Principal Component Image Analysis of MODIS for Volcanic Ash. Part II: Simulation of Current GOES and GOES-M Imagers

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ABSTRACT

In Part I of this paper the infrared bands of the Moderate Resolution Imaging Spectroradiometer (MODIS) were analyzed using principal component image analysis for volcanic ash signals. The analyses performed determined that several of the thermal infrared bands of MODIS contributed significantly to detecting volcanic ash in the cases examined. Most, but not all, of these bands will be included in the next major upgrade to the Geostationary Operational Environmental Satellite (GOES) Imager scheduled for 2012. In Part II, MODIS data for the same volcanic cases examined in Part I (Popocatepetl near Mexico City and Cleveland in the Aleutian Islands) are used to simulate the impact of changes that will occur in spectral bands between current and near-term GOES imagery. The change from the 12.0-μm band to a 13.3-μm band on GOES-M (launched in 2001 and renamed *GOES-12*) was made to improve cloud-height determinations. However, when GOES-M becomes operational, the change in bands will have a potential negative impact on image products that are heavily utilized for volcanic ash detection. Image products generated from the three GOES infrared bands with the 13.3-μm band substituted for the 12.0-μm band indicate that volcanic ash can be detected but with diminished ability, especially for diffuse ash. For both day and night cases the increased contamination by clouds leads to increased chances of false ash detection.

1. Introduction

The next three satellites in the Geostationary Operational Environmental Satellite (GOES) series, GOES-M through -O, (GOES-M was launched in 2001 and renamed *GOES-12*), will have slightly modified imager instruments, with a new band at 13.3 μm (Schmit et al. 2002). The new band was introduced to improve cloud height determinations. Unfortunately, this band is not an additional band. Instead, it replaces the 12.0-μm band currently used, along with the GOES longwave infrared band at 11 μm, to identify airborne volcanic ash. This technique was pioneered by Prata (1989) but has been applied by many [e.g., Oppenheimer 1998; Ellrod et al. 2001, manuscript submitted to *J. Geophys. Res.,* (hereinafter ECH)].

To simulate the effect of the new band on usage of GOES for volcanic ash detection, selected bands of Moderate Resolution Imaging Spectroradiometer (MODIS) data were used. Table 1 lists both the old and new GOES Imager band numbers. The new 13.3-μm band will be called band 6 even on the new five-band arrangement (bands 1–4 and 6). The current 12.0-μm band will continue to be called band 5, to avoid confusion between band numbers on current and new versions of the GOES Imager.

Table 1 also lists the MODIS bands that correspond to the six bands available between the two versions of the GOES Imager. MODIS contains 36 bands, and 6 of those bands have central wavelengths that correspond to the 6 GOES bands. Those MODIS bands are 1, 22, 27, 31, 32, and 33, respectively. In general, the MODIS bandwidths are narrower than those of the equivalent GOES bands, but simulating both the current and new bands using MODIS minimizes any differences this may cause.

In section 2 the analysis technique is applied to both day and nighttime volcanic cases. Section 3 covers additional daytime and nighttime cases. Section 4 contains a summary and the conclusions of this work.

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2. Analysis using principal component imagery

To determine the effect of the change from band 5 to band 6 on GOES-M, band 6 was substituted into a

TABLE 1. Simulation of GOES-M Imager using MODIS bands.

GOES Imager		MODIS	
Band No.	Central wavelength (μm)	Band No.	Central wavelength (μm)
1	0.65	1	0.645
2	3.9	22	3.96
3	6.7	27	6.7
4	10.7	31	11.0
5	12.0	32	12.0
6	13.3	33	13.3

volcanic ash product used operationally by the Washington Volcanic Ash Advisory Center (VAAC). That product consists of multiple image differences generated by principal component image (PCI) analysis of the three GOES thermal infrared bands (bands 2, 4, and 5). PCI analysis creates images that explain all of the variance in the original bands by separating the common from the difference information in the original bands (Hillger 1996a,b; Hillger and Ellrod 2000). The mechanics of the PCI technique (see www.cira.colostate.edu/ramm/cal_val/pci.htm) as applied to satellite imagery appeared in the appendix of Part I of this paper (Hillger and Clark 2002, this issue). PCI-1 contains the common signal from the three GOES bands that are input, generally meteorological cloud/no-cloud information. The band-2/4 (shortwave/longwave) difference usually seen in PCI-2 is useful for detecting volcanic hot spots, and the band-4/5 (split window) difference usually seen in PCI-3 is good for detecting volcanic ash.

Two test versions of the PCIs were generated, one using simulated current GOES bands 2, 4, and 5; and the other using simulated GOES-M bands 2, 4, and 6. In addition, both day and night cases will be examined. The first daytime case for this study was a large eruption of ash on 20 December 2000 from Popocatepetl volcano (hereinafter abbreviated Popo; 19.02°N, 98.62°W) at

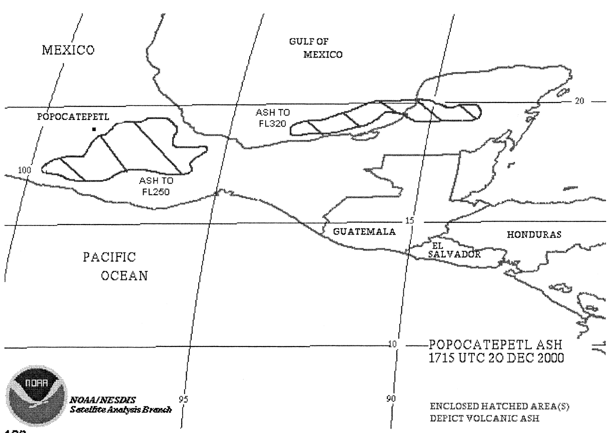

FIG. 1. Volcanic ash analysis for 1715 UTC (daytime) 20 Dec 2000 for Popocatepetl volcano near Mexico City. Analysis based on GOES multispectral imagery by the Satellite Analysis Branch (SAB) Washington VAAC.

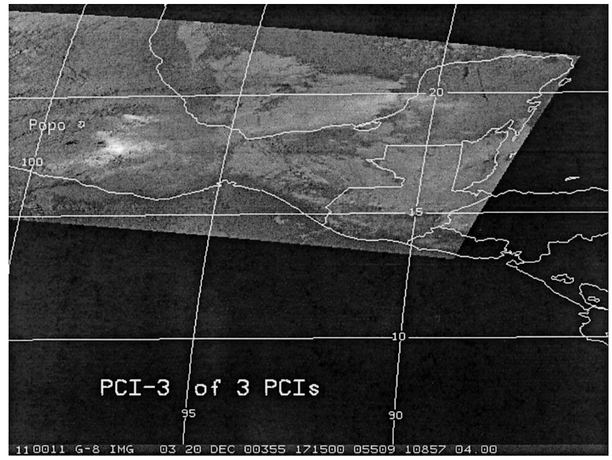

FIG. 2. PCI-3 of three PCIs that were generated from a simulation of the three thermal infrared bands of *GOES-8* through *-11* (bands 2, 4, and 5) using MODIS bands 22, 31, and 32 for 1715 UTC (daytime) 20 Dec 2000 over Popocatepetl volcano near Mexico City. PCI-3 shows the ash cloud (white) by heavily utilizing GOES bands 4 and 5.

5465-m elevation near Mexico City. For this case MODIS data were available at 1715 UTC from the polar-orbiting EOS *Terra* satellite. The MODIS data were analyzed at 2-km spatial resolution (at nadir) and afterward remapped into a GOES projection at 4-km resolution to match the ash analyses that are available for verification.

Figure 1 is an analysis issued by the Washington VAAC (1999) giving the extent of the ash cloud based on GOES multispectral imagery for 1715 UTC. This analysis time matches the time of the MODIS imagery analyzed using PCIs. Tracking of the ash over time, using half-hourly GOES imagery, helped to more clearly identify the extent of the ash cloud. The ash extends

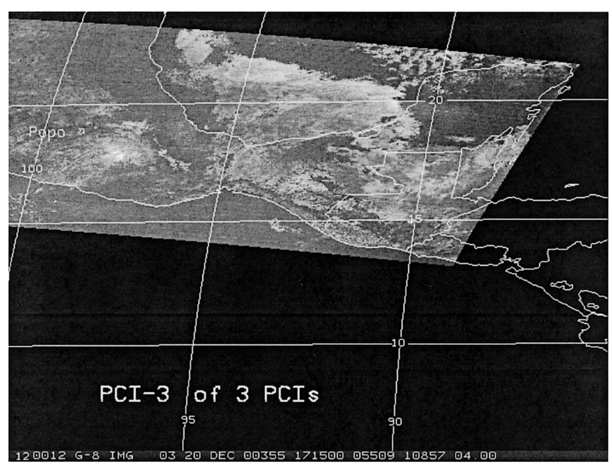

FIG. 3. Same as in Fig. 2 except generated from a simulation of the three thermal infrared bands of GOES-M through -O (bands 2, 4, and 6; using MODIS bands 22, 31, and 33). PCI-3 shows only the parts of the ash cloud where the ash signal is most concentrated, when compared with the current version of PCI-3 in Fig. 2, and also suffers from contamination by low clouds.

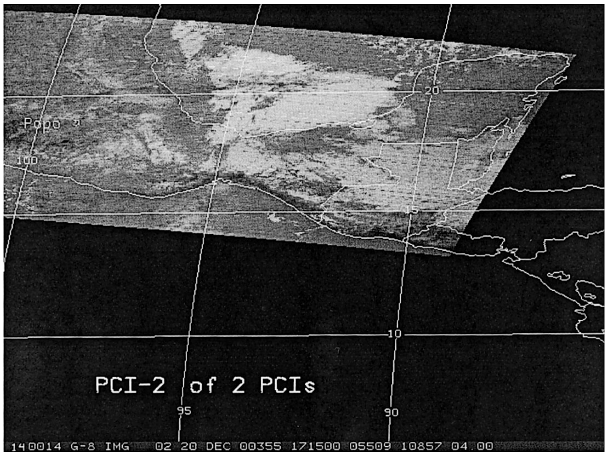

FIG. 4. A two-band (band 4/6)-difference image generated from a simulation of the two longwave infrared bands of GOES-M through -O using MODIS bands 31 and 33 for 1715 UTC (daytime) 20 Dec 2000 over Popocatepetl volcano near Mexico City. This image product is far inferior for volcanic ash detection when compared with the three-band product in Fig. 3.

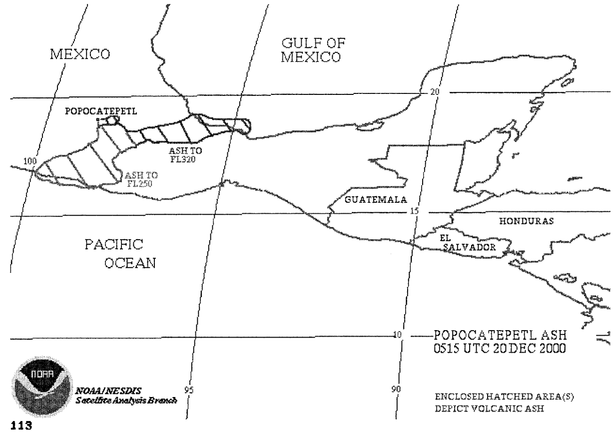

FIG. 5. Volcanic ash analysis for 0515 UTC (nighttime) 20 Dec 2000 for Popocatepetl volcano near Mexico City. Analysis based on GOES multispectral imagery by the Satellite Analysis Branch Washington VAAC.

mainly east and south of Popo (indicated by an arrow and a label), to as far east as the Yucatan Peninsula. In the ash analysis the ash is given in two parts, at different flight levels [FL250 (25 000 ft/7600 m) and FL320 (32 000 ft/9800 m)]. These levels were estimated by effectively matching the derived vector motion of the ash as seen in GOES imagery to the appropriate height levels from the Mexico City upper-air sounding and a model sounding. The extent of the ash in this analysis is a guide for the simulated GOES analyses to follow.

There was no volcanic hot spot detected for Popo for this case since clouds obscured the volcanic vent. Otherwise PCI-2 is often effective at detecting hot spots or thermal anomalies. Since PCI-2 is generally a longwave versus shortwave (band 2/4) difference, the change from band 5 to band 6 does not cause a significant change in this PCI. Similarly PCI-1, since it shows the overall cloud conditions common to all three infrared bands (and not any of the volcanic features that are often seen only in image differences), does not change significantly. Therefore we will focus here on PCI-3, a product that will change primarily from a band-4/5 difference to a band-4/6 difference, with much less contribution from GOES band 2.

Figure 2 contains PCI-3 as it is now available from a simulation of current GOES Imager bands 2, 4, and 5. The remapped MODIS data do not cover the entire area of the figure, but the image size is kept the same to simplify comparisons with Fig. 1. This multispectral image product generally depicts the volcanic ash very well. Ash is seen as white, in contrast to the image background and other image features. The ash is concentrated mainly to the east and southeast of Popo where there is a maximum in the ash signal. A secondary maximum also exists, to the east over the Yucatan Peninsula. Some ash can also be seen connecting the two maxima, but that ash has much less contrast to the background of the image.

For comparison, Fig. 3 is PCI-3 generated from simulated GOES bands 2, 4, and 6 in place of bands 2, 4, and 5 used in Fig. 2. In this figure the densest part of the ash cloud can still be seen east and south of Popo, as well as faint ash signal as far east as the Yucatan. However, the immediate difference compared to the current version of PCI-3 (Fig. 2) is the lessened contrast of the ash to the image background and the more significant contribution from clouds. These cloud features tend to obscure the ash cloud except at locations where the ash signal is the greatest. The secondary maximum, east off the coast of the Yucatan, which is easily seen

TABLE 2. Contributions of MODIS-simulated GOES infrared bands to PCIs used for volcanic ash detection [1715 UTC 20 Dec 2000, Popocatepetl (day) case]. Negative contributions are in parentheses. Boldface values are explained in text.

GOES-8 through *-11*				GOES-M through -O			
PCI	Explained variance and sign of GOES band contributions			PCI	Explained variance and sign of GOES band contributions		
No.	2	4	5	No.	2	4	6
1	46%	26%	27%	1	37%	22%	41%
2	54%	(20%)	(26%)	2	52%	~0%	(48%)
3	(~0%)	**53%**	**(47%)**	3	(11%)	**78%**	(11%)

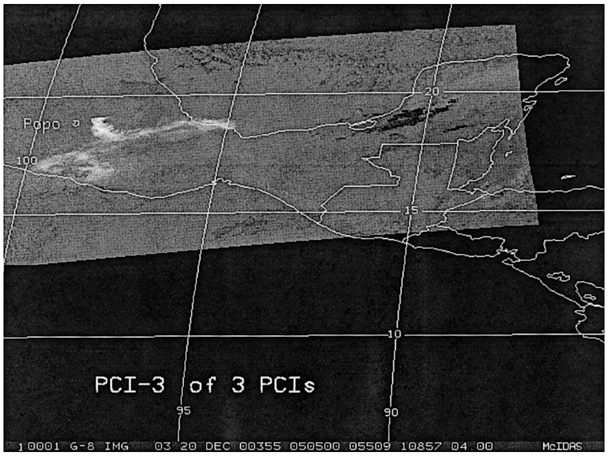

FIG. 6. PCI-3 of three PCIs that were generated from a simulation of the three thermal infrared bands of *GOES-8* through *-11* (bands 2, 4, and 5) using MODIS bands 22, 31, and 32 for 0505 UTC (nighttime) 20 Dec 2000 over Popocatepetl volcano near Mexico City. PCI-3 shows the ash cloud (white) by heavily utilizing GOES bands 4 and 5.

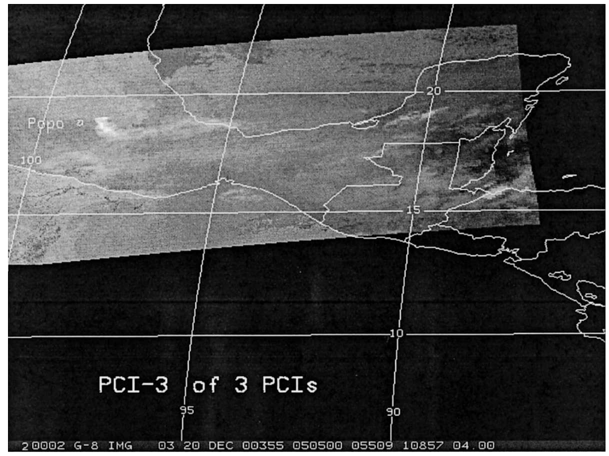

FIG. 7. Same as in Fig. 6 except generated from a simulation of the three thermal infrared bands of GOES-M through -O (bands 2, 4, and 6; using MODIS bands 22, 31, and 33). PCI-3 shows most of the ash cloud seen in Fig. 6, but with diminished contrast to the image background and other image features.

in Fig. 2 is hard to discern in this new image due to low clouds underlying the ash. This cloud contamination is a major drawback to this three-band product with the change in bands planned for GOES-M.

In an attempt to isolate the cloud problem, we have examined the contributions of the component bands to the current and new versions of the three-band product. Table 2 gives the contributions of the GOES bands to the PCIs for both current and new simulations of this volcanic ash case. In the new version of PCI-3, band 2 contributes 11% of the explained variance, compared to approximately 0% for the current version of PCI-3. If it is assumed that the cloud contamination is due to the increased contribution from GOES band 2 in PCI-3, the immediate thought for fixing the cloud contamination is to eliminate band 2 from the analysis to generate a two-band (band 4/6)-difference image that may not suffer from this low-cloud contamination. The reasoning is that PCI-3 generated from current GOES bands 2, 4, and 5 is basically a two-band (band 4/5) difference with little or no contribution from GOES band 2. When generated, the two-band difference is identical to the three-band image in Fig. 2 and is therefore not shown.

For comparison, Fig. 4 is a two-band difference generated from simulated bands 4 and 6. This image product shows the ash cloud only very faintly southeast of Popo, where the ash signal is greatest in Figs. 2 and 3. The two-band difference is not as good for ash detection as the three-band product in this case and continues to have significant cloud contamination. The clouds therefore are not due to the contribution from band 2, but are inherent in the difference between bands 4 and 6. Band 6 was added to detect clouds, the kind that are contaminating both the two-band and the three-band products in attempts to see volcanic ash. That cloud signal comes at the expense of ash detection that is easily accomplished with the current split-window bands. It is at least some consolation that PCI-3 generated from the new combination of bands (Fig. 3), although inferior for ash detection to PCI-3 generated from the current combination of bands (Fig. 2), is far superior to a two-band difference that uses the new band 6 (Fig. 4). In fact, without prior knowledge of the location of the ash, it is doubtful that any ash could be distinguished from clouds in this image.

Simulation of GOES-M (five-band) Imager at night

The simulation of GOES-M Imager data continues with a nighttime volcanic ash case from Popo, utilizing

TABLE 3. Contributions of MODIS-simulated GOES infrared bands to PCIs used for volcanic ash detection [0505 UTC 20 Dec 2000 Popocatepetl (night) case]. Negative contributions are in parentheses. Boldface values are explained in text.

GOES-8 through *-11*				GOES-M through -O			
PCI No.	Explained variance and sign of GOES band contributions: 2	4	5	PCI No.	Explained variance and sign of GOES band contributions: 2	4	6
1	60%	21%	19%	1	53%	21%	26%
2	40%	(23%)	(37%)	2	(37%)	1%	62%
3	(~0%)	**56%**	**(44%)**	3	(9%)	**78%**	**(12%)**

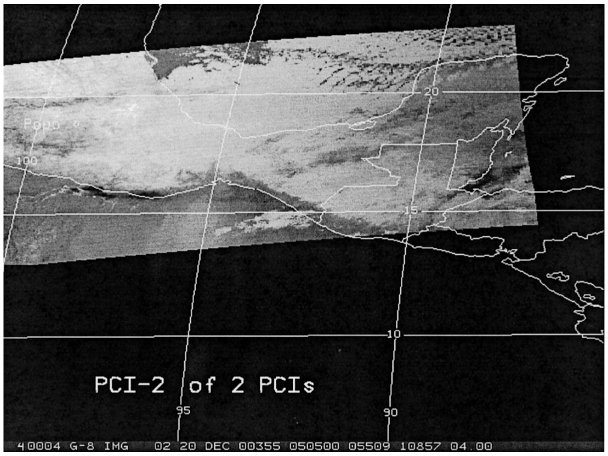

FIG. 8. A two-band (band 4/6)-difference image generated from a simulation of the two longwave infrared bands of GOES-M through -O using MODIS bands 31 and 33 for 0505 UTC (nighttime) 20 Dec 2000 over Popocatepetl volcano near Mexico City. This image product is far inferior for volcanic ash detection when compared with the three-band products in Figs. 6 and 7.

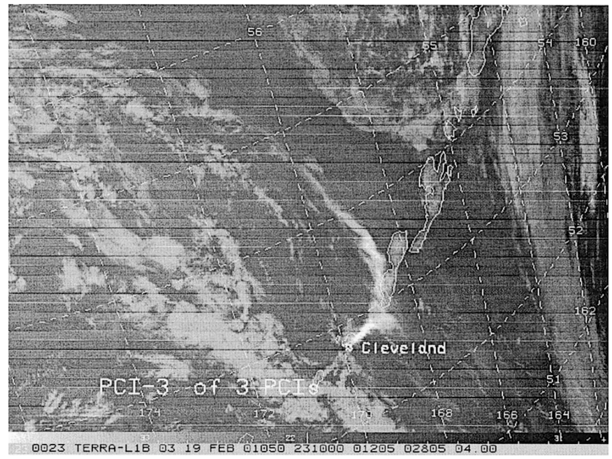

FIG. 10. Same as in Fig. 9 except generated from a simulation of the three thermal infrared bands of GOES-M through -O (bands 2, 4, and 6; using MODIS bands 22, 31, and 33). PCI-3 shows the parts of the ash cloud where the ash signal is most concentrated, but in general with less contrast to the image background and with more chance for cloud contamination when compared with the current version of PCI-3 in Fig. 9.

MODIS data for 0505 UTC on 20 December 2000, about 12 h earlier than the daytime case already examined. The main difference at night is the changed characteristic of GOES band 2 due to the lack of reflected solar radiation in that shortwave infrared band.

Figure 5 shows the operational ash analysis for the second case. As in Fig. 1, the analysis of the ash cloud is given in two parts, at different flight levels [FL250 (25 000 ft/7600 m) and FL320 (32 000 ft/9800 m)]. The extent of the ash in this analysis is a guide for the MODIS analysis to follow.

Figure 6 is PCI-3 derived from simulated infrared bands 2, 4, and 5, the combination of bands on the current GOES Imager often used for volcanic ash detection. The ash cloud is clearly seen in this case emanating from Popo with very strong contrast to the image background and with little or no cloud contamination.

For comparison, Fig. 7 is PCI-3 derived from simulated GOES bands 2, 4, and 6 that will be available on the GOES-M Imager. Here the contrast of the ash cloud to the image background is diminished, with most of the ash still detectable. However, there is more chance of confusion between ash and low clouds. One possible

FIG. 9. PCI-3 of three PCIs that were generated from a simulation of the three thermal infrared bands of *GOES-8* through *-11* (bands 2, 4, and 5) using MODIS bands 22, 31, and 32 for 2310 UTC (daytime) 19 Feb 2001 over Cleveland volcano in the Aleutian Islands. PCI-3 shows the ash cloud (white) by heavily utilizing GOES bands 4 and 5.

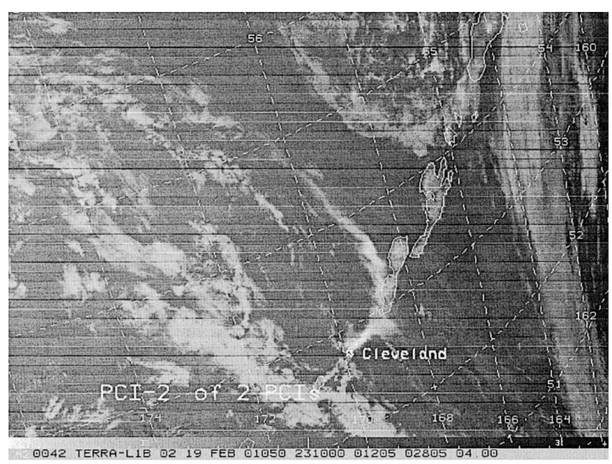

FIG. 11. A two-band (band 4/6)-difference image generated from a simulation of the two longwave infrared bands of GOES-M through -O using MODIS bands 31 and 33 for 2310 UTC (daytime) 19 Feb 2001 over Cleveland volcano in the Aleutian Islands. This image product is nearly identical to the new three-band product in Fig. 10, but inferior for volcanic ash detection when compared with the current three-band product in Fig. 9.

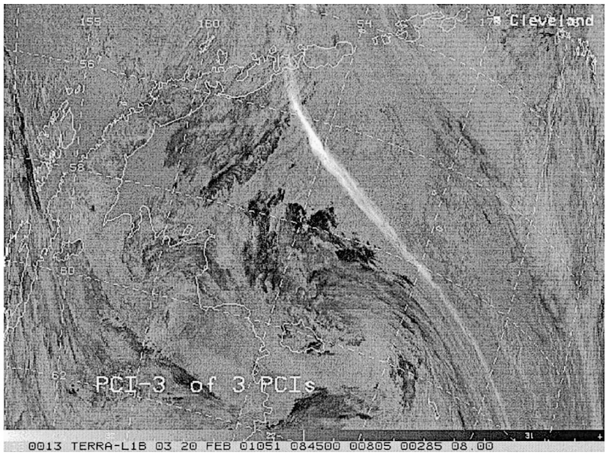

FIG. 12. PCI-3 of three PCIs that were generated from a simulation of the three thermal infrared bands of *GOES-8* through *-11* (bands 2, 4, and 5) using MODIS bands 22, 31, and 32 for 0845 UTC (nighttime) 20 Feb 2001 over Cleveland volcano in the Aleutian Islands. PCI-3 shows the ash cloud (white) by heavily utilizing GOES bands 4 and 5.

FIG. 13. Same as in Fig. 12 except generated from a simulation of the three thermal infrared bands of GOES-M through -O (bands 2, 4, and 6; using MODIS bands 22, 31, and 33). PCI-3 shows the parts of the ash cloud where the ash signal is most concentrated, but in general with less contrast to the image background and with more chance for cloud contamination when compared with the current version of PCI-3 in Fig. 12.

area of confusion is the extent of diffuse ash cloud as it approaches the west coast of Mexico directly south of Popo. It is very difficult to determine where the more diffuse ash ends and the marine stratus cloud layer begins. The lighter gray area further east along the coast in this figure could be mistaken for ash when it is actually an area of low clouds. In contrast, it is much easier to detect the areal extent of the ash in Fig. 6. A three-band volcanic ash product, such as is available from PCI-3, is able to detect most of the ash cloud in this case using band 6, but not nearly as well as with band 5.

Table 3 gives the contributions of the GOES bands to the PCIs for this case. In the new version of PCI-3, band 6 contributes only 12% of the explained variance, compared to 44% for band 5 in the current version of PCI-3 (similar to the numbers for the daytime case in Table 2). This indicates that band 6 has a much-reduced role in volcanic ash detection compared to band 5.

As with the daytime case, basic two-band combinations were also tested. The two-band product utilizing band 5 looks identical to the three-band image in Fig. 6 and is therefore not shown. For comparison, Fig. 8 is a two-band product that utilizes band 6 instead of band 5. This image product is not suitable for volcanic ash detection, with a diminished ash signal compared to the background of the image, except possibly in the most concentrated part of the ash cloud. The ash analyst therefore needs to use a three-band product that is configured somewhat closely to the way bands 2, 4, and 6 are combined in PCI-3.

3. Other day and night simulations of GOES-M

Two more simulations of the GOES-M Imager products for volcanic ash detection were performed, this time for a volcano in a different part of the world. MODIS data were obtained for both a day and a night case with a significant amount of ash from Cleveland volcano in Alaska. Mount Cleveland is on Chuginadak Island in the Aleutian Island chain (52.49°N, 169.57°W) at 1730-m elevation. For both of these cases no graphical depictions of the ash were generated by either the Washington or Alaskan VAACs. Therefore there is no need to remap the MODIS data to match those analyses, as was done for the first two cases. Rather, the MODIS images are presented directly in their polar-orbit pro-

TABLE 4. Contributions of MODIS-simulated GOES infrared bands to PCIs used for volcanic ash detection [2310 UTC 19 Feb 2001, Cleveland (day) case]. Negative contributions are in parentheses. Boldface values are explained in text.

GOES-8 through *-11*				GOES-M through -O			
PCI No.	Explained variance and sign of GOES band contributions: 2	4	5	PCI No.	Explained variance and sign of GOES band contributions: 2	4	6
1	4.2%	45.4%	50.3%	1	2.5%	29.4%	68.2%
2	95.8%	(2.2%)	(2.1%)	2	97.2%	(0.2%)	(2.6%)
3	~0%	**52.4%**	**(47.6%)**	3	(0.3%)	**70.6%**	**(29.3%)**

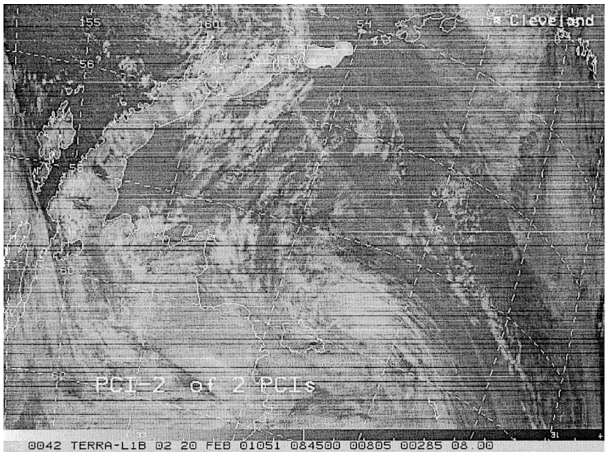

FIG. 14. A two-band (band 4/6)-difference image generated from a simulation of the two longwave infrared bands of GOES-M through -O using MODIS bands 31 and 33 for 0845 UTC (nighttime) 20 Feb 2001 over Cleveland volcano in the Aleutian Islands. This image product is far inferior for volcanic ash detection when compared with the three-band products in Figs. 11 and 12.

jections based on scan lines taken along the orbit track (at 1- and 2-km spatial resolution for the day and night cases, respectively).

The daytime case for Cleveland volcano involves MODIS data taken at 2310 UTC on 19 February 2001. Figure 9 shows PCI-3 generated from simulated bands 2, 4, and 5 of the current GOES Imager. In this figure the ash cloud ranges from white to light gray. Ash is being carried by winds to the east and north (to the right and continuing in a curve extending up and to the left) of Cleveland (indicated by an arrow and a label).

For comparison, Fig. 10 is PCI-3, a three-band combination of bands 2, 4, and 6 from the GOES-M Imager. As in the previous examples for Popo, the contrast of the ash cloud with the image background is diminished, so that the more diffuse parts of the ash cloud west of 170°W are barely discernable. There is also greater possibility of confusion between ash and nonash clouds in the area. In addition, both low and high clouds are equally enhanced in PCI-3.

Table 4 gives the combination of GOES bands that make up the PCIs, for both the current GOES and the GOES-M Imagers. Concentrating on PCI-3, neither combination of current or new bands utilizes band 2 to any significant degree, unlike the previous examples for Popo. Rather, most of the explained variance of band 2 is manifest in PCI-2, possibly due to the large amount and varying height of clouds in this case. This leaves PCI-3 represented by simple two-band combinations of bands 4 and 5, and bands 4 and 6, respectively. This is confirmed by Fig. 11, which is a two-band combination of GOES bands 4 and 6, and nearly identical in appearance to Fig. 10.

The nighttime case for Cleveland volcano involves MODIS data taken at 0845 UTC on 20 February 2001. Figure 12 is PCI-3 for this case, with the MODIS orbit from south-to-north, giving a rotated (north at the bottom) view compared to the daytime example for this volcano. At this time Cleveland is no longer emitting ash. Rather, the ash cloud (which ranges from white to light gray) is detached from the volcano (indicated by an arrow and a label, near the upper-right corner of the figure) and the ash is being carried by the prevailing winds to the east and far north (to the left and down in the figure). The ash cloud, which is over 1000-km long and seems to extend off the bottom of the image, is clearly detectable in PCI-3 as derived from current GOES bands 2, 4, and 5.

For comparison, Fig. 13 is PCI-3, a three-band combination of GOES-M bands 2, 4, and 6. When compared with the current version of PCI-3 (Fig. 12), only the densest parts of the ash cloud are easily discernable. The more diffuse parts of the ash cloud are much harder to distinguish because of less contrast with the image background and contamination from the surrounding clouds. This is especially true for the cirrus clouds that appear to line up with the ash cloud as it is carried farther downwind (near the bottom of the image). Band 6 is again allowing more chance for confusion between ash and surrounding clouds compared to band 5.

In this nighttime case, as compared with all previous examples, there is a much larger contribution from GOES band 2 (see Table 5), when band 6 is used instead of band 5. Both low and high clouds can be the source of the false ash signal. However, removing band 2 from the band 2, 4, and 6 combination results in Fig. 14. In the two-band product the ash is very poorly represented so as to be almost undetectable except for the very densest parts of the ash cloud. As in the Popo cases, and especially at night, a three-band combination of the

TABLE 5. Contributions of MODIS-simulated GOES infrared bands to PCIs used for volcanic ash detection [0845 UTC 20 Feb 2001, Cleveland (night) case]. Negative contributions are in parentheses. Boldface values are explained in text.

GOES-8 through *-11*				GOES-M through -O			
PCI No.	Explained variance and sign of GOES band contributions: 2	4	5	PCI No.	Explained variance and sign of GOES band contributions: 2	4	6
1	16.4%	39.4%	44.2%	1	10.5%	26.6%	62.9%
2	82.4%	(3.5%)	(14.1%)	2	52.9%	16.1%	(31.1%)
3	(1.2%)	**57.0%**	**(41.7%)**	3	**(36.7%)**	**57.3%**	(6.0%)

new bands, although worse at detecting ash than a three-band combination of the current GOES bands, is much better than a two-band product using bands 4 and 6 alone.

4. Summary and conclusions

This study has provided simulated cases using MODIS data (both day and night) where two-band volcanic ash products (when differenced with GOES band 4) are not suitable for ash detection with the new GOES-M band 6 substituted for the current-GOES band 5. Rather, a three-band product of GOES-M bands 2, 4, and 6 depicts the ash cloud better, although not as well as a similar three-band product generated from the current set of GOES infrared bands (bands 2, 4, and 5). This result is true for both the day and night cases examined. However, since only two target volcanoes were examined, the specific results may not be directly applicable to other targets.

When GOES-M becomes operational, further tests with the 13.3-μm band for ash detection can be performed. The ash analyst can choose either to generate PCIs directly from the new set of thermal infrared bands or to utilize similarly configured combinations of the three GOES bands, as suggested by the contributions of the bands to PCI-3. However, the main drawback of the new band 6 remains, that is, a greatly increased chance of contamination by clouds that can obscure the extent of the ash cloud, causing decreased ability to monitor diffuse ash and increased chance of false ash detection.

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