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Impact on volcanic ash detection caused by the loss of the 12.0 μm "Split Window" band on GOES Imagers

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Abstract

Geostationary Operational Environmental Satellite (GOES) Imager and Sounder data were evaluated to determine the potential effects of volcanic ash detection without the use of a 12 μm infrared (IR) band, on GOES-M (12) through Q (a period of at least 10 years). Principal component analysis (PCA) images with and without 12 μm IR data were compared subjectively for six weak to moderate eruptions using pattern recognition techniques, and objectively by determining a false detection rate parameter. GOES Sounder data were also evaluated in a few instances to assess any potential contributions from the new 13.3 μm Imager band.

Results indicated that, during periods of daylight, there was little apparent difference in the quality of IR detection without the 12 μm IR, likely due to a maximum in solar reflectance of silicate ash in a shortwave IR (SWIR) band centered near 3.9 μm. At night when SWIR reflectance diminished, the ash detection capability appeared to be significantly worse, evidenced by increased ambiguity between volcanic ash and meteorological clouds or surface features. The possible effects of this degradation on aviation operations are discussed. The new 13.3 μm IR band on GOES has the capability to help distinguish ash from cirrus clouds, but not from low level clouds consisting of water droplets.

Multi-spectral data from higher resolution polar orbiting satellites may also be used to supplement analyses from lower resolution GOES for long-lived ash cloud events. The Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments appear to be the best options in accomplishing this, with additional satellite missions becoming available later in the decade. In summary, it will still be possible to observe and track significant volcanic ash clouds in the GOES-M through Q era (2003–2012) without the benefit of 12 μm IR data, but with some degradation that will be most significant at night.
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Keywords: volcanic ash; aerosols; remote sensing; aviation hazards; multi-spectral imaging

1. Introduction

Brightness temperature differences (BTD) between infrared (IR) window channels centered at 10.7 and 12.0 μm have been successfully used in tracking hazardous volcanic ash clouds since they first became available on Geostationary Operational Environmental Satellite (GOES)-8 in 1994. Negative values of the 10.7 μm minus 12.0 μm BTD are typical of volcanic ash, while positive values denote meteorological clouds, based on the use of similar wavelengths from the Advanced Very High Resolution Radiometer

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(AVHRR) on the polar orbiting National Oceanic and Atmospheric Administration (NOAA) series (e.g. Prata, 1989). Multi-spectral products that are derived from the 12 μm IR data, such as the "Two-Band Split Window" (TBSW) from GOES, are utilized extensively at the Washington Volcanic Ash Advisory Center (VAAC), which is responsible for operational hazard monitoring of a large, volcanically active portion of Mexico, the Caribbean, and Central and South America. Other North or South American VAACs (Anchorage, Montreal, Buenos Aires) also employ the TBSW from GOES to monitor their area of responsibility.

Beginning with the GOES-M (12) spacecraft (successfully launched on 23 July 2001 and activated as the operational eastern spacecraft on April 1, 2003) through GOES-Q (scheduled for launch in late 2008), the 12.0 μm band (4 km resolution) on the Imager will be replaced by a 13.3 μm CO_2 absorption band (8 km resolution). Table 1 summarizes the changes planned for the reconfigured GOES Imagers. A more detailed description of GOES-M, with an assessment of effects on many environmental parameters, is available in Schmit et al. (2001).

The replacement of the 12 μm IR band was completed in order to provide more accurate height assignment for cloud tops and cloud motion vectors from thin clouds that are attainable from a "CO_2-slicing technique" (Menzel et al., 1983) that employs the 13.3 μm band in combination with other longwave channels. More accurate height assignments are expected to result in a reduction in the slow speed bias in satellite-derived winds, and thus a greater positive effect in numerical prediction models. It is expected that more accurate middle and upper level steering winds will also result in better tropical cyclone track predictions. It was not anticipated, however, that there would be such widespread use of the 12 μm IR channel in such applications as volcanic ash detection, and sea surface temperature estimation. The initial purpose of including a 12 μm IR band on GOES was to provide information on low level moisture and precipitable water for numerical models.

The purpose of this paper is to describe the possible impact of the loss of this IR channel on volcanic ash detection within the GOES field-of-view, and discuss alternative strategies to mitigate this loss. The latter comprise: (1) utilization of all possible GOES Imager channels; (2) greater use of an 18 channel GOES Sounder; and (3) exploitation of the global constellation of polar orbiting meteorological satellites, including the operational (NOAA) series, and research satellites launched by the National Aeronautics and Space Administration (NASA).

2. Data and analysis procedures

In order to assess the effect of the GOES-M-Q Imager channel reconfiguration on volcanic ash detection, GOES-8 Imager or Sounder data from several prior eruptions were analyzed to determine how volcanic ash coverage would be depicted with and without the use of the 12 μm IR band. The GOES-8 Sounder (see Menzel et al., 1998) has all IR bands currently on the Imager, plus the 13.3 μm band, although at a lower sub-point resolution (10 km). Characteristics of the GOES Sounder bands are summarized in Table 2. Note that there are also some minor differences in spectral band central wavelengths between the Imager and Sounder.

Table 1
Imager channel configuration of GOES: current versus GOES M-Q

Imager Band	GOES 8 through 11		GOES M-Q (2002–2012)		Description
	Wavelength (μm)	Resolution (km)	Wavelength (μm)	Resolution (km)	
1	0.6	1	0.6	1	Daytime visible
2	3.9	4	3.9	4	Shortwave IR
3	6.7	8	6.7	4	Water Vapor
4	10.7	4	10.7	4	Window IR
5	12.0	4	–	–	Split Window
6	–	–	13.3	8	CO_2 absorption

Table 2
GOES Sounder channel characteristics

Channel	Detector/ absorption	Spectral peak (μm)	Purpose
1	Longwave	14.71	Stratosphere temperature
2		14.37	Tropopause temperature
3		14.06	Upper level temperature
4		13.96	Mid-level temperature
5		13.37	Low-level temperature
6	Window	12.66	Total precipitable water
7		12.06	Surface temperature, H_2O
8		11.03	Surface temperature
9	Ozone	9.71	Total ozone
10	Water vapor	7.43	Low-level moisture
11		7.02	Mid-level moisture
12		6.51	Upper level moisture
13	Shortwave	4.57	Low-level temperature
14		4.52	Mid-level temperature
15		4.45	Upper level temperature
16	Nitrogen	4.13	Boundary layer temperature
17	Shortwave Window	3.98	Surface temperature
18		3.74	Surface temperature, H_2O
19	Visible	0.67	Clouds

The analysis was completed using Principal Component Analysis (PCA) (or eigenvector analysis) software developed by Hillger (1996), which displays statistically significant information available from the input IR wavelengths in the form of gray scale images. PCA techniques have been used previously in the analysis of volcanic clouds to discriminate ash clouds from surrounding terrain for an eruption of Redoubt Volcano, Alaska (Dean et al., 1994). Detailed descriptions of PCA techniques applicable to physical and atmospheric sciences are available in the literature (Preisendorfer, 1988; Hillger and Clark, 2002a; Hillger and Ellrod, 2003). For a multi-spectral data set such as that from the GOES Imager and Sounder, the process can be summarized as a translation and rotation of the original coordinate system into a new coordinate system that better reflects the principal modes of variability in the data set.

PCA techniques separate information that is common to all images within a multi-spectral data set from information which is independent from the original images. The number of images in a PCA data set is equal to the number of spectral band images input. The images resulting from the PCA are ordered such that higher numbered images explain progressively less of the total variance between the bands. The sum of the variance of the PCA images equals the sum of the variance of the original images. The first PCA image contains information common to all bands being screened, such as clouds. The second and subsequent PCA images contain information not explained by previous components, such as differences between the bands. Since volcanic ash detection is dependent on very small BTDs, the higher numbered images normally contain the most information on volcanic ash coverage.

The best PCA depiction of the ash cloud for each event was compared to a subjective "best visual estimate" of the actual ash cloud coverage based on: (1) user analysis of all available GOES data, including visible images for daytime cases; (2) the evolution of the volcanic cloud from its eruption to image time; and (3) VAAC advisories. Animation of the GOES data at 30-min intervals from the start of an eruption was extremely helpful in isolating the most likely area for the ash cloud at the analysis time. In most cases, however, there were no completely independent sources of data upon which to assess the true coverage of the ash cloud.

In addition to qualitative comparisons, a quantitative parameter, termed "false pixel rate" (FPR) was determined. The FPR describes the percentage of an image that is comprised of "false ash" pixels (based on the subjective "true" ash plume described above). This can be described as:

$$\mathrm{FPR} = (T - A)/N \qquad (1)$$

where T is the total of ash plus false pixels, A is the number of "true" ash pixels, and N is the total number of pixels in the image scene. Values of N were approximately 4.7×10^5 for the Sounder, and 2.7×10^5 for the Imager cases. The Sounder image data were analyzed for the entire sector scan area (see Fig. 10) at full 10 km resolution (approximate surface area $= 4.7 \times 10^7$ km^2). The Imager cases were displayed at a magnification factor of two, resulting in a 2 km scale apparent resolution (approximate surface area $= 1.1 \times 10^6$ km^2). All images were in the native GOES (orthographic) projection.

A threshold minimum brightness count value that best related to the edge of the analyzed ash cloud was determined in each case. The resulting bright-

Table 3
Volcanic eruption cases evaluated for GOES ash detection capability

Volcano	Date	Time	Type	Intensity
Soufrière Hills, Montserrat	29 September 1997	1620 UTC	Sounder	Weak
Soufrière Hills, Montserrat	23 September 1997	1520 UTC	Sounder	Weak
Soufrière Hills, Montserrat	26 December 1997	1520 UTC	Sounder	Moderate
Guagua Pichincha, Ecuador	5 October 1999	2015–2215 UTC	Imager	Moderate
Lascar, Chile	20 July 2000	1539–1739 UTC	Imager	Moderate
Popocatépetl, Mexico	23 January 2001	0420 UTC	Sounder	Moderate

ness count range was empirically determined by the analyst using all of the tools available for the subjective comparison describe previously. Statistical analysis programs were then used to determine pixel counts for the various parameters in the FPR. Areas with brightness count values that exceeded the threshold, but were considered outside the analyzed ash cloud were analyzed separately to determine values of T in Eq. (1). In most situations, the analyzed ash cloud area was not contiguous with the "false" ash regions.

The six cases analyzed are summarized in Table 3, which contains information on the volcano name, date, time(s), type of data evaluated (Imager versus Sounder) and relative strength of the eruption. Two cases (Lascar, 20 July 2000 and Guagua Pichincha, 5 October 1999) were evaluated at hourly intervals for a period of several hours. For some minor eruption cases that utilized only Sounder data, only data for single times were analyzed. The GOES Sounder views volcanically active regions infrequently (once every 6 h for the Caribbean, 1–3 h for the Gulf of Mexico, none over South America).

3. Results

Results of the analysis indicate that the loss of the 12 μm IR band will result in an increase of misidentified ("false") ash pixels, the magnitude of which will vary diurnally. During the daytime, the increase in false pixel rate without the 12 μm IR will be minimal (~ 1–2%) due to the positive contribution of reflectance in the 3.9 μm SWIR band. At night, the false pixel rate increases by a factor of ~ 4, likely due to the loss of SWIR reflectance, while the differential absorption effects of the 11 μm thermal IR and 12 μm channels continue to provide useful information. The following is a discussion of several cases from this data set.

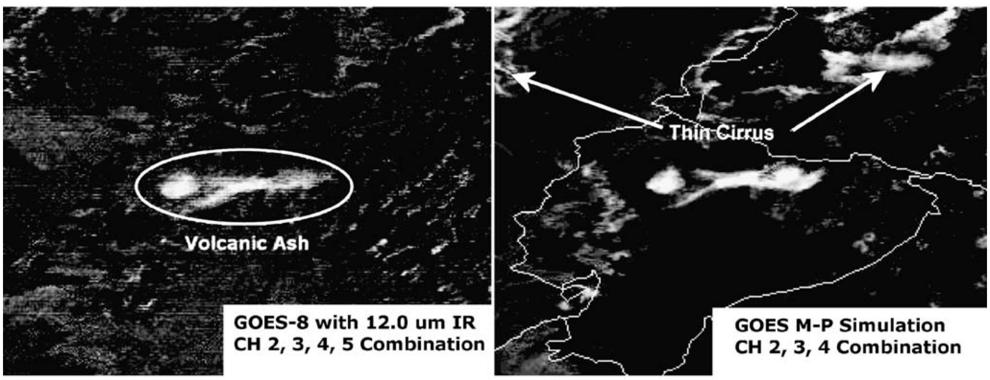

Fig. 1. Comparison of ash cloud depiction from the GOES Imager on 5 October 1999 at 2215 UTC based on a principal component image using all five IR bands, including 12 μm (left) versus only four bands (right). The ash was produced by a moderate eruption of Guagua Pichincha volcano near Quito, Ecuador (shown by the ^) that occurred around 1945 UTC.

3.1. Guagua Pichincha, Ecuador, 5 October 1999

A representative daytime example is shown by a PCA image comparison at 2215 UTC, 5 October 1999 for a moderate eruption of Guagua Pichnicha, Ecuador (Fig. 1). The higher portions of the ash cloud (estimated by the Washington VAAC to have reached 19.8 km) extended eastward at 20 m s^{-1}, while the lower portions drifted west at 10–15 m s^{-1} toward the Pacific coast of Ecuador. The left-hand PCA image uses all four IR bands on the GOES Imager (2–5 in Table 1), including the 12 μm IR band. The right-hand image uses just three IR bands, excluding the 12 μm IR channel. Both images depict the ash cloud (circled) quite well, but in the image that does not include contribution from the 12 μm IR, there is a considerable area where thin cirrus clouds have the same gray scale brightness as the ash, which could result in mis-identification. In this case, an estimate of the true extent of the ash could be obtained by animating 30-min interval GOES images. The operational analysis from the Washington VAAC at 2145 UTC is shown in Fig. 2.

The histograms in Fig. 3 show the false pixel rates of the Guagua Pichincha ash cloud for three 1-h intervals. At 2015 UTC (~ 1.5 h after eruption), the FPR is >5 times larger when including 12 μm IR data than when it is excluded. It is well known that use of the 12 μm IR is less effective shortly after an eruption, due to the opacity of the volcanic cloud caused by large ash particles and considerable condensed water droplets and/or ice (Schneider and Rose, 1994; Simpson et al., 2000). Since the TBSW technique employs the difference in transmissivity at the two wavelengths, this cannot occur until the ash cloud becomes semi-transparent. At the later times (2115 and 2215 UTC) the FPR is ~ 3%, comparable to that obtained from the best image with no 12 μm IR contribution. The increase in the latter to ~ 5% by 2215 UTC is partially due to less contribution from solar reflectance as sunset approaches.

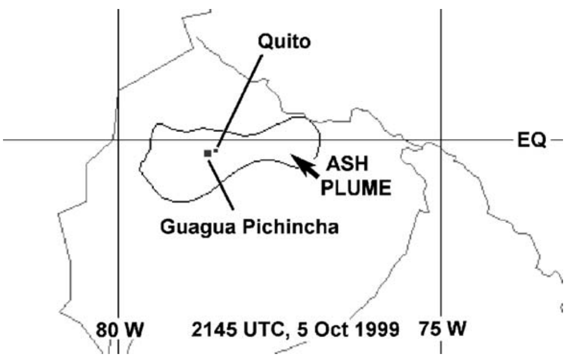

Fig. 2. Analysis of ash cloud coverage from Guagua Pichincha eruption, valid at 2145 UTC, 5 October 1999, from Washington Volcanic Ash Advisory Center (NOAA) (not in same scale as Fig. 1).

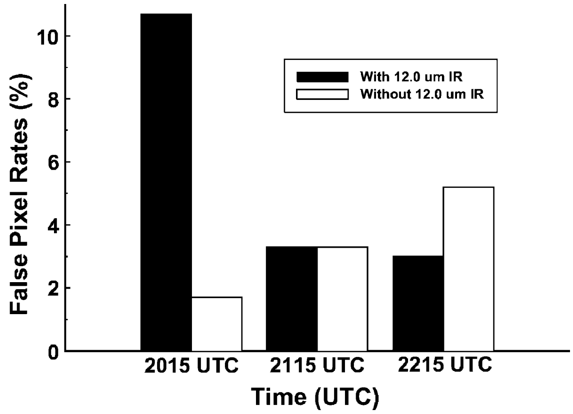

Fig. 3. Histogram of false pixel rates (%) for Guagua Pichincha, Ecuador eruption on 5 October 1999 at three image times based on principal component images using five IR bands including 12.0 μm (filled bars) and four IR bands without the 12.0 μm band (open bars) on the GOES Imager.

The role of reflectance at SWIR wavelengths has been described by Schneider and Rose (1994) for analysis of Spurr volcano ash samples in Alaska. Fig. 4 illustrates the magnitude of reflectance for silicate ash samples for wavelengths of 2–14 μm. The maximum is centered near 4 μm wavelength for all samples, illustrating the utility of SWIR bands on satellite sensors.

3.2. Lascar, Chile, 20 July 2000

A similar analysis was performed for an ash cloud from Lascar volcano, Chile on the afternoon of 20 July 2000. This moderately strong eruption also occurred during daylight hours (time of initial eruption was 1445 UTC) but was in a dry, relatively cloud-free environment compared to the Guagua Pichincha case. Ash reached a maximum height of 10.7 km (Washington VAAC advisory) and drifted rapidly eastward into northern Argentina and eventually,

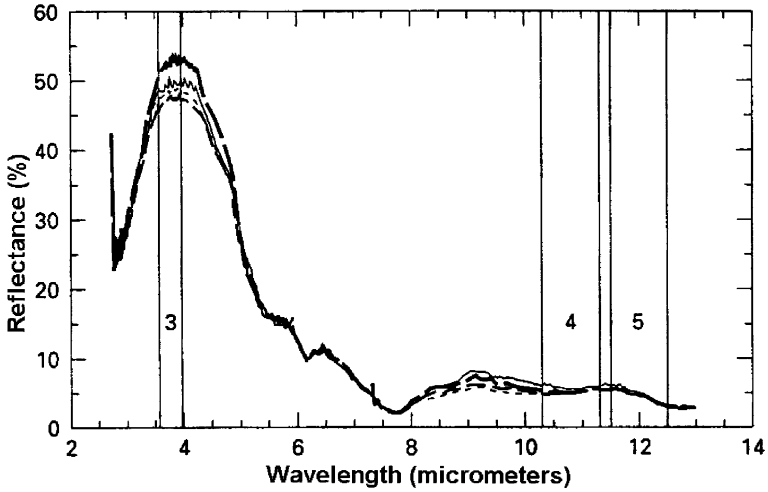

Fig. 4. Reflectance of several ash samples for an eruption of Spurr volcano, Alaska showing a peak reflectance near 4 μm. The spectral band numbers correspond to the Advanced Very High Resolution Radiometer on NOAA polar orbiting spacecraft (from Schneider and Rose, 1994).

Paraguay. GOES Imager data from three times were analyzed from 1539 UTC to 1739 UTC. PCA images (not shown) discriminated the ash cloud from surrounding terrain and clouds equally well with and without the 12 μm IR channel. Most of the false ash was associated with some cumulus clouds in southern Bolivia and various land features presumably associated with desert soils. An objective analysis of FPR (Fig. 5) revealed that the PCA image that included the 12 μm IR band has a significantly higher FPR than the one without that channel. In the two subsequent hours, the FPR from both types of imagery equalized and increased significantly to around 5%, and by the last time (1739 UTC) to 6–7%. The FPR values are not significantly high for either type of PCA image, showing that the loss of the 12 μm IR band did not result in significant reduction in detection capability.

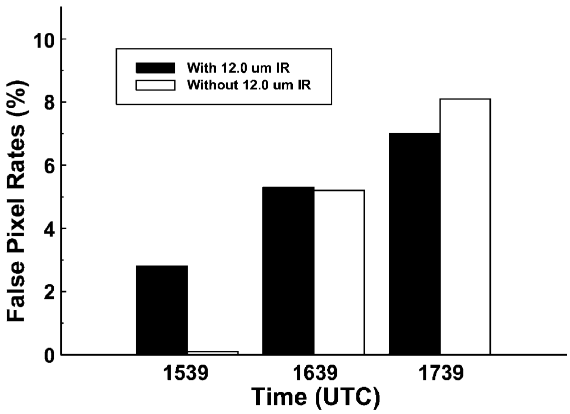

Fig. 5. Same as Fig. 3 for Lascar, Chile eruption on 20 July 2000 at the indicated times.

3.3. Popocatépetl, Mexico, 22–23 January 2001

A nighttime example from the GOES Sounder was obtained for an ash cloud from Popocatépetl volcano in Mexico that drifted across eastern Mexico on 22–23 January 2001. A quantitative evaluation at 0420 UTC showed that the FPR values for the PCA image based on all four IR bands (including 12 μm IR) are ~ 4 times less than for an image that uses only three IR bands (Fig. 6). The latter were the Sounder equivalents to Imager bands 2, 3, 4 and 2, 3, 4, and 6, respectively (see Tables 1 and 2). Inclusion of data from the 13.3 μm band appears to provide a slight positive impact, allowing for better discrimination of ash from thin cirrus clouds. A scatter plot of the Sounder data at this time for 11 μm minus 13.3 μm BTD (the equivalent of Imager Bands 4 minus 6) versus 11 μm temperature (T (K)) (Fig. 7) indicated a nearly linear relationship between BTD and T for both cirrus clouds and volcanic ash. Furthermore, at any given value of T, the 11 μm minus 13.3 μm BTD is significantly larger for cirrus than for volcanic ash. The best PCA images for this event (Fig. 8) shows

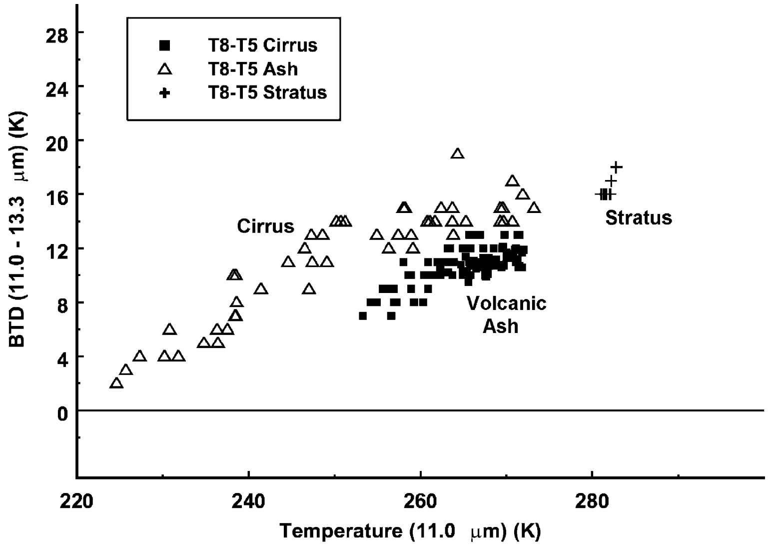

Fig. 6. Scatter plot of GOES Sounder IR Bands 8-5 BTD (equivalent to GOES-M Imager Bands 4–6) versus thermal IR temperature (K) from Band 8 for volcanic ash (solid boxes), cirrus clouds (open triangles), and stratus (crosses) at 0420 UTC on 23 January 2001.

that when the 13.3 μm IR band is substituted for 12 μm IR, the depiction of the ash cloud (circled) is acceptable, but there are areas with similar brightness values resulting from the low clouds or ocean surface farther to the east. Any gain achieved from the 13.3 μm IR data in differentiating ash from cirrus will be offset somewhat by its lower resolution (8 km), until GOES-O becomes available (around 2005), when the resolution at nadir will improve to 4 km (the same as all other IR bands).

Subjective evaluation of Fig. 8 indicates that most of the mis-identified ash is not contiguous with the "true" ash plume or cloud, however, suggesting that a human analyst can successfully track an ash cloud, and provide a reasonably good estimate of its area coverage. The capability to animate GOES imagery at 15- to 30-min intervals provides valuable continuity in this analysis.

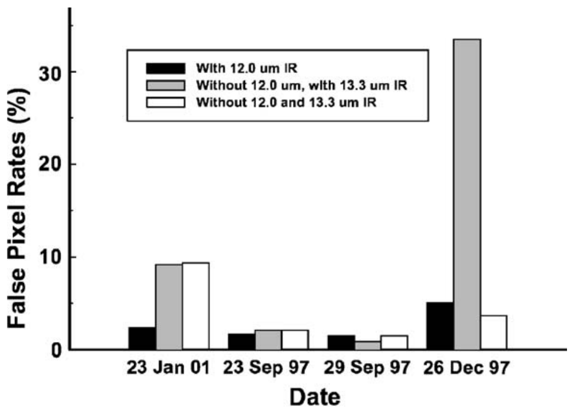

Fig. 7. As in Fig. 3, except from the GOES-8 Sounder for ash clouds from Popocatépetl, Mexico on 23 January 2001 (0420 UTC), and Soufrière Hills, Montserrat on 23 September 1997 (1520 UTC), 29 September 1997 (1620 UTC) and 26 December 1997 (1520 UTC).

3.4. Soufrière Hills, Montserrat, 23 September and 29 September 1997

Soufrière Hills volcano, on the island of Montserrat in the eastern Caribbean, was quite active throughout the latter half of September 1997. The eruptions consisted of short period but frequent bursts of ash leading to fairly discrete ash clouds that were small in areal extent and extended vertically only into the middle Troposphere. Two events were analyzed during this period, on 23 September, and 29 September. One GOES Sounder image data set was analyzed on each day at 1520 UTC and 1620 UTC, respectively. Ash clouds heights were estimated to be only around 3.2 km on 23 September, and at least 6.4 km for the strongest of three explosions on 29 September.

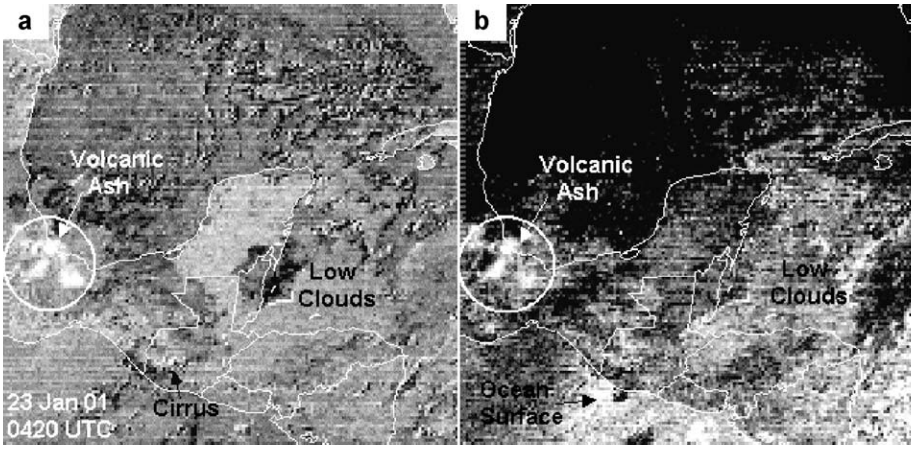

Fig. 8. Principal component images from GOES-8 Sounder at 0420 UTC, 23 January 2001 showing ash cloud depiction using the 12.0 μm (a), versus the 13.3 μm (b), in addition to IR bands at 11 and 3.9 μm. Circled areas are believed to contain the majority of the ash cloud.

For visible and TBSW images of the 29 September ash clouds from the GOES Imager and Sounder, see Fig. 11. An objective analysis of FPR for these two daytime cases (Fig. 6) showed that there was little advantage to be obtained from the use of the 12 μm IR band, as the FPR values were only in the 2–3% range.

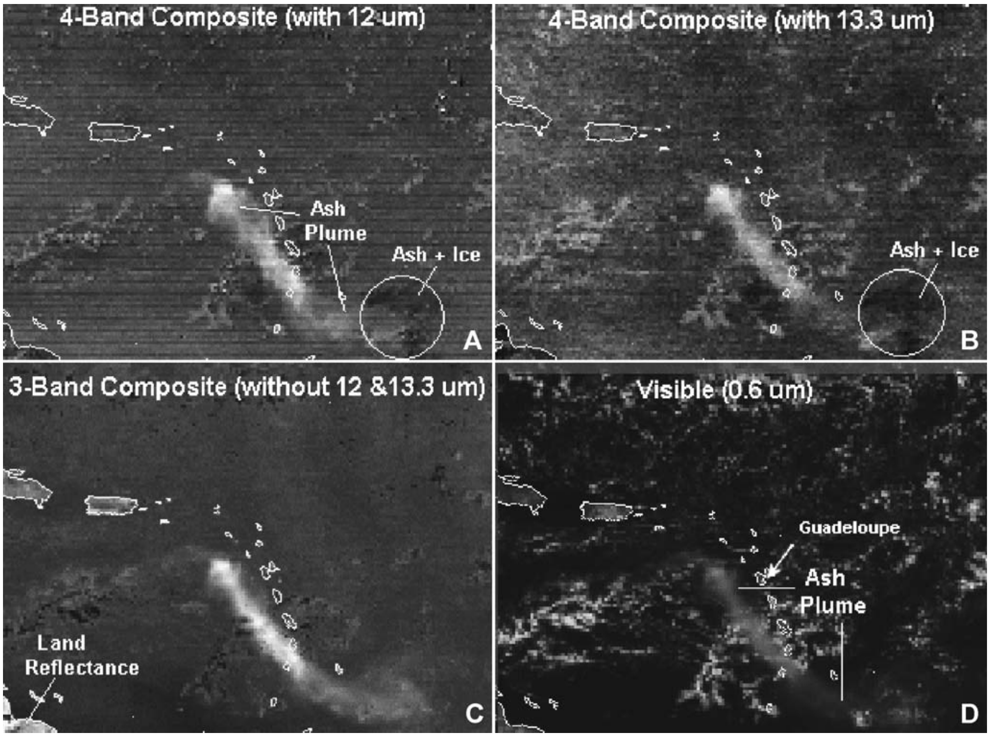

Fig. 9. Comparison of images depicting the volcanic cloud from Soufrière Hills volcano, Montserrat on 26 December 1997 at 1520 UTC. Principal component images from the GOES-8 Sounder are shown based on: four IR bands including 12 μm (A), four IR bands substituting 13.3 μm in place of 12.0 μm (B), and three IR bands at 3.9, 6.7 and 11 μm (C). A Sounder visible image (0.6 μm) is shown in panel D.

This is likely due to the relatively low cloud heights and high moisture content of the ash clouds, which negated the effectiveness of the TBSW technique.

3.5. Soufrière Hills, Montserrat, 26 December 1997

Early in the morning on 26 December 1997, there was a major eruption of Soufrière Hills volcano, Montserrat, the largest in the series of events that began in 1995. The maximum height of the ash cloud in this "Boxing Day" eruption was estimated to be ~ 15 km (Mayberry et al., 2001). An unusual aspect of the eruption cloud was the large content of condensed water and ice believed to be present, caused by the superheating of sea water by a pyroclastic flow that spread offshore following the dome collapse (Mayberry et al., 2001). The eruption cloud drifted south and southeast during the night, extending well to the east of Barbados by the morning of 26 December.

At 1520 UTC on 26 December, GOES-8 Sounder imagery was analyzed to determine the importance of the 12 μm IR in ash identification. Fig. 9 shows PCA images with and without the 12 μm IR in panels A, B and C. Substituting the 13.3 μm band in place of the 12 μm IR (panel B) provides depiction of the eruption cloud that is comparable to panel A, except that many of the low clouds have similar brightness values. When three IR bands are used, excluding both 12 μm IR and 13.3 μm (panel C), there appears to be a slight underestimate of the width of the volcanic cloud, indicating the value of 12 μm IR in detecting very thin ash. The single IR (11 μm) image (panel D) does a relatively poor job of distinguishing the eruption cloud from other features. In the GOES visible image (panel D), the hazy texture provides an analyst with additional, independent information on the presence of ash, although the absence of meteorological cirrus clouds (based on the IR image) reduces ambiguity. The Earth Probe TOMS Aerosol Index indicated a region of large index values not shown that related well with the GOES eruption cloud depiction.

4. Possible impacts on aviation operations

The possible effects of the loss of GOES 12 μm IR data on aviation operations can only be estimated based on the results of this and other studies (e.g. Hillger and Clark, 2002b), and a knowledge of the volcanic ash warning system. Aircraft in flight are warned of ongoing volcanic eruptions via SIGnificant METerological (SIGMET) messages from regional Meteorological Warning Offices (MWOs) established by the International Civil Aviation Organization (ICAO, 2000). The SIGMETs are based on Volcanic Ash Advisories (VAAs) issued by VAACs, which describe details of the volcanic eruption such as: volcano name, date, time, location, height and extent of the ash cloud, and speed and direction of movement of the ash cloud. Information in the VAAs is obtained from analysis of: (1) satellite imagery; (2) aircraft pilot reports; (3) volcano observatory advisories; (4) on rare occasions, ground-based radars; and (5) other surface observations. Thus, remote sensing data is but one part of the volcanic hazard observation system.

It is well known that many of the smaller volcanic eruptions are completely undetected by multi-spectral satellite techniques, particularly in moist tropical or subtropical regions where there is extensive cloud cover. For example, Davies and Rose (1998) estimated that about 25% of the emissions from Soufrière Hills Volcano, Montserrat were not observed by GOES TBSW images due to clouds, moisture, or the predominance of ice particles which suppress the typical TBSW signal for ash. As stated earlier, it is also well known that the TBSW technique using 12 μm IR data is not especially useful during the early stages of some volcanic clouds when there is significant water source contamination (glaciers, ground water, etc), leading to a cloud that is nearly opaque. For this reason, loss of 12 μm IR data should not significantly affect initial warnings of volcanic eruptions, except possibly for thinner ash emissions which tend to be at altitudes close to the summit.

One could surmise that for significant, long-lived eruptions with ash clouds that persist over thousands of kilometers, GOES multi-spectral IR images without the 12 μm IR band will slightly under-detect the horizontal extent of the thinner portions of the ash as appears to be case in Fig. 9. A more significant effect may be the increase in false signatures for ash caused by meteorological clouds or surface features. Some portion of the latter could be contiguous with the actual volcanic cloud, increasing the difficulty of the analysis. The magnitude of the false signatures would usually vary between 5% and 10% of a 2 km scale image, based on the results of this study, and would be more troublesome during nighttime hours. The result could be a larger initial analysis area, and thus forecast area of airborne volcanic ash, to err on the side of safety. The larger warned area would cause diversion of aircraft over somewhat longer distances (both pre-flight and enroute) across busy air routes in regions such as Latin America and the North Pacific. For example, the February 2001 Cleveland Volcano in the Aleutian Islands resulted in extensive diversion of air traffic across the Alaskan Flight Information Region (Simpson et al., 2002). These diversions are very expensive to the airlines, costing as much as $6 thousand per aircraft for a Great Circle flight from the West Coast of the United States to Japan (Simpson et al., 2002). Assuming that for a major eruption in the North Pacific region with a ash cloud that persists for three days, there are flight diversions that result in a 5% longer route than normal due to the uncertainty of the location of the ash cloud boundary. Assuming approximately 100 flights per day are affected, this would lead to an extra cost to the airlines of about $30 thousand per day, or $90 thousand for the event.

5. Alternative strategies for volcanic ash detection

In addition to the GOES Imager, the GOES Sounder provides 18 IR bands at 10 km resolution. All spectral bands currently on the Imager are also on the Sounder, although the spectral width of the Sounder is narrower than the Imager for many IR bands. The BTD differences between the Imager and Sounder caused by spectral width differences for the IR bands discussed here is typically $\sim +1$ C (Schmit, 2003). The Sounder has limited spatial and temporal coverage, however, as shown by Fig. 10 for GOES-East. The slow scanning rate of the Sounder results in

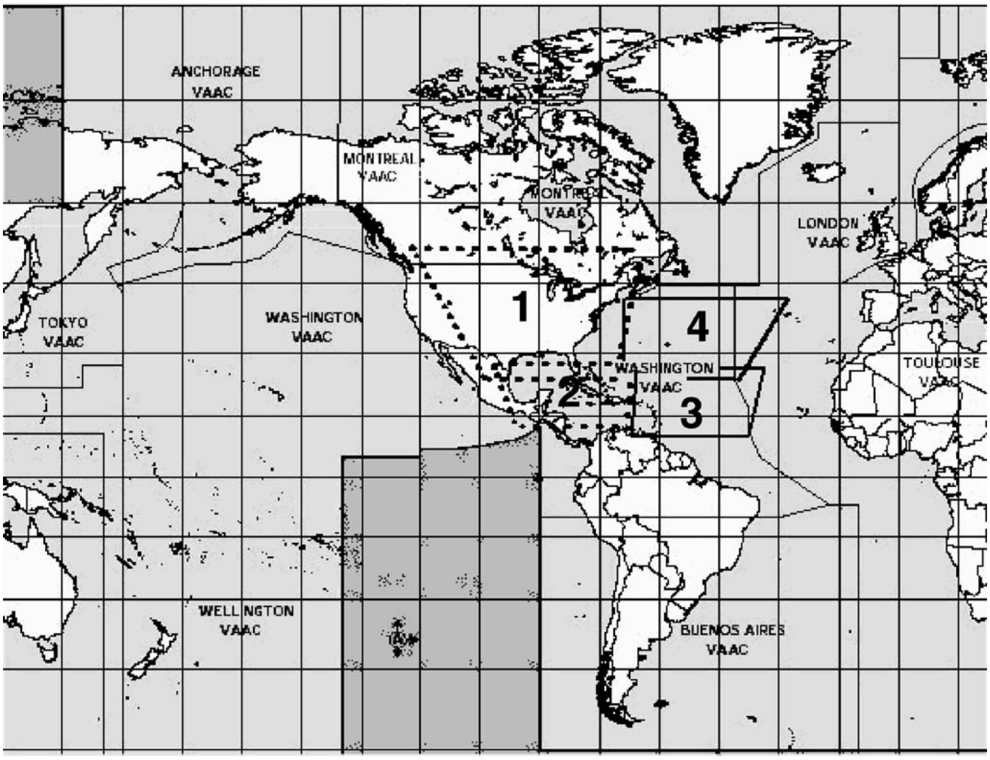

Fig. 10. Global Volcanic Ash Advisory Center (VAAC) areas of responsibility, superimposed by GOES-East Sounder sector areas: (1) Continental United States (CONUS), (2) Gulf of Mexico, (3) Caribbean, and (4) Atlantic. Scan times required are 50 min for CONUS, and 25 min for the other sectors. (VAAC map from ICAO, 2000).

revisit times of 1–6 hours for the areas shown. (Current GOES operational scanning areas and schedules may be viewed at: http://www.ssd.noaa.gov). Nevertheless, if dedicated to view volcanic regions more frequently, the Sounder can provide useful TBSW-based image products (Ellrod, 1998) in a timely manner. A comparison of the TBSW image from the GOES Sounder versus the Imager is shown in Fig. 11. The images, which were acquired within 15 min of each other, indicate a small ash cloud from Soufrière Hills, Montserrat on 29 September 1997, as well as two areas of thinner ash to the west that resulted from earlier eruptions. While the Sounder depiction of the ash is not as precise as the Imager version, the general area of ash coverage is representative, and would provide information helpful in the issuance of advisories or short-term warnings.

The 12 μm IR channel will continue to be available at 1 km resolution from the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA polar spacecraft The Moderate Resolution Infrared Spectrometer (MODIS) on the NASA Earth Observation Satellites (Aqua and Terra) will also have a 12 μm band, along with 35 others, also at 1 km. The Chinese Fun Yueng (FY)-1C has recently become available to the Anchorage VAAC to fill some data gaps at high latitudes. The polar satellite data can provide better quality images to supplement (or calibrate) ash products generated from GOES. This is especially important for long-lived ash clouds resulting from very strong eruptions. Products derived from the merger of concurrent GOES and polar satellite images are also a possibility.

Data from the NASA MODIS appears to hold special promise as a tool to enhance volcanic ash detection capabilities from GOES. There are several MODIS spectral bands that have been observed to be useful for either ash or SO_2 detection (e.g. Watson et al., 2004-this issue). There are plans in place at the U.S. National Environmental Satellite Data and Information Service to obtain MODIS data in near real-time to assist the Washington Volcanic Ash Advisory Center with its international volcanic ash detection responsibilities. Two components of this effort are to install a high speed data line from the NASA Goddard Space Flight Center in Greenbelt, Maryland to the

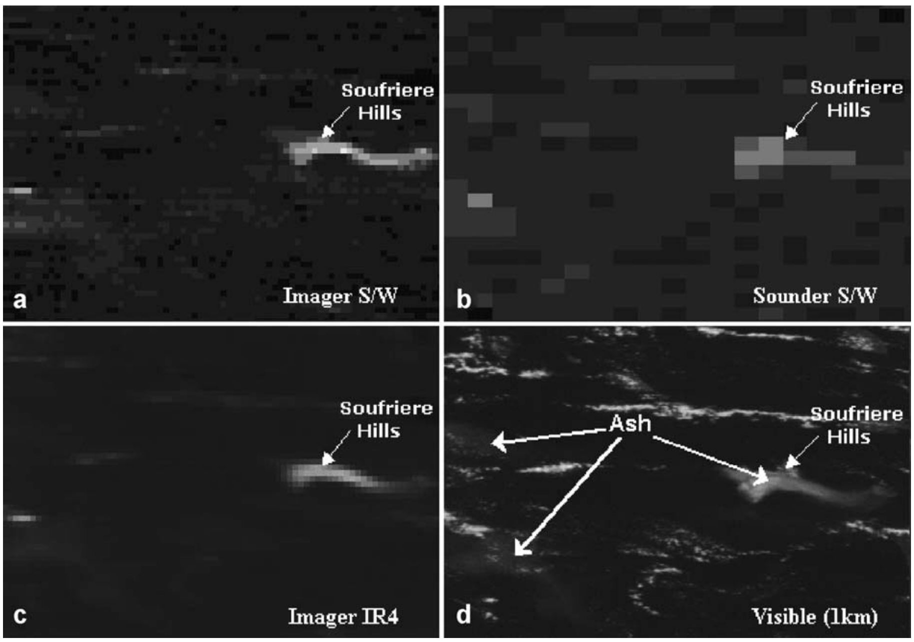

Fig. 11. Comparison of GOES-8 images for three small eruption clouds from Soufrière Hills volcano, Montserrat on 29 September 1997. Two-Band Split Window (TBSW) images for the Imager (a) and Sounder (b) are compared with the Band 4 IR (10.7 μm) (c) and high resolution visible (d). Imager data is valid at 1615 UTC, Sounder imagery at 1620 UTC.

NOAA Science Center in nearby Camp Springs, Maryland, and to develop prototype products using appropriate MODIS spectral bands. An example of such a product for an eruption of Popocatépetl during the night of 20 December 2000 is shown in Fig. 12. The image in Fig. 12 is derived from BTDs (obtained by simple numeric combination) of MODIS spectral channels centered near 8.6, 11 and 12 μm (Bands 29, 31 and 32, respectively). Previous analysis of MODIS IR bands using PCA techniques has indicated that MODIS Bands 29, 31 and 32 contribute significantly to volcanic ash detection (Hillger and Clark, 2002a). The concurrent operational analysis of volcanic ash coverage derived from animated, multi-spectral GOES data by the Washington VAAC is shown for comparison. There is generally good agreement, although the MODIS image product appears to show some thin ash over southern Mexico that is not detectable from the GOES data. Analysis of MODIS data from an eruption of Cleveland volcano, Alaska on 20 February 2001 showed similar results.

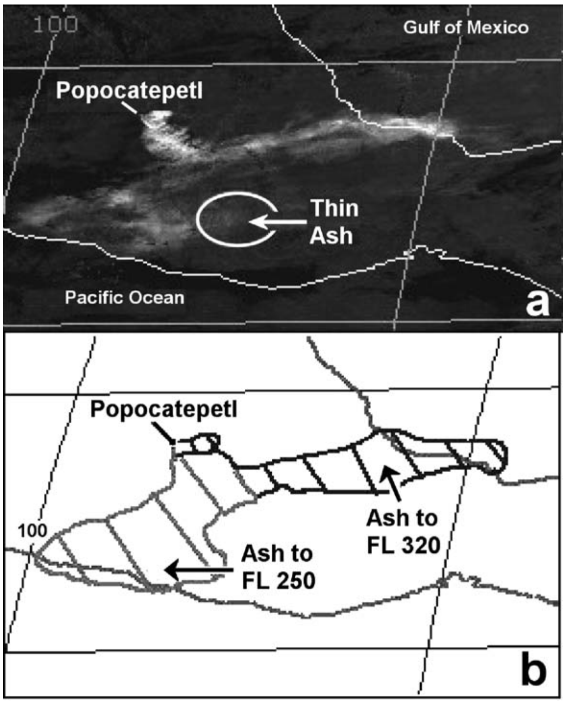

Fig. 12. MODIS image product based on the 8.6, 11 and 12 μm channels at 0505 UTC, 20 December 2000 (a), compared with a Washington VAAC analysis of ash coverage based on GOES data (b) valid at the same time. White to light gray shades indicate volcanic ash from Popocatépetl volcano, Mexico. Ash cloud top heights are shown in hundreds of feet. FL = Flight Level.

6. Summary and conclusions

GOES Imager and Sounder data were evaluated for six weak to moderate eruptions to estimate possible negative effects resulting from loss of the 12 μm IR band, on GOES-M (12) through Q (a period of at least 10 years). Principal component images with and without the 12 μm IR were compared qualitatively using subjective visual evaluation techniques, and objectively by means of a "false alarm" parameter. GOES Sounder data were also evaluated in two of the cases to assess any potential contributions from the new 13.3 μm Imager band. Animation of GOES visible and IR images was used to locate the probable area covered by the ash cloud at the analysis times.

During periods of daylight, there was little or no apparent difference in the quality of IR detection without the 12 μm IR, likely due to the reflectance peak of silicate ash near 3.9 μm. At night, the ash detection capability appeared to be significantly worse, due to increased ambiguity with clouds or surface features. The effects of this degradation on aviation operations could be an occasional increase in the area of analyzed ash coverage to err on the side of safety, resulting in somewhat longer enroute diversions. However, it is important to note that based on two cases described in this study, the ash detection capability within the first several hours of a volcanic eruption will likely be unaffected due to the ineffectiveness of techniques that use the 12 μm IR band when the eruption cloud is nearly opaque. During the later phases of the volcanic cloud evolution, it is believed that an analyst should be able to track volcanic ash clouds sequentially to determine approximate locations with the aid of image animation.

For long-lasting ash clouds caused by major eruptions, there is the risk of "losing" the ash cloud, especially where there is a significant amount of high level cirrus cloud cover. The new 13.3 μm IR band on GOES appears to be capable of distinguishing ash from cirrus clouds, but not from low level clouds consisting of liquid cloud droplets. The 3.9 μm SWIR channel has the capability to perform the latter function both day and night. Thus, it is recommended that three IR bands (3.9, 10.7 and 13.3 μm) from the GOES M-Q Imagers would be the optimum combination for use in operational volcanic ash detection. This is in agreement with the results of a study that evaluated MODIS IR bands equivalent to those available on GOES-M (Hillger and Clark, 2002b). Multispectral data from higher resolution polar orbiting satellites may also be used to supplement analyses from lower resolution GOES for long-lived ash cloud events. The AVHRR and MODIS instruments appear to be the best options in accomplishing this, with satellite missions becoming available later in the decade. Recently completed analysis of MODIS data for eruption clouds in Alaska (Cleveland Volcano) and Mexico (Popocatépetl Volcano) (Ellrod and Im, 2003) show that significant improvements in multi-spectral volcanic ash products are possible. In summary, we will still be able to observe and track significant volcanic ash clouds in the GOES-M through Q era (2003–2012), but with some degradation that will be most significant at night.

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