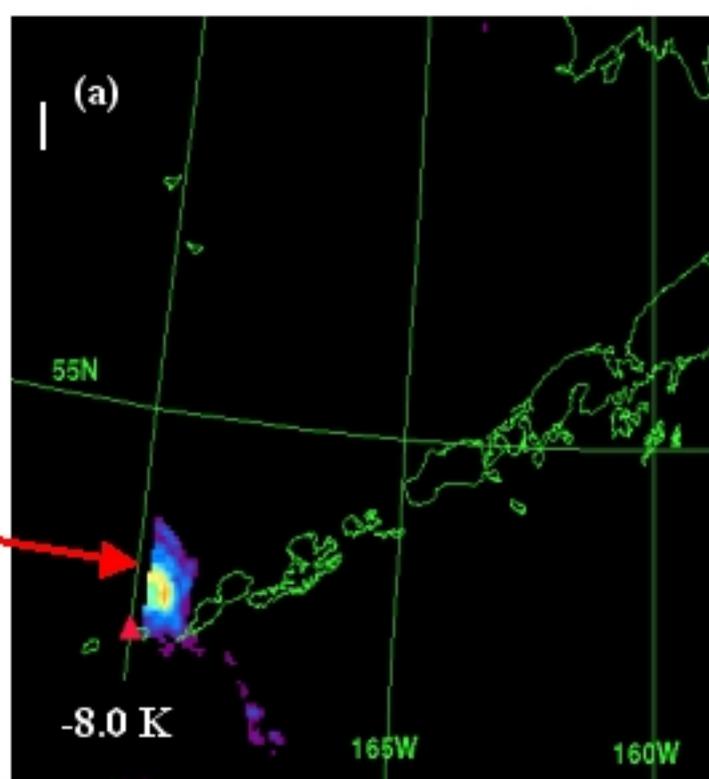
4. Conclusions

[9] GOES 10 satellite data collected at high latitudes with high zenith angles produces advantageous data on volcanic ash-bearing clouds as long as the zenith is around 70 degrees. The high zenith angles enhance the aged, optically thin volcanic clouds, and in fact produce cloud images which overestimate the "true" 2-dimensional areas. Volcanic ash mass retrievals from GOES 10, MODIS, and AVHRR data (utilizing similar wavelengths) are generally in agreement with each other during early stages (tens of hours) of cloud transport. One of the data comparisons (February 20 images) produced a large disagreement, which is mostly due to the significant difference of the zenith angle of different sensors. The MODIS and AVHRR data give consistent retrievals of the ash cloud evolution over time and are good corrections for the GOES 10 data, when such mass estimates are needed.
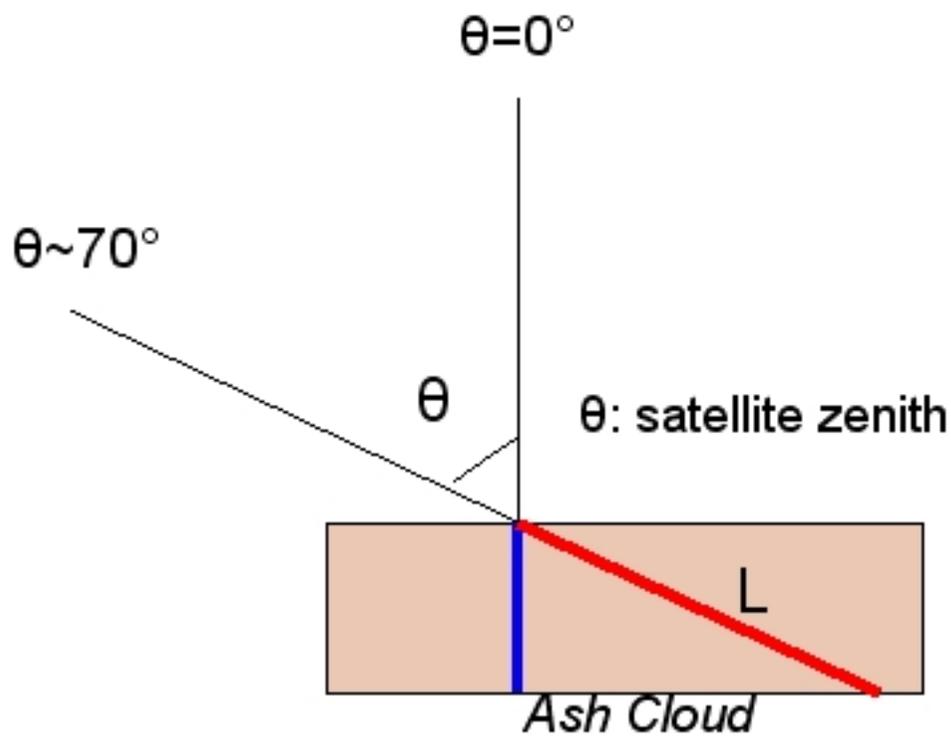
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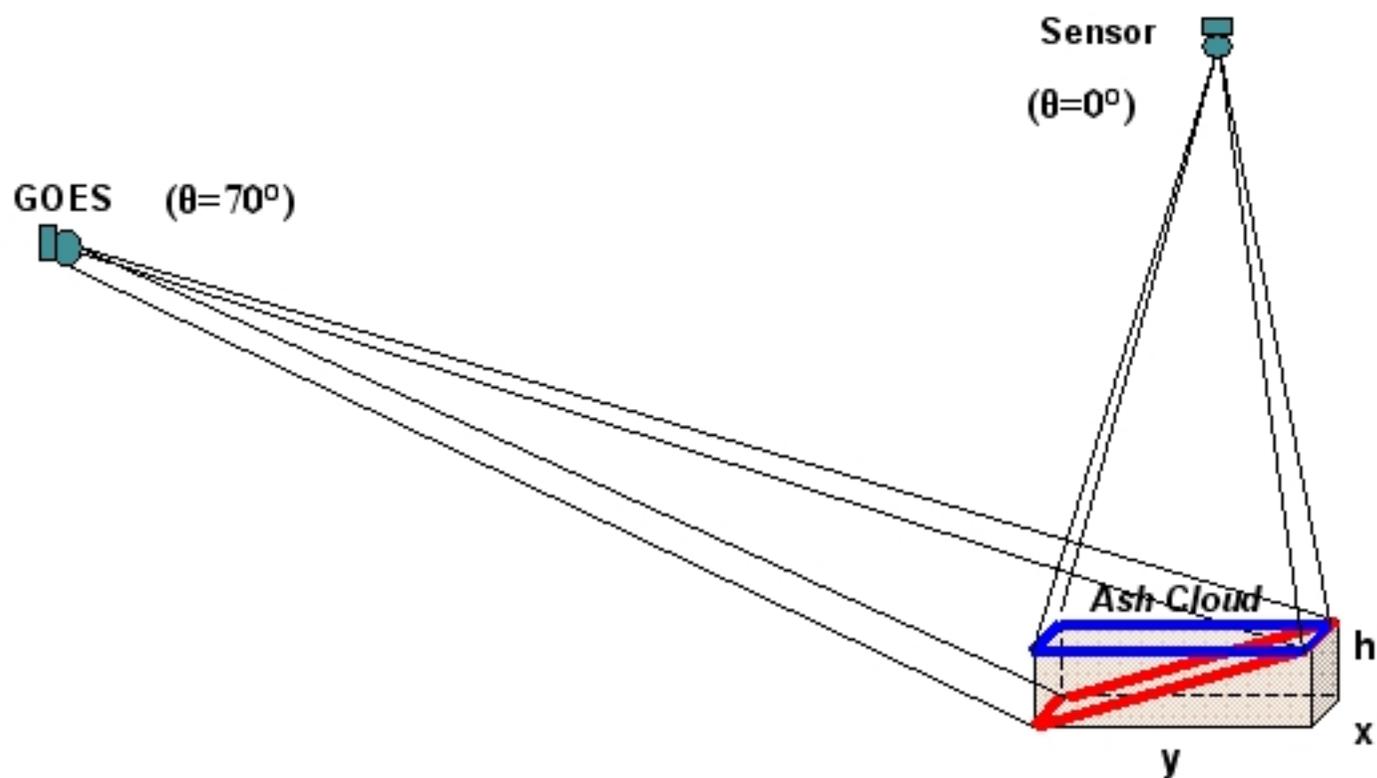
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G. J. S. Bluth, Y. Gu, W. I. Rose, D. J. Schneider, and I. M. Watson, Department of Geological Engineering and Sciences, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931-1295, USA. (yigu@mtu.edu)

(a)

-8.0 K

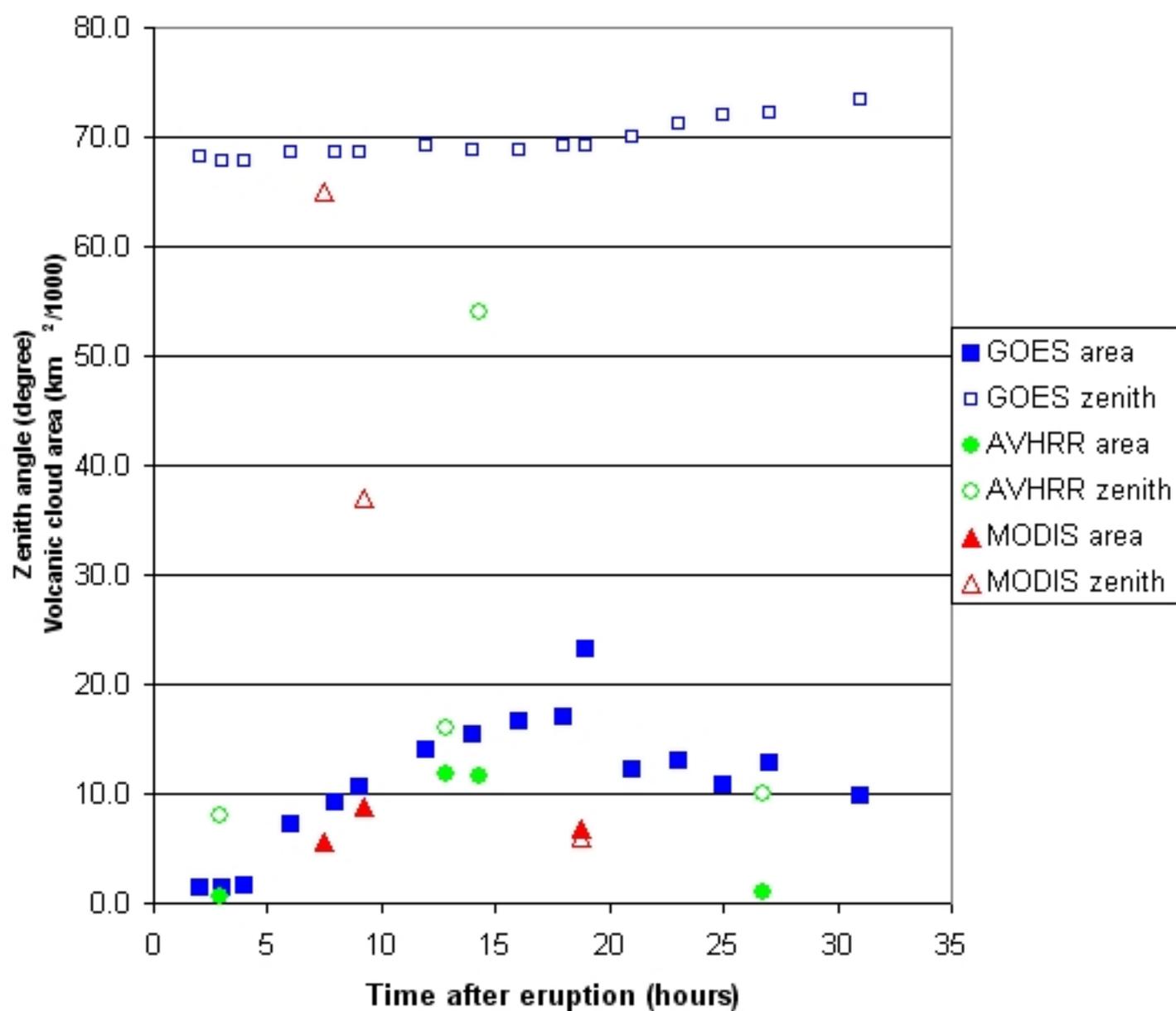Edge of
swath

55N

165W

160W

(b)

55N

170W

165W

160W

(c)

55N

-0.5 K

170W

165W

(d)

55N

170W

165W

160W

(e)

55N

170W

165W

160W

(f)

55N

170W

165W

160W

θ=0°

θ~70°

θ

θ: satellite zenith

(a)

L
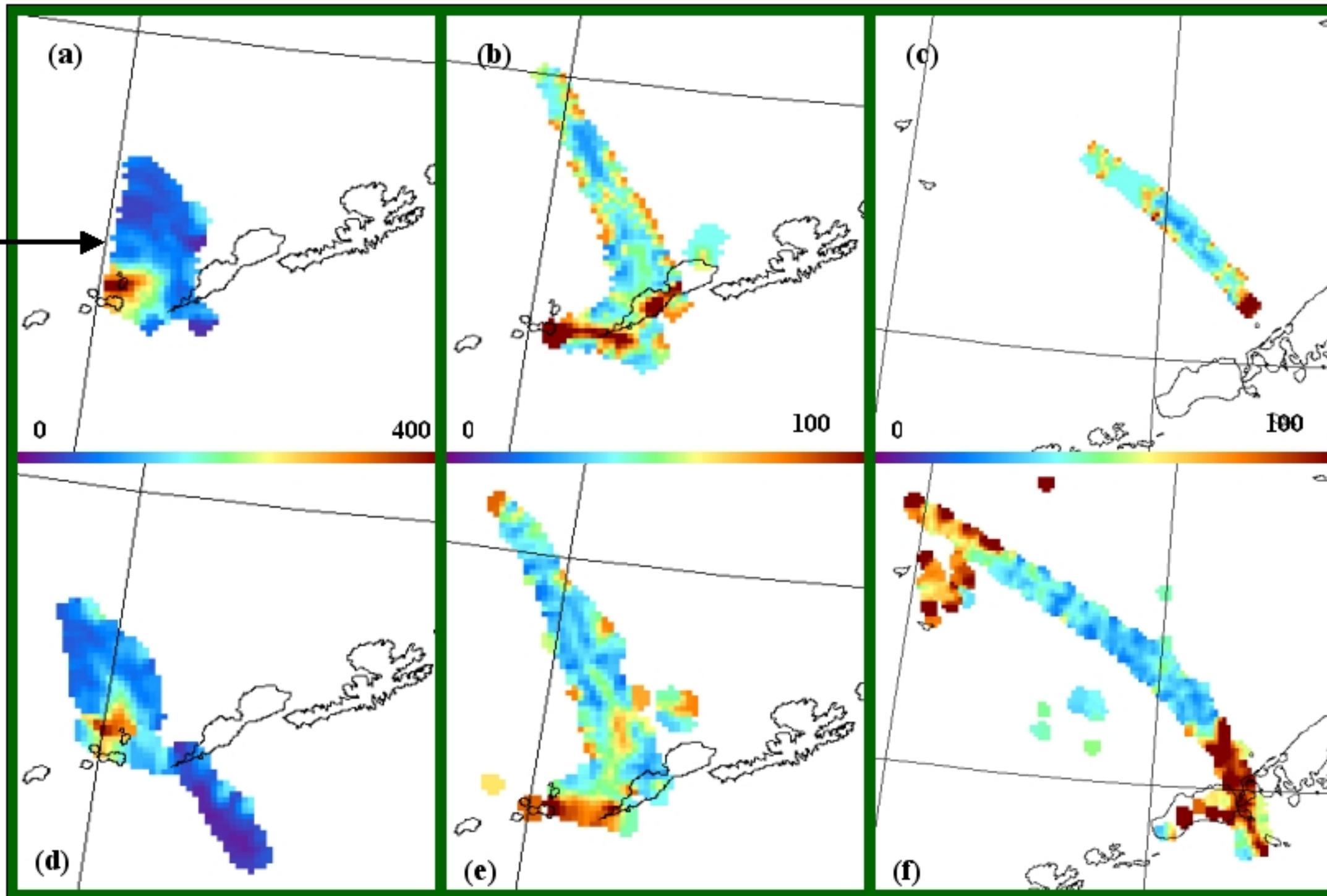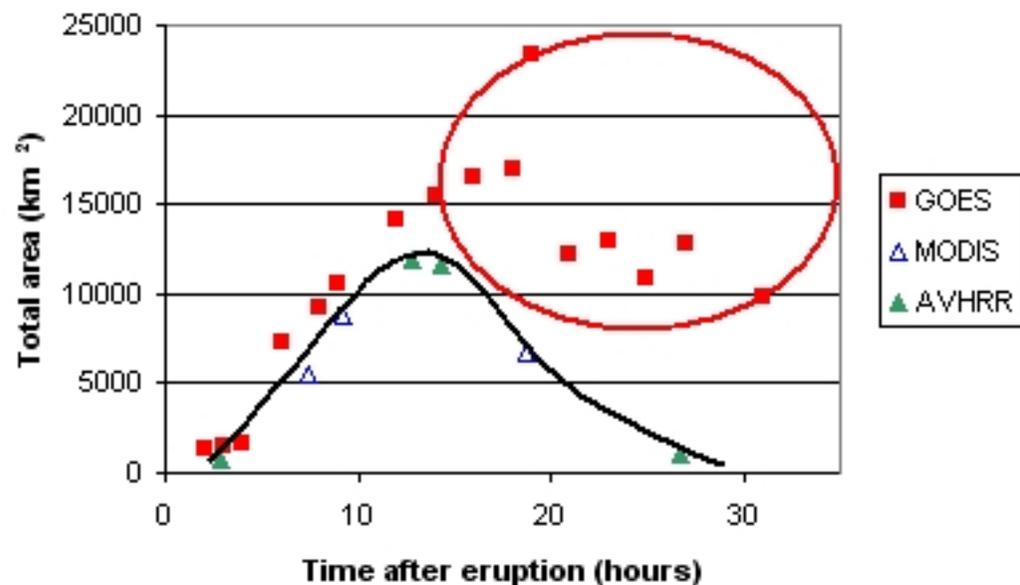
Ash Cloud

Sensor

(θ=0°)

GOES (θ=70°)

Ash Cloud

h

x

y
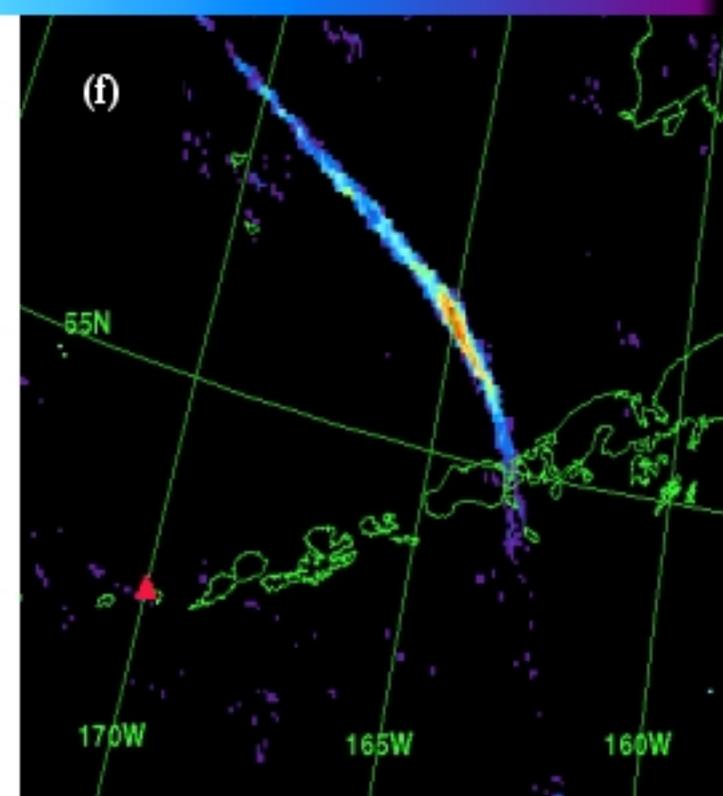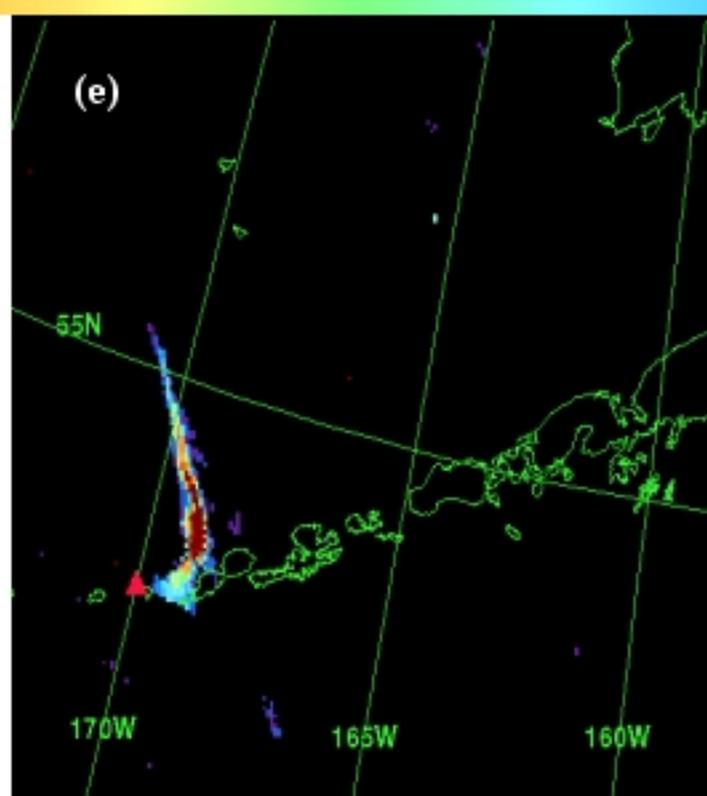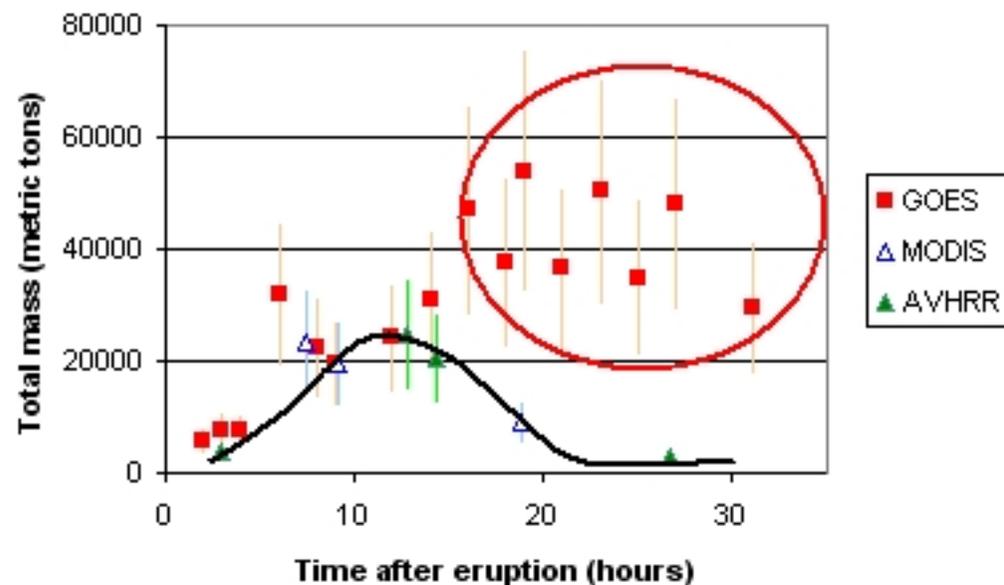
(b)

Volcanic cloud areas/satellite zenith angles vs time

Edge of swath
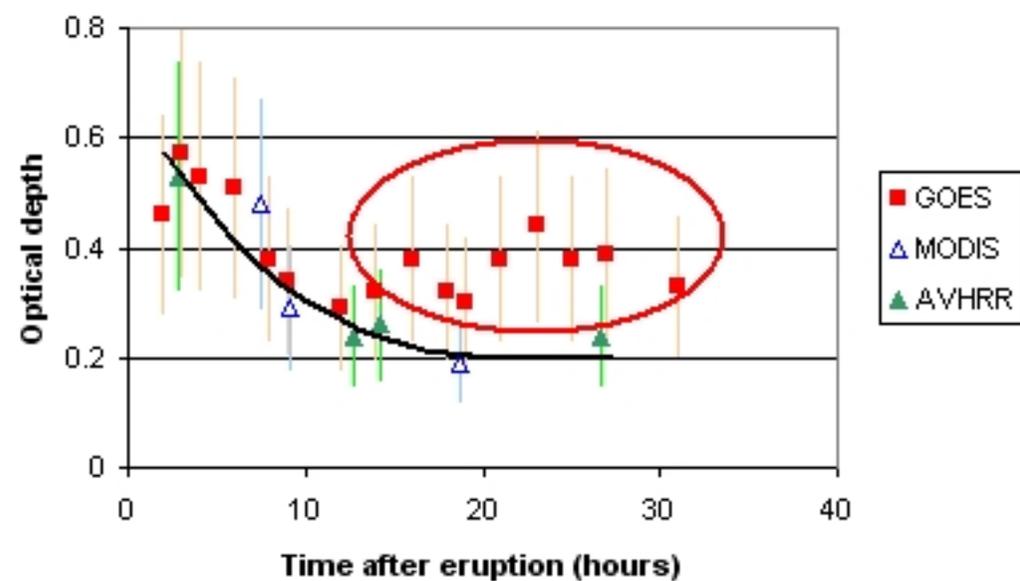
Total volcanic cloud area

Total volcanic ash mass

Mean optical depth

Mean effective radius