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Volcanic Ash Cloud Heights Using the MODIS CO_2-Slicing Algorithm

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1. INTRODUCTION

Volcanic ash suspended in the atmosphere poses significant threats to the aviation community. These threats include loss of life and the severe damage to aircraft that can occur from airborne encounters with volcanic ash. Detection, monitoring, and the forecasting of the position of volcanic eruption clouds has become necessary to ensure aircraft and passenger safety. Avoidance of ash might be a relatively trivial issue when in close proximity to an erupting volcano in clear skies. However, volcanic ash is a significant hazard even at far distances from the eruption (Casadevall, 1994). In addition, it is not publicly known what ash particle concentrations are safe for jet engines, making it an extreme liability to safely route aircraft through thinning ash clouds. These problems are compounded by the fact that, at present, radar instrumentation onboard commercial aircraft is not able to detect airborne volcanic ash (Simpson et al., 2000a). In order to ensure safety, complete avoidance of airborne volcanic ash is required (Casadevall, 1994). To safely route aircraft around a volcanic ash cloud, it is necessary to know where the ash cloud is located in three-dimensional space. Knowledge of the ash cloud position also enables forecasters to alert aircraft to potentially dangerous airborne environments that may exist in future time. The knowledge of cloud height is essential to accurate forecasting of cloud position. Accurate determination of cloud height is, therefore, necessary for the avoidance of airborne volcanic ash by aircraft. Algorithms to detect the geographic location of ash using satellite observations have been developed for various instruments and platforms. This paper investigates the height assignment of volcanic ash plumes using the "CO_2-slicing" methodology applied to MODIS and compares the MODIS retrievals with height estimates obtained from the Multiangle Imaging SpectroRadiometer (MISR). We also compare CO_2-slicing heights with estimates from operational post-eruption analyses by meteorologists at the Darwin Volcanic Ash Advisory Centre (VAAC), Australia

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2. CO_2-SLICING ALGORITHM

Cloud top pressure may be inferred by application of the radiance-ratioing version of the CO_2-slicing technique (Wielicki and Coakley, 1981; Menzel et al., 1983; Wylie and Menzel, 1989; Baum and Wielicki, 1994; Wylie et al., 1994). The CO_2-slicing technique uses five infrared bands available on the Moderate Resolution Imaging Spectrometer (MODIS): 13.3μm – band 33; 13.6μm – band 34; 13.9μm – band 35, and 14.2μm – band 36. The fifth infrared band utilized in this method is the 11μm window (band 31). For clouds above three kilometers above sea level (asl) (approximately 700hPa), cloud top pressures derived from the CO_2-slicing method have accuracies to within approximately ±50hPa (Menzel et al., 1983; Wylie and Menzel, 1989; Platnick et al., 2003, Bedka et al., 2005) for many cases. We present only a brief description of the technique here.

Cloud top pressures are obtained from solution of Equation A. Equation A is a ratio of cloud signals (changes in radiance due to the presence of a cloud) that has been derived for two frequencies (ν_1 and ν_2) for a specific field-of-view (FOV). This may be written as,

$$\frac{I_m(\nu_1)-I_{clr}(\nu_1)}{I_m(\nu_2)-I_{clr}(\nu_2)} = \frac{\varepsilon_1 \int_{Ps}^{Pc} \tau(\nu_1, p) \frac{dB[\nu_1, T(p)]}{dp} dp}{\varepsilon_2 \int_{Ps}^{Pc} \tau(\nu_2, p) \frac{dB[\nu_2, T(p)]}{dp} dp} \quad \text{(A)}$$

where ε is the cloud emissivity, P_s is the surface pressure, P_c is the cloud pressure, $\tau(\nu,p)$ is the fractional transmittance of radiation of frequency emitted from the atmospheric pressure level *(p)* arriving at the top of the atmosphere *(p*=0), and B[ν,T(*p*)] is the Planck radiance of frequency for temperature T(*p*). There are two fundamental assumptions inherent in this method: 1) the cloud emissivity is the same for both ν_1 and ν_2, and 2) the cloud has infinitesimal thickness. We also make the assumption that scattering may be neglected.

The cloud signal ratio on the left side of Equation A is determined from radiances measured by MODIS (subscript "m") and the NOAA NCEP Global Data Assimilation System (GDAS) gridded meteorological product (subscript "clr"), with the cloud signal ratio on the right side of Equation A calculated from a forward radiative transfer model (Menzel et al., 1983). The cloud signal ratios are set up using pre-determined combinations of the four MODIS CO_2 bands, as outlined in Platnick et al. (2003), with the use of one additional band combination. For each band combination, the cloud pressure P_c that best minimizes the difference between the left- and right-hand-sides of Equation A is considered the most representative for that pair. We will now be left with five representative values for P_c. Following the work of Menzel et al. (1983), a final cloud-top pressure is chosen from the five representative P_c values by error analysis. The cloud top pressure is then converted to height asl in meters.

There are several situations known to produce problems in the CO_2-slicing methodology. These problem areas include situations where the wavelength specific noise delta equivalent radiances (NEDR) are larger than the cloud signals, as well as atmospheric profile interpolation limitations. Another problem area for CO_2-slicing involves isothermal regions. Unfortunately, cloud top pressures at or near the tropopause cannot be retrieved using this algorithm at this time. A special version of the CO_2-slicing algorithm is used for stratospheric clouds, however this version cannot identify clouds as being stratospheric, rather, it merely retrieves cloud top pressures for clouds known to be independently located well above the tropopause. Invalid CO_2-slicing results are supplemented with heights obtained by using an 11μm brightness temperature method (section 4). For more detailed descriptions on the limitations of this method, the reader is referred to Smith and Platt (1978), Wielicki and Coakley (1981), Menzel et al. (1983), Menzel et al. (1992), Baum and Wielicki (1994), and Frey et al. (1999).

3. MISR HEIGHT RETRIEVAL

The Multi-angle Imaging SpectroRadiometer (MISR) was one of five instruments aboard NASA's Terra spacecraft. MISR utilizes nine separate cameras that observe the earth in "pushbroom" fashion in four spectral bands (446.3nm, 557.5nm, 671.8nm, and 866.5nm) from Terra's near-polar, sun-synchronous orbit. These nine cameras "acquire moderately high-resolution imagery over a wide angular range in the along-track direction" (Diner et al., 2002), with each camera viewing the earth at unique angles to the local vertical. This unique nine-camera configuration allows MISR to retrieve such cloud parameters as cloud-top heights using a "purely geometrical technique" (Moroney, et al., 2002). Provided here is a brief overview of the cloud-top height retrieval methodology. A more complete description of the MISR instrument may be found in Diner et al. (1998). Analyses from early on in MISR's operational life suggest cloud-top heights to be accurate to within ±562 meters at 1.1 kilometer resolution (Moroney et al., 2002).

The MISR cloud-top height product is produced using a stereophotogrammetric technique. The cloud-top height retrieval consists of two main steps, both of which require the use of stereo-matching algorithms, which are described in detail in Moroney et al. (2002) and Muller et al. (2002). The first step involves retrieving cloud-motion vectors (hereafter referred to as 'wind') and cloud-top height values at relatively low resolution, with the second step being the cloud-top height retrieval at a higher resolution. In truth, cloud-top heights may be retrieved without utilizing the aforementioned first step. However, wind retrievals allow for height corrections due to cloud advection and may limit significant errors. The wind correction process utilizes three cameras, which allows for solutions from the stereo-matching algorithm to be achieved for both wind and cloud-top height simultaneously. These retrievals are made at a coarse 70.4-kilometer resolution. The winds are then decomposed into their north-south and east-west components and are binned in a two-dimensional histogram. For each 70.4-kilometer domain, the modal value of the histogram is considered its representative wind field. Additionally, all winds must pass a quality test. Error analysis suggests wind speed errors of ±3 m/s, corresponding to heights errors (from these winds) of ±400 meters (Moroney et al., 2002).

The second step in the MISR cloud-top height retrieval method first consists of dividing the 70.4-kilometer domain into smaller, 1.1-kilometer sub-region. Considering the previously calculated wind correction values (identical for each 1.1-km sub-region within a 70.4-km domain), the stereo-matching algorithm is run twice (using different camera pairs) in each sub-region to obtain cloud-top height values. While the data ingested by the stereo-matching algorithm is at 275-kilometer resolution, time restrictions require cloud-top height values to be retrieved for every fourth pixel (1.1-kilometer resolution). If only one camera pair retrieves a valid match, the height is accepted. If both camera pairs return valid matches and both resultants heights agree within a certain threshold, the higher of the two heights is retained. If the two heights do not agree, both are rejected. The reader is referred to Moroney et al. (2002) for details on this “height-agreement” threshold.

The final cloud-top height product can be viewed in several ways. The two main ways the height products are presented are as “Best Winds” and “Without Winds”. Without Winds simply means that there was no wind correction applied in the two-step height retrieval process. This view does not yield the “true” height field (unless the real wind speed was uniformly zero), but rather gives an “overview” of the heights in the scene. Best Winds considers the wind correction and yields the “best guess” as to the true height field.

One limitation to the height algorithm occurs in the presence of multi-layered clouds. A recent investigation published in Naud et al. (2004) concludes “Optically thin clouds were found to be accurately characterized by the MISR cloud-top height product as long as no other cloud was present at a lower altitude.” A more detailed description of the limitations to MISR’s cloud-top height retrieval methodology may be found in Moroney et al. (2002).

4. ADDITIONAL HEIGHT ESTIMATION METHODS

Volcanic ash cloud heights can be estimated using both space-borne and ground based techniques. At present, the most common methodology for ash cloud height estimation is correlating atmospheric profiles with infrared brightness temperatures (BT) retrieved from satellites (Holasek et al., 1996; Sawada, 1987; Oppenheimer, 1998; Prata and Grant, 2001; Sawada, 2002; Tupper et al., 2004). This method consists of comparing BTs retrieved from the ash cloud (normally utilizing the 11μm window channel) with the local atmospheric temperature profile. The altitude at which the retrieved BT matches the atmospheric temperature profile is considered to be the height of the ash cloud. Oppenheimer (1998) and Prata and Grant (2001) suggest there are several potential limiting factors to this technique, however. These factors include assumptions made about the emissivity of volcanic ash, inaccuracies with the local atmospheric temperature profiles, and potential ‘undercooling’ of stratosphere piercing clouds.

BT estimations are often supplemented with heights estimates based on wind correlations (Holasek et al., 1996; Lynch and Stephens, 1996; Oppenheimer, 1998; Tupper et al, 2004), which may themselves be sufficient to give reasonable height estimates (Tupper et al., 2003). This method takes advantage of the fact that vertical wind profiles in the troposphere and lower stratosphere are often quite diversified. In other terms, the horizontal wind component at any given altitude will likely be unique in its direction and/or speed as compared to horizontal wind components at neighboring altitudes. It has been found that airborne ash will move downwind with a rate and direction “closely matching the prevailing wind” (Lynch and Stephens, 1996). If the direction and speed of the airborne ash cloud can be determined with confidence, an estimation of its height may be made by matching the ash cloud “vector” with the corresponding wind “vector”, assuming the altitude of the wind vector to be that of the ash cloud.

It is possible to estimate the height of the edge of a volcanic cloud using a geometric technique (Holasek et al., 1996; Oppenheimer, 1998; Simpson et al., 2000b; Prata and Grant, 2001) should the ash cloud cast a visible shadow on the underlying Earth’s surface. To make heights estimates using this technique, data regarding the underlying terrain, as well as satellite viewing and sun angle information, must be known. A complete description of a height-from-shadow methodology can be found in Prata and Grant (2001). In addition, should the visible shadow from a volcanic cloud fall on an underlying meteorological cloud, the volcanic cloud height may be assessed if the height of the meteorological cloud is known (Oppenheimer, 1998). Prata and Grant (2001), apply their shadow technique separately over ocean and land. This height estimation technique is relatively simple when the shadow is cast on a uniform ocean surface. “Addition complexity” occurs, however, when the shadow falls onto land, where the change in slope and elevation of the underlying surface must be taken into consideration when applying this geometric technique. Problem areas for this method are discussed in Oppenheimer (1998). BT-method and shadow height estimations have been compared in Glaze et al. (1989), Holasek et al. (1996), and Tupper et al. (2004).

Additional methods of volcanic cloud height estimation include the use of weather radar (Lacasse et al., 2004; Tupper et al., 2004; Tupper et al., 2005), lidar (Tupper et al., 2004), and a process known as ‘photoclinometry’ (Glaze et al. (1999). Volcanic ash cloud heights are also being estimated through video and seismic techniques by the Research Laboratory of Seismic and Volcanic Activity at the Kamchatkan Experimental-Methodical Seismological Department in Russia (Sergey Senyukov – personal communication 2004-2005).

5. RESULTS

Cloud top heights have been retrieved using the MODIS CO_2-slicing methodology for numerous volcanic plumes. To investigate the accuracy of the CO_2-slicing method for volcanic ash clouds, we compare the CO_2-slicing results with several other methods of height estimation. First, we compare the CO_2-slicing heights with cloud top heights retrieved from MISR. Second, we compare CO_2-slicing heights retrieved for eruptions from the Manam Volcano (Papau New Guinea) with post-eruption analysis from the Darwin VAAC.

5.1 MODIS vs. MISR

The MODIS CO_2-slicing height product (produced at 1.0 km resolution) is compared with the MISR “Best Winds” height product (1.1 km resolution) available from the Langley DAAC. The MISR “Best Winds” product often yields less coverage than the “Without Winds” product and may also suffer from height ‘discontinuities’ due to the 70.4 km resolution height correction algorithm.

The “Best Winds” product does, however, yield the most representative heights for these volcanic plumes and is therefore presented here for image analysis. Results introduced in this section are preliminary. More definitive, quantitative studies are in-progress.

The MODIS and MISR height products are compared for four independent volcanic plumes (Figure 1). Figure 1 indicates that the MODIS and MISR height product values for the Anatahan eruption (panels “1a” and “1b”) are similar. Height values for the Etna eruptions (panels “2a,b”, “3a,b” and “4a,b”) between the two instruments tend to stray, however. For these eruptions, MISR height values are greater overall than those produced by the CO_2-slicing algorithm, and height differences may approach 1-3km in areas.

MODIS and MISR mean height values for six independent volcanic eruptions (including the four illustrated in Figure 1) are presented in Figure 2. Although only six individual eruptions were investigated, two separate sections of the Etna 27 Oct. 2002 plume were isolated, creating a total of seven cases. Pixels for these statistics were isolated from the entire scenes by customized lat/lon ‘boxes’. These boxes were chosen to encompass volcanic cloud over ocean while leaving out meteorological cloud and cloud over land.

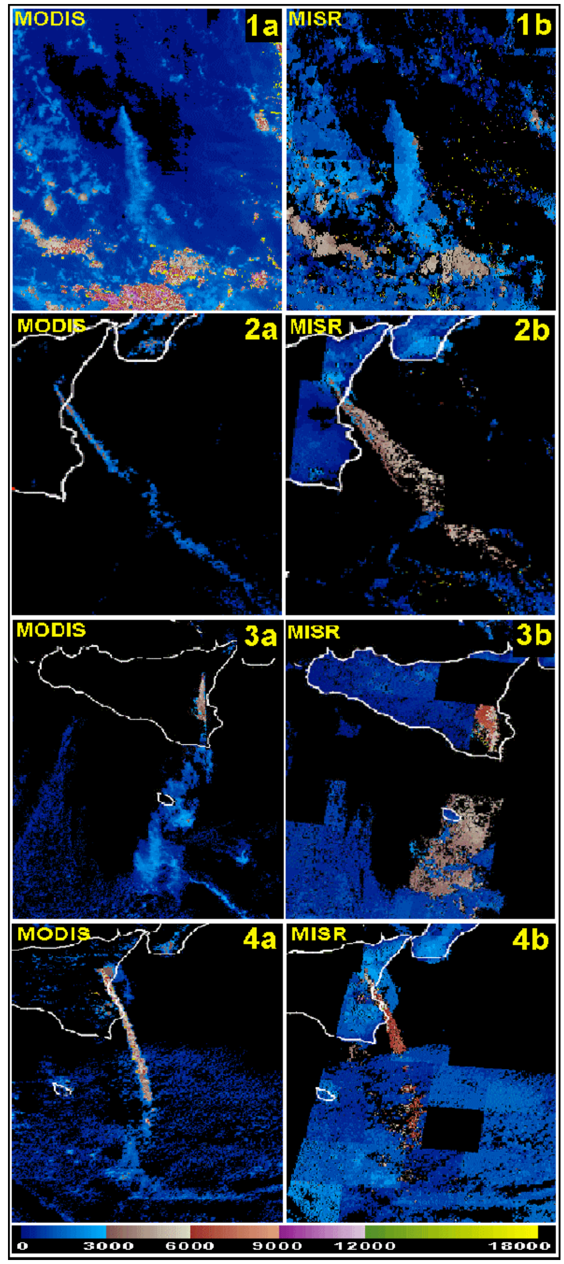

FIGURE 1. Panel comparing MODIS CO_2-slicing height product at 1km resolution from TERRA (images labeled “a”) with MISR ‘Best Winds’ height product (images labeled “b”) for various volcanic eruptions. 1) Anatahan, 24 May 2003, 0055Z. 2) Etna, 22 July 2001, 0955Z. 3) Etna, 27 October 2002, 1000Z. 4) Etna, 29 October 2002, 0945Z.

Intrusion of very thin cirrus is possible, however there is no obvious evidence of any thin cirrus corruption for multiple pixel groups in these preliminary results. Once isolated, pixels with values of 0.0 were thrown out to prevent corruption by erroneous surface height retrievals. An additional screen was made where pixels with height values of less or equal to 1000.0 meters were eliminated to reduce contamination by anomalously low height retrievals. No screen was run to prevent contamination by anomalously high height retrievals. Statistics were run separately for these two groups. Figure 2 indicates that the mean heights retrieved by MISR were higher than the heights retrieved by the MODIS CO_2-slicing method

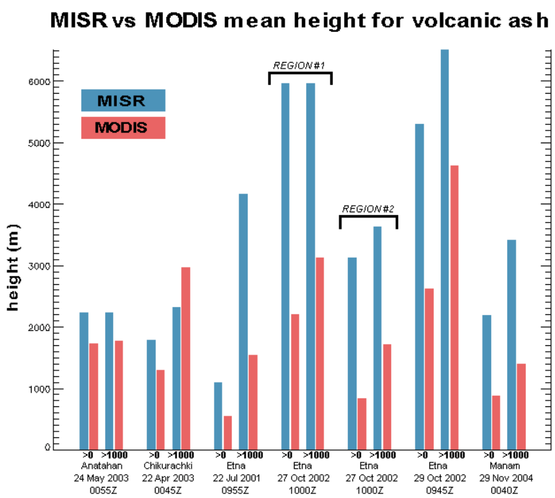

FIGURE 2. Bargraph depicting the mean height values retrieved by MODIS and MISR for six independent volcanic plumes. One volcanic plume has been divided into two distinct regions. Pixels for these means were screened by values greater than 0.0 and values greater than 1000.0 meters.

for 13 of the 14 groups. In several cases, the mean value retrieved by MISR exceeds means retrieved by MODIS by close to 3km. At present, there is code under development that will allow pixel-to-pixel matching for MODIS and MISR. These products will be used to produce more definitive statistics for these height retrievals.

It must be noted that the MISR data used in this study has been flagged with several problem areas that may affect the height products (Catherine Moroney/JPL – personal communication 2005). An updated version of the production code is currently being made operational that includes a more precise wind-correction algorithm, as well as an updated wind quality screening. The new wind quality screening will take into account any 'misregistration' of the MISR cameras, potentially reducing coverage but making the height retrievals more realistic. The updated MISR code will be the focus of future MODIS/MISR comparisons.

5.2 MODIS vs. OPERATIONAL ESTIMATES

MODIS CO_2-slicing heights are compared with post-eruption analysis by the Darwin VAAC for two eruptions of the Manam Volcano near the Papua New Guinea mainland. Complete analyses of the cases presented here, as well as other CO_2-slicing comparisons for the Manam Volcano, may be found in (Tupper, A., I. Itakarai, M. S. Richards, F. Prata, S. Carn, and D. Rosenfeld: Facing the challenges of the International Airways Volcano Watch: the 2004/05 eruptions of Manam, Papua New Guinea, manuscript under preparation, 2005).

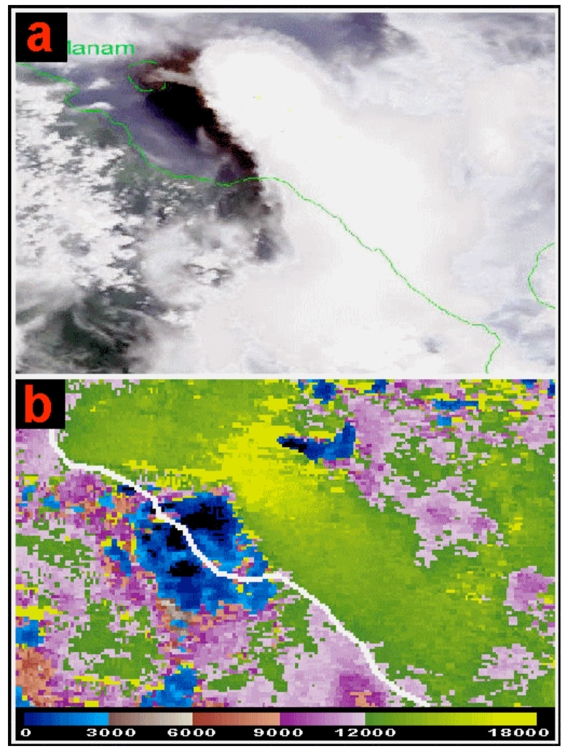

FIGURE 3. Eruption of Manam Volcano, 31 October 2004, 0110Z, observed by TERRA. a) MODIS true color image b) MODIS CO_2-slicing height product for the troposphere at 1km resolution.

CO_2-slicing heights for the 31 October 2004 eruption of the Manam Volcano are illustrated in Figure 3. The highest height value retrieved by CO_2-slicing in this eruption cloud is near 16.8 km. An atmospheric sounding at 00Z on 31 October 2004 from Momote, approximately 348km from Manam and one hour prior to the MODIS overpass, put the tropopause at approximately 16.4km. Darwin VAAC estimates for the height of this eruption cloud were made using shadow height methods (estimate heights greater than 15km) and the BT method (~80^{o}C cloud top, height estimate near 16.4km trop). Final height estimate for this cloud by the Darwin VAAC was 16-16.5km, with a final CO_2-slicing height estimate of 16.5-17.0km.

These estimates are within 25hPa of each other, which is less than the ±50hPa published error (Platnick et al., 2003) for CO_2-slicing.

CO_2-slicing heights were also retrieved for the Manam eruption of 27 January 2005 (Figure 4). The center portions of this cloud were stratospheric with an overshooting, 'undercooled' top of –71°C, with a total stratospheric overshoot of 19°-22°C. The tropospheric version of the CO_2-slicing algorithm (panel "b") is not able to identify the warmer stratospheric portions of the cloud as being above the tropopause and places heights near 12km. Because this portion of the cloud is independently known to be stratospheric, the stratospheric version of the CO_2-slicing algorithm may be applied to this case (panel "c"). CO_2-slicing yields maximum heights of 22-23km for the stratospheric cloud that had not been 'undercooled', and the Darwin VAAC estimates 21-24km. These estimates correspond very well.

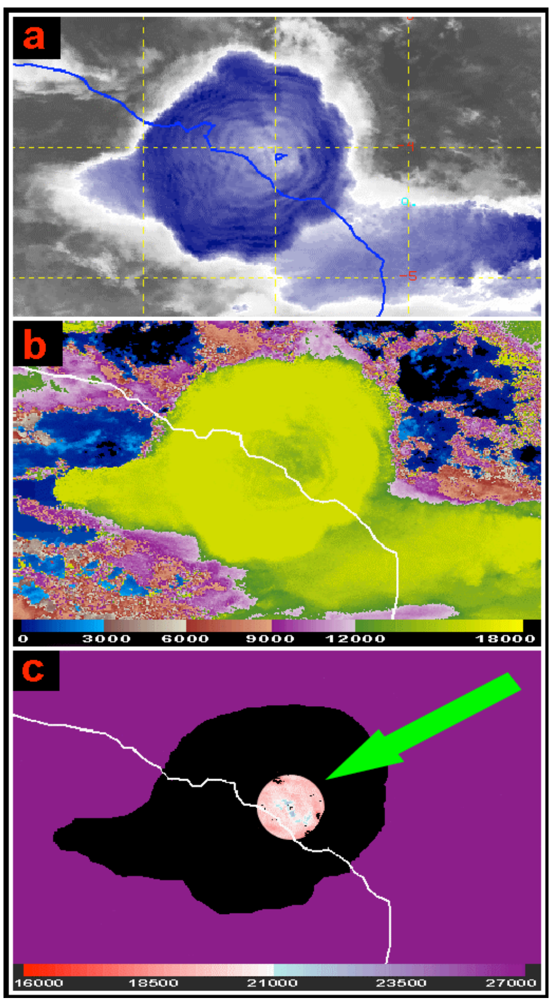

FIGURE 4. Eruption of Manam Volcano, 27 January 2005, 1535Z, observed by AQUA. a) MODIS 11μm image, b) MODIS CO_2-slicing height product for the troposphere at 1km resolution, c) MODIS CO_2-slicing product for stratosphere at 1kn resolution.

6. FUTURE WORK

More definitive, quantitative studies are needed to assess the applicability of the CO_2-slicing method to the height estimation of volcanic ash clouds. Future work includes pixel-to-pixel comparisons of the MODIS and updated MISR height products. Comparisons of CO_2-slicing with other methods of height estimation (video, seismic) are also planned, including comparisons with an independent split window 1DVAR retrieval. Changes to the CO_2-slicing algorithm itself may improve height retrievals for volcanic ash, including the adjustment of emissivity ratios (Equation A) in consideration of volcanic properties.

7. ACKNOWLEDGMENTS

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