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Development of Volcanic Ash Image Products Using MODIS Multi-spectral Data

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1. INTRODUCTION

The Moderate Resolution Imaging Spectroradiometer (MODIS) on National Aeronautics and Space Administration's (NASA) Aqua and Terra polar-orbiting spacecraft provides a total of thirty-six spectral bands: twenty 1 km resolution Infrared (IR) bands, and sixteen higher resolution (250-500m) visible and near-IR bands available for daytime applications. Based on studies with data from aircraft or other satellite sensors, several of the spectral bands available from MODIS have been shown to be useful for the detection of airborne volcanic ash clouds that pose hazards to aircraft (Miller and Casadevall 2000). For example, the brightness temperature difference (BTD) of MODIS Band 31 (11 µm) and Band 32 (12 µm) is able to distinguish silicate volcanic ash from meteorological clouds (Prata 1989) due to differential absorption. Another longwave IR channel (Band 29 - 8.6 µm) exhibits strong absorption in the presence of volcanic ash as well as sulfur dioxide (SO_2) gas emitted by volcanoes (Realmuto et al 1997).

Due to some degradation in the volcanic ash detection capability of the Geostationary Operational Environmental Satellite (GOES) Imager series beginning with GOES-12 (2002) through GOES-Q (late 2008 launch), there is a need for polar orbiting satellite image products to augment GOES in support of the operational aviation volcanic ash warning system. The reduced capability of GOES is due to the temporary removal of a 12 µm IR band that has a proven capability for volcanic ash detection (Prata 1989; Schneider and Rose 1994). The global aviation warning system consists of Volcanic Ash Advisory Centers (VAACs) established in 1997 by the World Meteorological Organization to provide timely alerts of active volcanic hazards and predictions of ash cloud locations to Meteorological Watch Offices (MWOs) (Miller and Casadevall 2000). Each VAAC has multi-spectral satellite data and derived products at its disposal to help detect and monitor airborne ash clouds.

Work has begun within NOAA/NESDIS to develop prototype volcanic ash image products from MODIS to support the VAACs, as well as to prepare for advanced satellite systems such as the National Polar Orbiting Environmental Satellite System (NPOESS) scheduled for a prototype launch in 2006, and the GOES Advanced Baseline Imager (2012) that will have multi-spectral capabilities and resolutions similar to the MODIS.

2. DATA ANALYSIS

Initial analysis of MODIS data has been completed for two volcanic eruptions: (1) Cleveland volcano in the Aleutian Islands on 19-20 February 2001, and (2) Popocatepetl volcano near Mexico City on 19-20 December 2000. MODIS data has also been obtained for the eruption of Hekla volcano, Iceland, beginning on 26 February 2000, and is being analyzed. The latter case is unique in that there was an accidental encounter with the remnants of the eruption cloud by an instrumented NASA aircraft on 28 February 2000 between Norway and Greenland.

Two data sets were analyzed for each of the first two cases (one daytime, one nighttime) using Man-computer Interactive Data Access System (McIDAS) image processing software on PC workstations. A listing of the spectral bands analyzed is shown in Table 1. The emphasis in this work was to develop an optimum IR volcanic ash product that could be used twenty-four hours a day, regardless of location. However, visible and

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near-IR bands were also evaluated for daytime applications.

Various combinations of MODIS IR bands have been evaluated. Some initial tests involved producing multi-spectral ash products used operationally at VAACs such as the Two-Band Split Window (TBSW) based on the BTD of Bands 32 (12.0 µm) and 31 (11 µm) described earlier in this paper, the Three-band Volcanic Ash Product (TVAP) that is based on the TBSW plus Band 22 (3.9 µm) (Ellrod et al 2002) and a four-channel algorithm (Mosher 2000) that also incorporates visible channel information. Other combinations were evaluated that utilized Band 30 (9.7 µm), Band 29 (8.6 µm), Band 28 (7.3 µm), and Band 25 (4.5 µm). Previous experiments with principal component analysis of MODIS data by Hillger and Clark (2002) were helpful in deciding which channels would be most useful.

The best results for ash cloud discrimination were obtained from a three-channel combination of Band 32 (12.0 µm), Band 31 (11.0 µm) and Band 29 (8.6 µm) (hereafter referred to as the Longwave Volcanic Ash Product (LVAP)). The most useful shortwave IR channel was determined to be Band 25 (4.5 µm), which supports the results of Hillger and Clark (2002). An advantage of Band 25 is that it exhibits considerably less solar reflectance than the other shortwave bands, which provides more consistent results for both day and night. By examining scatter plots of the BTD's for each of the channels, appropriate BTD ranges were empirically selected to highlight the likely ash cloud, and minimize the meteorological clouds and surface features.

3. CASES ANALYZED

3.1 *Popocatepetl, 18-20 December 2000*

On the evening of 18 December 2000, Popocatepetl Volcano near Mexico City began an eruption of ash that was not explosive, but persisted until the afternoon of the 20th. Ash spewed southward from the volcano across southern Mexico, reaching the Pacific coast on the south, and the Gulf of Mexico on the east after Midnight, 20 December 2000. Maximum height of the ash was estimated to be about 10.6 km (35,000 ft) (Washington VAAC advisory).

MODIS observed the ash clouds over southern Mexico at 0505 UTC on 20 December 2000. The three-band LVAP (Figure 1) provided depiction of the ash cloud extent that was in good agreement with concurrent GOES imagery, shown in an analysis by the Washington VAAC (Figure 2). Comparison with the TBSW image in Figure 1 indicates that the addition of Band 29 has resulted in a slightly larger area of ash compared with the TBSW alone. The LVAP detects more of the thin ash over southern Mexico, but may also be observing some surface features, possibly due to the presence of underlying silicate soils.

Scatter plots of Band 32 - 31 and Bands 32 - 29 versus Band 31 IR temperature (Figure 3) reveal that the TBSW alone provides the best discrimination, but Band 32 - 29 contains some additional information on the presence of ash.

3.2 *Cleveland, 19 February 2001*

On the afternoon of 19 February 2001, Cleveland Volcano in the Aleutian Islands of Alaska erupted, sending ash as high as 9.1 km (30,000 ft) (Alaska Volcano Observatory (AVO) Web site). The ash cloud bifurcated as it drifted eastward, with the highest portion of the cloud stretching northward across the Bering Sea, and the portion below about 6.1 km moving southeast into the Gulf of Alaska.

A MODIS LVAP image was produced at 2310 UTC, 19 February 2001 (A - Figure 4). The majority of the ash cloud is shown being elongated north and northwest of the Aleutian chain, with a thinner component to the southeast. Comparison with a simple TBSW product (B) indicates that the addition of Band 29 data adds significant value to the analysis by detecting the thinner ash to the east and southeast of the main ash cloud. The increased sensitivity of Band 29 to ash for this event was also observed in other studies (Schneider et al 2001). The ash cloud coverage from MODIS compares favorably with the 2315 UTC analysis based on 30-minute interval GOES TBSW images from the Alaska Volcano Observatory (Figure 5).

A scatter plot of the BTD's for Bands 32 – 31 and Bands 32 – 29 versus Band 31 IR temperature (Figure 6) shows that both allow good discrimination of ash from meteorological water and ice clouds, but the latter provides the best result in this case.

3.3 *Hekla, 26-28 February 2000*

Hekla volcano, located in southern Iceland, erupted on the evening of 26 February 2000. The eruption cloud rose quickly to an altitude of at least 11 km, then elongated rapidly to the north-northeast. The cloud eventually became absorbed by a North Atlantic storm system, with the majority of the plume continuing in a northeasterly direction across the Norwegian Sea.

The Band 32-31 TBSW signal indicated a predominance of ice in the eruption cloud throughout the period of MODIS observations, in agreement with other studies of this event (e.g. Rose et al 2001). However, differences in the Band 30-28 imagery suggested an abundance of volcanic gasses such as SO_2. This was confirmed by Total Ozone Mapping System (TOMS) data from the Earth Probe spacecraft. The NASA DC-8 aircraft, which traversed the cloud starting around 0510 UTC, 28 February 2000, observed many trace gases associated with volcanic plumes such as: SO_2, CO, and HNO_3 (Shelton 2000).

4. ADDITIONAL EXPERIMENTS

Tests of techniques for detection of sulfur dioxide (SO_2) and hot spots caused by lava domes or lava flows near the volcano craters were also conducted. The SO_2 test involved the use of a multi-channel, stepwise threshold test developed by Crisp (1995). The Crisp technique employs Bands 27, 28, 31, and 36. The tests were negative for the Cleveland and Popocatepetl cases, presumably because the technique is only able to detect SO_2 at altitudes between 6 km and 25 km. The first two eruption cases studied in this paper were relatively weak eruptions that did not emit ash and SO_2 into the Stratosphere. The Hekla event was believed to have emitted some SO_2 gas, and the Crisp algorithm showed a strong signal in the Band 27 - Band 28 test, but was negative for the other three threshold tests.

The hot spot technique that we evaluated is a normalized radiance ratio described by Wright et al (2002). A pronounced hot spot was detected after the Cleveland eruption at 2310 UTC, 19 February 2001 using a slightly different minimum threshold than prescribed by Wright et al.

Experiments with Red-Green-Blue (RGB) color composite techniques were also conducted to produce images that provide optimum color depiction of the ash cloud, meteorological cloud types, and surface conditions to aid in interpretation of the event. One result of the tests is a daytime image product that combines information from the three-band IR volcanic ash image with visible Band 1 (0.6 µm) and near-Infrared Band 6 (1.6 µm) data. The latter two channels help distinguish ice versus water clouds due to the lower solar reflectance of ice cloud particles and snow cover in Band 6 than in Band 1. An example of this RGB image for the Cleveland eruption derived using the McIDAS software is shown in Figure 7. Volcanic ash appears red, water droplet clouds as a greenish hue, and ice clouds and snow as blue.

A similar RGB composite is under development using exclusively IR Bands on MODIS for day or night applications. In this approach, the volcanic ash detected in the three band technique is displayed in red as before, with Band 31 depicting cold cirrus clouds in blue, and the BTD of Bands 25 - 31 or Bands 29 - 31 showing water droplet clouds in a greenish hue.

5. ANALYSIS OF REAL-TIME MODIS DATA

Procedures were developed to analyze near real-time “Level 1b” MODIS data downloaded from the NASA VAAC via a file transfer protocol (FTP) site at Federal Building 4 in Suitland, Maryland. Once the data were downloaded, a program written in McIDAS was run to generate LVAP images in an effort to evaluate the MODIS data for “null” events in which no known volcanic activity was occurring. In these images it was discovered that there are some regions over land areas where “false alarms” for ash clouds were observed. These are believed to be due to the radiation characteristics of sandy soils consisting of silicate minerals. In order to avoid this, a sequential test can be used, requiring that a Band 32 – Band 31 threshold be satisfied before information from the Band 32 – Band 29 can be incorporated into the final image product.

Future efforts will involve the near real-time processing of MODIS data in native Heirarchal Data Format (HDF), which will soon be available via a high speed fiber optic data line from NASA to NOAA/NESDIS in Camp Springs, Maryland.

6. SUMMARY AND CONCLUSIONS

Experimental volcanic ash products have been derived and evaluated using MODIS data from the Terra spacecraft for three volcanic eruptions: Popocatepetl, Mexico (20 December 2000), Cleveland, Alaska (19 February 2001), and Hekla, Iceland (26-28 February 2000). The best ash detection, based on subjective comparisons with frequent interval GOES imagery, were obtained from a tri-spectral combination of Bands 29 (8.6 µm), 31 (11.0 µm) and 32 (12.0 µm). Volcanic ash detection using a simple two-band split window (TBSW) derived from Band 32 - Band 31 was only slightly less effective. Optimum color composite images have been developed to provide information on ash cloud location, as well as cloud phase and surface characteristics, to aid in interpretation both day and night. Additional work will attempt to reduce false alarms from silicate soils in Band 29, and develop procedures for real-time production of operational products for use in VAACs.

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Table 1.
MODIS Channels Used for Volcanic Hazards Detection

Band #	Central Wavelength (μm)	Resolution (km)	Applications
1	0.65	0.5	Visible cloud detection, aerosols
6	1.64	0.5	Cloud phase, snow & ice cover
22	3.96	1.0	Lava flows, fires, ash detection
25	4.52	1.0	Lava flows, fires, ash detection
27	6.72	1.0	Upper tropospheric water vapor
28	7.33	1.0	Mid-tropospheric water vapor, SO_2
29	8.55	1.0	Ash, SO_2, sulfate detection
30	9.73	1.0	Ozone detection
31	10.98	1.0	Cloud coverage and top temperature
32	11.95	1.0	Volcanic ash; low level moisture

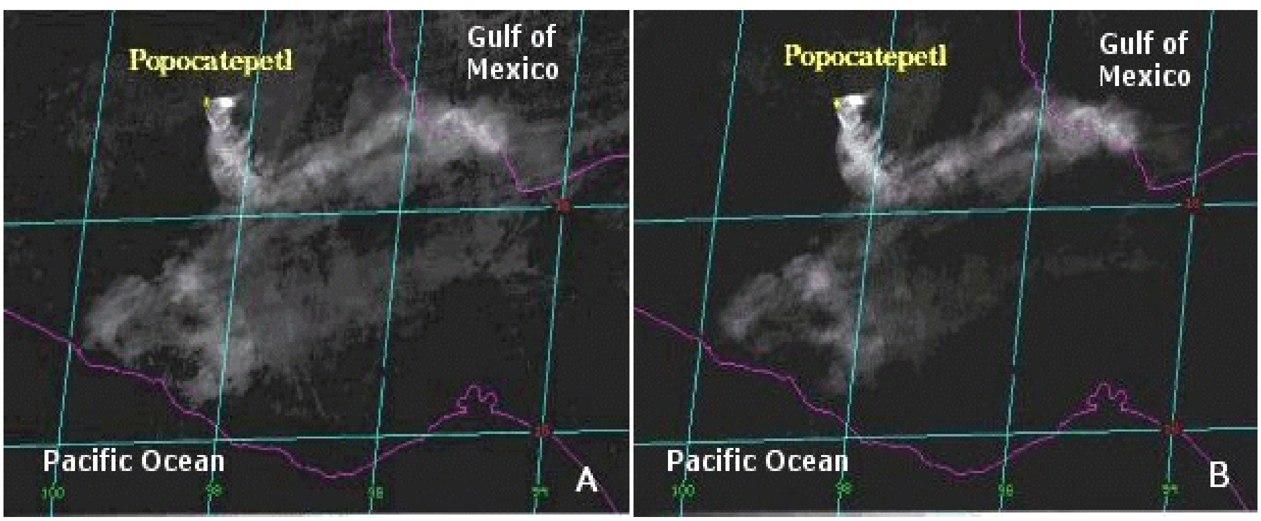

Figure 1. *Comparison of MODIS LVAP image based on Bands 32, 31 and 29 (A), and a TBSW image based only on Bands 32 and 31 (B) at 0505 UTC, 20 December 2000.*

Figure 2. *VAAC analysis near the time of MODIS image in Figure 1, based on animation of multi-spectral GOES imagery.*

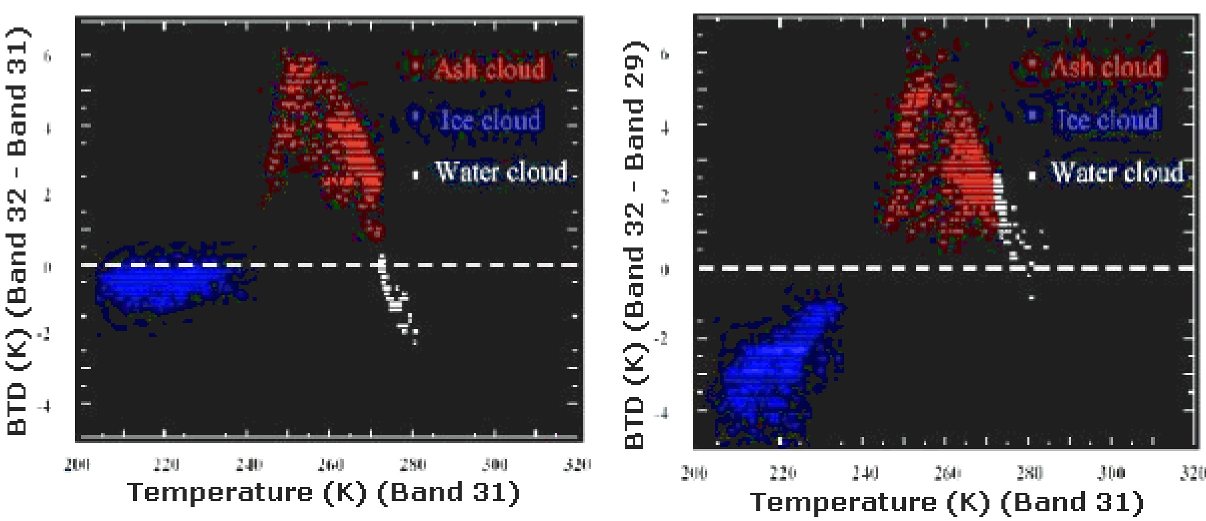

Figure 3. *Scatter plots showing BTDs for MODIS Bands 32 - 31 (left) and Bands 32 – 29 (right) versus Band 31 temperature for the Popocatepetl ash cloud (red), cirrus clouds (blue), and stratus (white), at 0505 UTC, 20 December 2000.*

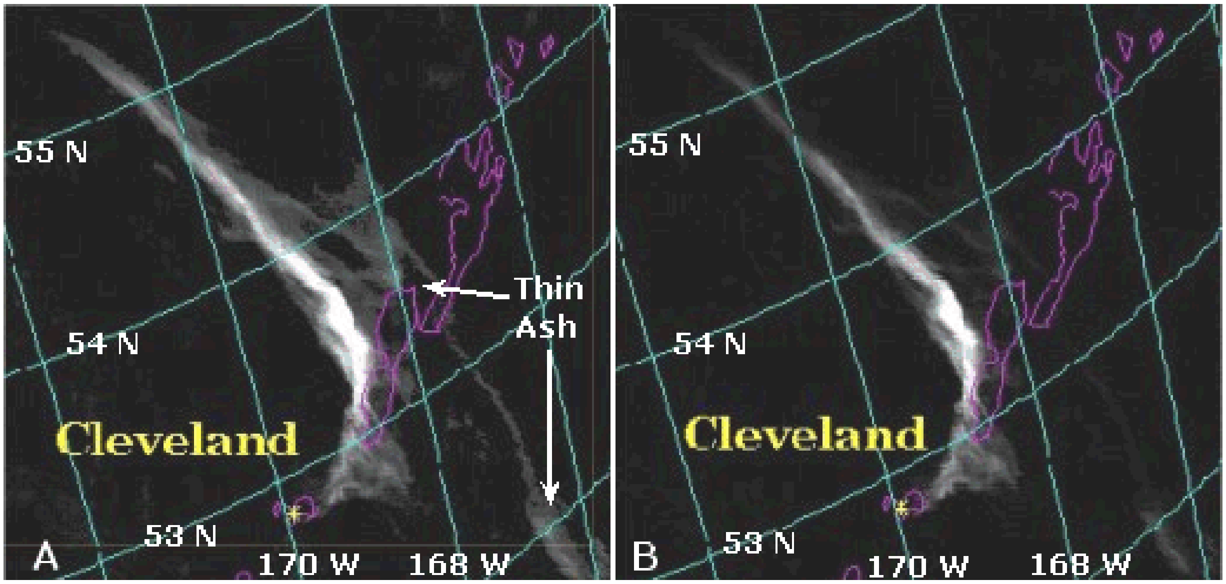

Figure 4. *Comparison of MODIS LVAP image based on Bands 32, 31 and 29 (A) with a TBSW image using Bands 32 and 31 (B) at 2310 UTC, 19 February 2001.*

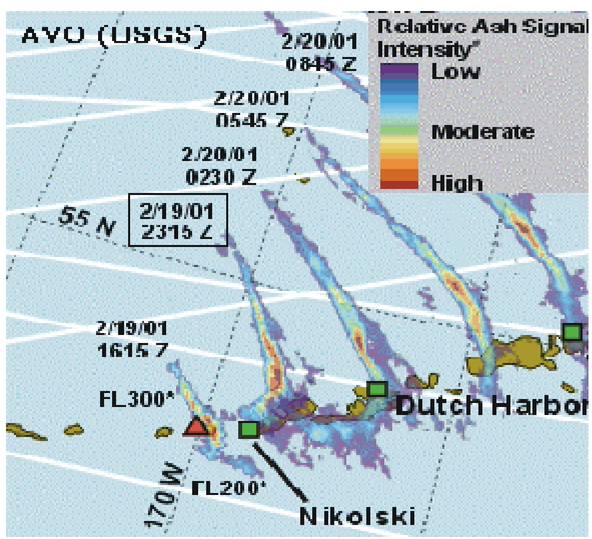

Figure 5. *Spreading of ash cloud from Cleveland eruption on 19 February 2001 based on GOES TBSW animation. Time closest to MODIS data is outlined. (Alaska Volcano Observatory)*

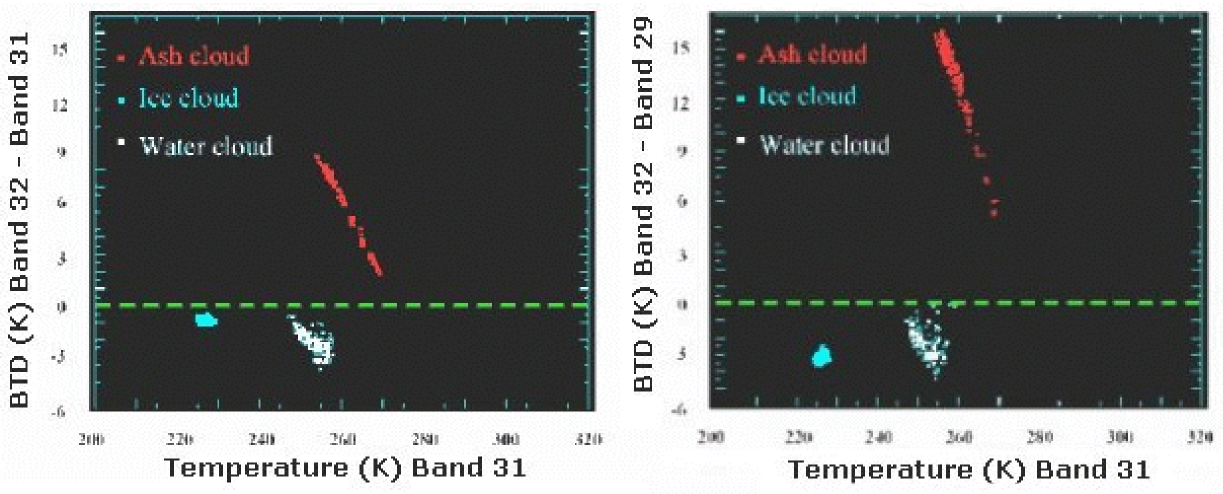

Figure 6. *Scatter plots of MODIS Bands 32 – 31 (left) and Bands 32 – 29 (right) versus Band 31 temperature for the Cleveland ash cloud (red), cirrus cloud (cyan), and stratus (white) at 2310 UTC, 19 February 2001.*

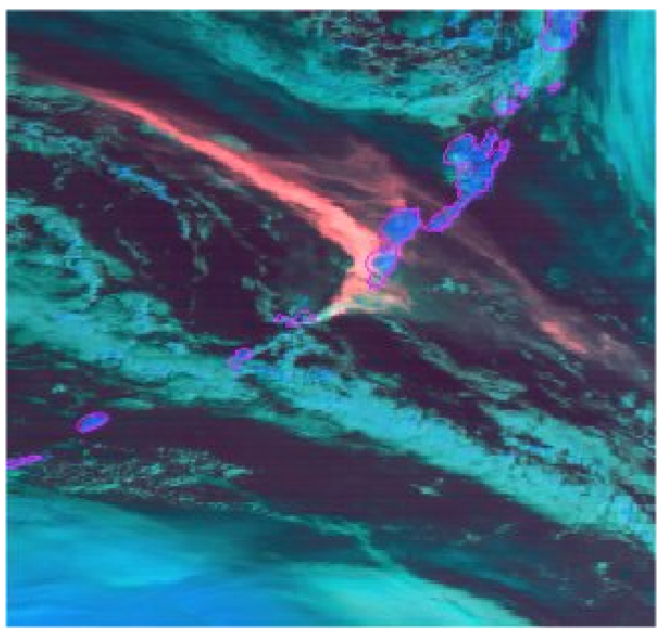

Figure 7. *Red-Green-Blue composite showing ash coverage from MODIS LVAP (Bands 32, 31, and 29) as red, Band 6 (1.6 µm) as green, and Band 1 (0.6 µm visible) as blue.*