Response to "Comments on 'Failures in Detecting Volcanic Ash from a Satellite-Based Technique'"

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I. Introduction

Prata *et al.* (2000) in their comment on our recent paper entitled "Failures in Detecting Volcanic Ash from a Satellite-Based Technique" (Simpson *et al.*, 2000a) state that our analysis "suffers from a fundamental flaw in its methodology and numerous errors of fact and interpretation". We assert that Prata *et al.* (2000) are incorrect in their analysis of our work and will so demonstrate below. For reader convenience our response contains nine sections, including this introduction. Section II provides an overview of operational user requirements for volcanic ash detection. Section III briefly summarizes what was done in the original Simpson *et al.* (2000a) paper. Our responses to general issues raised by Prata *et al.* (2000) in their introduction are given in Section IV. Our responses to criticism by Prata *et al.* (2000) of individual volcanic event analyses presented by Simpson *et al.* (2000a) are given in Section V. Section VI contains our responses to other issues raised by Prata *et al.* (2000) under their titles "Other Considerations" and "Discussion". Radiative transfer issues are discussed in section VII. Independent evidence from other users of the split-window technique is provided in section VIII. A concise summary is provided in section IX.

II. Operational User Requirements

Airborne volcanic ash poses a real threat of loss of life and property to the aviation community. The ash can clog engines, pitot-static systems, and sensors used to fly the aircraft. In addition, ash is abrasive and capable of causing serious damage to aircraft engines, control surfaces, windshields, and landing lights (Miller and Casadevall, 1999). The aviation community has clearly stated that they need immediate notification so they can avoid and/or mitigate encounters with the ash. **Salinas (1999) of United**

Airlines and Foreman (1995 - personal communication to Pieri) of Canadian Airlines have explicitly stated that an ash warning system must strive to provide a 5-minute response time to the pilot in the cockpit once an ash eruption has been detected. The airlines view volcanic ash a threat to air safety from the moment the volcano erupts. Captain Edward Miller of the Air Lines Pilot's Association (ALPA), which represents more than 58,000 airline pilots from 50 airlines in the United States and Canada, has stated that pilots, to be effective in response to an ash event, must have accurate and immediate notification to meet their rapid response needs (personal communication). Mr. Thomas George of the Alaska Airmen's Association, which represents over 1,200 regional and general aviation members, states that the small plane pilot also requires immediate notification of a volcanic ash event so they can rapidly respond to the ash hazard (personal communication). The time between the start of an eruption and first notification to the pilot is a period of great risk to aircraft. Thus, early and accurate detection of the eruption ash cloud is essential to flight safety. The requirement of a 5 minute response time to mitigate encounters of airborne volcanic ash by aircraft has been acknowledged as a true and immediate aviation need (Miller and Casadevall, 1999; Alexander, 2000). While the 5 minute response time has important implications for aircraft in cruise at high altitudes (*i.e.,* >10,000mASL), a rapid and accurate response is even more crucial for encounters at low altitudes (*i.e.,* <5,000mASL) in approach and departure corridors for airports near active volcanoes (*e.g.,* Kagoshima International Airport, Japan; Catania Airport, (Sicily) Italy). In such cases, lateral proximity to the eruption source and low altitude present an even more hazardous situation.

The agencies that are responsible for issuing notification and warnings to the aviation community are tasked with a critical time imperative to meet user needs. Any tool or technique used to monitor, detect and track airborne volcanic ash must be truly robust, in that it must: 1) maximize accurate ash detection; 2) minimize false alarms; and 3) determine the vertical and horizontal extent of the ash. Because of the time constraint, any technique must be real-time and as automated as possible. In addition, agencies often have to deal simultaneously with several emergencies. Thus, there is a compelling operational need to mitigate any requirement for human interaction to determine accurate from false detection events, the technique must be unambiguous and well understood. In short, it must be as "bullet proof" as possible.

The most used technique to monitor, detect and track airborne volcanic ash in satellite data is the split-window $T_4 - T_5$ volcanic ash algorithm (*e.g.,* Prata, 1989a, b; Schneider *et al.*, 1995). It provides global coverage and covers remote volcanoes where other monitoring techniques are not feasible.

This overview of the operational requirements of the aviation community is supported by the extensive U.S. National Weather Service's National Volcanic Ash Strategic Plan now under review at the Department of Commerce (William Alexander, National Volcanic Ash Program leader, National Weather Service, personal communication). This plan already has been approved at all appropriate NOAA levels. For further information on operational implications of volcanic ash, the reader is referred to Hufford *et al.* (2000).

III. Overview of Simpson *et al.* (2000a) Analysis of Volcanic Ash Detection Failures

Prata *et al.* (2000) frequently refer to "the Simpson *et al.* method", implying we developed/used a new method of volcanic ash detection to classify and evaluate the satellite scenes discussed in Simpson *et al.* (2000a). **Such is not the case.** On p. 192 of our original article we explicitly state, "This article examines the effects of a variable atmosphere and of wet versus dry eruptions on volcanic plume detection. Then, results obtained by the current operational $T_4 - T_5$ detection method, applied to specific eruptions studied herein, are generalized to the global distribution of active volcanoes." The current operation technique is the split-window technique developed by Prata (1989a, b) and used extensively by his co-authors (Table 1). It is the only method used by Simpson *et al.* (2000a).

The current operational airborne volcanic ash detection algorithm evaluates the AVHRR (or equivalent, *e.g.,* GOES) 11 μm (T_4) and 12 μm (T_5) brightness temperature difference (BTD)

$$\Delta T = T_4 - T_5 \qquad (1)$$

A pixel is labeled as volcanic ash laden, if its ΔT is negative. The basis for this labeling rule is that meteorological clouds are presumed to generally have positive ΔT (Yamanouchi *et al.,* 1987) whereas volcanic clouds are presumed to have negative ΔT (*e.g.,* Prata, 1989a, b; Wen and Rose, 1994; Schneider *et al.*, 1995).

A consistent threshold value of zero, based on the references cited above and others (Table 1), was used by Simpson *et al.* (2000a) when applying Eq. 1 to separate (*i.e.,* classify) volcanic ash cloud from meteorological cloud in the satellite scenes evaluated. We have carefully re-examined the above-cited references. Our use of Eq. 1

and the zero threshold value is fully consistent with these references and the general method of operational implementation of the $T_4 - T_5$ volcanic ash detection algorithm currently in use by Volcanic Ash Advisory Centers (VAAC). VAACs are charged with the prompt detection of airborne volcanic ash hazards and notification to the aviation community.

Simpson *et al.* (2000a) evaluated every pixel in the scenes they studied using Eq. 1 and the zero threshold used by all the authors in Table 1 prior to 1999. All pixels with negative $T_4 - T_5$ values appear as green overlays in Simpson *et al.* 2000a (their Figures 3, 5, 7, 9, and 11). Our examination of these full scene-wide classifications showed large regions of underdetection and large regions of false detection. Forecasters from the Anchorage VAAC visually examined all results and interpreted the most likely areas of volcanic ash in the plume/cloud. The error rates reported in Figure 14 of Simpson *et al.* (2000a) are not for the entire scenes but only for the underdetection in the plume/cloud area as specified by VAAC volcanic ash forecasters. As poor as the results are for underdetection, especially during the early stages of the eruption most critical to aviation safety, Figure 14 does not highlight any of the false detections that occur simultaneously. This false detection, however, is a major source of difficulty for the forecaster (see below).

Errors necessarily occur in the classification (Haralick and Shapiro, 1992). A misidentification error for class c^k occurs when a decision rule assigns a unit whose true class is c^k to another class c^j, $c^k \neq c^j$. A false-identification error for class c^k occurs when the decision rule assigns a unit to class c^k but the true class is c^j, $c^k \neq c^j$. Operationally, these criteria translate to maximizing the true detection rate of volcanic ash pixels and minimizing the false detection rate of volcanic ash pixels in a satellite scene. As cited above, user constraints and operational imperatives require that this be done automatically in real-time, with minimum post-processing and/or human interaction "to fix" errors is an initial classification. The need for global coverage, as determined by airline routes/schedules and the location of potentially active volcanoes (see Simpson *et al.,* 2000a Figure 17) further strengthens the imperative for minimum post-processing / human interaction to "fix" or "interpret" incorrect or ambiguous initial classification.

IV. Response to General Issues Raised in the Introduction of Prata *et al.* (2000).

Prata *et al.* (2000) raise several general issues in the introduction of their paper.

a. The Plume vs. Cloud Issue

Prata *et al.* (2000) state that we "deal exclusively with 'plumes', which feature relatively rapid processes of active chemical and physical development such as adsorption and sedimentation, as opposed to 'clouds', which describe more stable, typically drifting masses or layers of ash, gas and/or aerosols".

Time series of images were used in the analysis of each volcanic episode examined. Time stamps are provided with each element of these time series (Simpson *et al.* (2000a), Figures 3, 5, 7, 9, 11 and 13). These time stamps indicate that we analyzed both plumes at the earliest possible stage of eruption imaged by the satellite and their continuing evolution into clouds. The split-window $T_4 - T_5$ algorithm of Prata (1989a, b) was applied to all pixels in all images in all time series. Percent of negative $T_4 - T_5$ pixels identified by the procedure (Figure 14) was computed only for pixels easily identifiable as volcanic plume/volcanic cloud by a forecasting meteorologist at the Anchorage Volcanic Ash Advisory Center (VAAC). VAACs have global responsibility for detecting airborne volcanic ash and reporting this information to the aviation community. This was done to minimize any bias that false identification of meteorological cloud as volcanic ash plume/cloud could potentially impose on the observed failure rates. Our procedure, if it erred, did so conservatively in favor of a valid $T_4 - T_5$ volcanic ash retrieval. The Prata *et al.* (2000) semantic distinction between "cloud" and "plume" has no bearing on our result. We stand by the failure rates as reported.

b. The "Truth" Issue

Prata *et al.* (2000) state "they must show that, against some independent 'truth' concerning the existence or non-existence of volcanic ash in a plume…" We are surprised by their sudden need for "truth" or validation. Two of the co-authors of Prata *et al.* (2000) have repeatedly published papers using the $T_4 - T_5$ volcanic ash detection algorithm in which either no validation method (4 studies) was given, a visual validation was made (2 studies) or radiosonde data (1 study) were used to validate plume/cloud height (Table 1). Areal extent of volcanic ash, not plume/cloud height, however, is the parameter derived from the $T_4 - T_5$ algorithm; therefore the radiosonde data do not provide a validation procedure even in this latter case.

Likewise, the inference of volcanic aerosol loading (species, concentration, particle size distribution, and the temporal evolution of these quantities) from ground fall of ash approximately four years after the event (Prata and Grant, 2000) clearly isn't relevant to a real-time, operation requirement. Moreover, the relevance of interferences of aerosol-related properties to the radiative transfer modeling required to improve airborne volcanic ash retrievals from satellite data is questionable. **The pertinent question is <u>much more data-related</u>, namely what are the types and particle size distributions of**

the aerosols from the time of the eruption until the airborne volcanic ash hazard has ended.

We agree that independent, direct observations of aerosol, indeed, are needed both for algorithm validation and improvement. To that end, we have recently secured NASA funding to fly aerosol-related instrumentation on miniature, unmanned aircraft directly into volcanic plumes/clouds during various stages of an eruption. This work is being done in close co-operation with the Italian National Institute of Geophysics and Volcanology, the entity with current statutory responsibility for volcanic eruption monitoring in Italy. However, Mt. Etna is only one of several planned experimental sites. Clearly, given the importance of these data to the general community, our intention is to share this information at the earliest possible, practical date. Moreover, we believe this direct *in situ* observation of aerosol is preferred to an aerosol inferred from ashfall.

c. Arbitrary Threshold Issue

The methodology for manually creating a plume "mask" from the satellite imagery presented in Simpson *et al.* (2000a) was based on the concept that for most of the scenes studied, the volcanic ash plume/cloud was visually distinguishable.

Smaller images were created, narrowing down the larger satellite scenes to only contain the area of the plume/cloud. These new images represented areas similar to the blue boxes presented in the figures of Simpson *et al.* (2000a), but slightly more accurate in surrounding the plume/cloud area and only the plume/cloud area. The blue boxes in Simpson *et al.* (2000a) are used simply to draw the reader's eye to the plume/cloud contained therein. Then a threshold value *T* was determined by trial and error, to find which value separated the ash plume/cloud from the surrounding ocean and/or land.

Once a value for T was determined, an image with the new ash plume/cloud mask was saved. As mentioned, all images, as well as selected volcanic plume/cloud sections, were shown to competent Anchorage VAAC analysts to ensure that the regions of plume/cloud selected for testing meet the criteria used operationally to identify such regions.

d. The all points in plume are volcanic ash issue

As stated in the introduction of Simpson *et al.* (2000a, p.191), "Complete avoidance is the only procedure that ensures flight safety (Campbell, 1994)." Captain Campbell represents the commercial airplane group at the Boeing Aircraft Company. Clearly, the recommended procedures of the dominant manufacturer of currently flying commercial aircraft must be followed. Moreover, Hinds and Salinas (1998) developed the volcanic eruption alert/advisory/avoidance procedure for United Airlines. Their procedure incorporates both the immediate warning response requirement cited in Section II herein and the avoidance criterion of Captain Campbell. Note that United Airlines serves as a focal point for the U.S. domestic airlines' policies regarding volcanic ash. Further details concerning the operational implications of airborne volcanic ash are given in Hufford *et al.* (2000).

The operational implementation of the above recommended procedures requires that the forecaster at the VAAC assume that all suspect pixels in a scene be avoided. This is precisely why the prescribed avoidance areas associated with a given eruption are so large relative to actual plume/cloud size.

For evaluation of the $T_4 - T_5$ procedure, we used the operationally mandated 100% avoidance criterion (*e.g.,* pixels in the plume/cloud are very likely to contain some volcanic material, therefore, they must be detected and avoided) but restricted the actual test regions to clearly discernable volcanic plumes/clouds as described earlier. Our visual procedure is consistent with the visual procedure used by Schneider and Rose (1994, p. 407) for studying the Redoubt eruption. Expert confirmation from analysts at the Anchorage VAAC ensured the accuracy of the visual delineations of plumes/clouds used for $T_4 - T_5$ evaluation.

e. The $T_4 - T_5$ information is only one piece of information

Clearly, the operational forecaster needs real-time access to as many pieces of independent evidence as possible for a volcanic event. Miller and Casadevall (1999) list many of these. Unfortunately, often only very limited information is available. Most volcanoes have no ground instrumentation to monitor seismic activity. In Alaska during 1999, for example, of the approximately forty-one active volcanoes only twenty were instrumented (Miller and Casadevall, 1999). Moreover, less than 20% of the world's active volcanoes have adequate seismic networks around them. Even those that are instrumented do not provide unambiguous evidence for all eruptive events (Miller and Casadevall, 1999). Total Ozone Mapping Spectrometer (TOMS) data are potentially very useful because the detection of sulfur dioxide will allow the analyst to distinguish between magmatic eruptions (which normally contain SO_2 and produce long-lived ash clouds) and phreatic eruptions (which do not contain SO_2 and from which ash falls out rapidly). Unfortunately, as Simpson *et al.* (2000a, p. 192) point out "operationally, relatively little use of [TOMS] data has been made in this application…" This occurs for two reasons: 1) TOMS data are restricted to daytime use; and 2) currently the use of TOMS data in a real-time, operational application requires a data down-link. Of the present 9 VAACs, only the Anchorage VAAC has a direct read out for TOMS data.

From a radiative transfer point of view, chemical speciation, concentration, particle size distribution and their temporal evolution over the period of the eruption would be most valuable (both for real-time detection and subsequent improvement of volcanic ash detection algorithms). Unfortunately, at present, such data generally aren't available, especially in real-time. A new NASA-funded program, which the co-authors of this reply have just started to implement, may well lead to the operational implementation of a volcanic aerosol measurement program designed to monitor, at least at selected locations, the temporal evolution of aerosol-related properties and their affects on accurate plume/cloud detection in satellite data.

Later in this response, we will document a recent Hekla eruption and demonstrate that the assumption of Prata *et al.* (2000) about the availability of different kinds of data to assist VAAC analysts in their tasks generally isn't correct.

f. The responsibility of the user issue

Prata *et al.* (2000) state "the user of the algorithm is responsible for its application and for interpreting the results." If the detection of airborne volcanic ash were simply an academic exercise with few societal consequences, then we would be more inclined to agree. The implications to life, limb and property, however, do not allow us to support such a cavelier attitude.

In the operational environment, the forecaster often must deal simultaneously with multiple, critical situations. Under such circumstances, the analyst may not have sufficient time to accurately access the reliability of all the data and data products he/she may be required to rapidly synthesize. Robust, reliable and generally applicable tools/analyses are the forecaster's real needs. Unfortunately, the $T_4 - T_5$ procedure has too many potential critical failure paths as documented by Simpson *et al.* (2000a). The Prata *et al.* (2000) position sounds too much like the ancient Roman adage "*caveat emptor*", buyer beware!

V. Analysis

Prata *et al.* (2000) criticized some aspects of our analysis of specific eruptions. We disagree with their positions. A brief retort is given below on an event-by-event basis.

a. Soufriere Hills (Montserrat)

We are surprised by the Prata *et al.* (2000) statement "it is very important to realize that these Montserrat eruptions are <u>all</u> very small in scale. … The Montserrat example used by Simpson *et al.* is poorly selected as representative of a tropical event." Clearly, in the context of aircraft safety, the crucial salient characteristic of eruption must be the threat that it poses to aircraft, rather than the absolute size of the eruption. As we shall see below, the effects of Montserrat ash plumes on regional and international aviation were manifest and substantial. Thus, the Montserrat eruption plumes, rather than being "poorly...representative," are *exceedingly well-posed* as tropical events with deleterious impact on air traffic, and we judge them as such.

The Montserrat Volcano Observatory Special Report 01 of the explosive event of September 17-18, 1996 (McGuire *et al.*, 1996) states that the Washington D.C. satellite analysis branch of NOAA/NESDIS (later – the Washington VAAC) issued a volcanic hazards alert on September 17. This alert followed an ash encounter at 10 km, within 3 hours of the explosive episode, by a civilian aircraft between 30 and 60 miles south of

Antigua. The alert was not based on satellite data. The pilot reported smoke in the cockpit together with engine compression problems.

On September 18, at 14:07 local time, an encounter between a civilian aircraft and volcanic ash at 3 km between 60 and 80 miles west of Montserrat was reported. The Guadeloupe Airport reported their closure due to ash covering the runway markings.

The aircraft that encountered ash on September 17 was an Air Canada A320. The plane suffered damage to the engines and the windshield had to be replaced. The plane was out of service for two days and passengers had to be placed in a hotel overnight (Tom Fox, International Civil Aviation Organization, (ICAO) – personal communication). The regional aircraft that encountered ash on September 18 had to be pulled from service for preventive maintenance.

On January 19, 1997 (a separate event) an Air Canada A320 and a Condor Airlines B767 encountered ash and reported the incidents through the Pilot Report (PIREP) process. Air Canada entered the ash near 22ºN / 64.5ºW at 34,000 ft. The pilot immediately changed course and descended to 24,000 ft to get out of the ash. Approximately 36 minutes later, Condor Airlines encountered ash at 34,000 ft at 22ºN / 68ºW on its way to Europe. The pilot further filed a Special Air Report of Volcanic Ash upon arrival at Dusseldorf, Germany. A copy of this report can be obtained from ICAO. Fortunately, damage to the aircraft was not significant.

Prata *et al.* (2000) state "The 18 September event studied by Simpson *et al.* was another order of magnitude smaller in scale than the larger Montserrat events and its silicate signal in the split-window is too weak (less than about 1,000 tonnes of fine ash of 1-25 μm in diameter) to overcome the effects of water vapor (Rose and Mayberry, 2000)." Moreover, Davies and Rose (1998) clearly state, "one unknown quantity is the high humidity in the Lesser Antilles and its effect on the BTD technique … Rose *et al.* [1997] have shown that high humidity in the tropical atmosphere suppresses extent radiances of the 10-12 micron range and possibly shifts the temperature differences enough to lose detection. Either high water vapor content or the presence of water droplets in the volcanic cloud from a variety of causes could potentially cause such a suppression. Researchers believe such conditions may occur in the Lesser Antilles and sometimes suppress negative values in BTD images" (Davies and Rose, 1998, pg. 507).

We conclude that Prata *et al.* (2000), as well as Rose and Mayberry (2000), agree with the earlier analysis of Simpson *et al.* (2000a) that the $T_4 - T_5$ algorithm failed. Perhaps, Prata *et al.* (2000) are more concerned with our selection of this event because it clearly demonstrates one of the multiple failure paths of the $T_4 - T_5$ algorithm. These potentially tragic aircraft incidences with the small Montserrat eruptive-type events elegantly point out the critical importance to detect both large and small volcanic ash events so they can <u>all</u> be avoided. Miller and Casadevall (1999), guiding authorities in the U.S. Geological Survey, state that once a slug of ash of any size is ejected to altitudes of greater than 9 km and carried into air routes, it is a hazard. We are shocked that Prata *et al.* (2000) choose to ignore the carefully thought out position of the U.S. Geological Survey. Moreover, we fail to see how the report of the interaction of volcanic material with the ocean surface (Mayberry *et al.,* 2000) about 4-5 years after the eruption will help a VAAC with its real-time analysis imperative in support of aviation.

b. Mt. Spurr/Crater Peak

The Mt. Spurr/Crater Peak example provides near ideal environmental conditions for optimal detection of volcanic ash by the $T_4 - T_5$ algorithm. Meteorological clouds range from near minimal to non-existent. Moreover, total atmospheric column water vapor was very low for this event (0.25-0.6 in). Typically, August is the rainiest month in Alaska (Simpson *et al.*, 2000b Figure 7).

Figure 5f of Simpson *et al.* (2000a), however, clearly shows that the $T_4 - T_5$ algorithm failed to clearly identify the overwhelming number of pixels in the eruptive plume. Moreover, Schneider *et al.* (1995), in their own study, stated about the image presented in Simpson *et al.*, 2000a (Figure 5f) that "the band 4 minus band 5 brightness temperature difference does not work well in this image" (Schneider *et al.*, 1995, pg 29). Panels g and h, about 2 and 4 hours, respectively later than panel f, again show failure to detect the core signature of the plume/evolving cloud. We believe that two reasons account for this failure. The particle size distribution generally contains the largest sized particles at the earliest stages of eruption. These particles, if > 2-3 μm in size, will interfere with detection (Prata, 1989b). Moreover, particle concentration is also likely to be largest during the earliest stages of an eruption because atmospheric advection/diffusion generally will not have had sufficient time to widely distribute particles. High concentrations of particles also contribute to enhanced absorption. These considerations indicate that, in general, the $T_4 - T_5$ algorithm is likely to have difficulties accurately detecting the early stages of the eruption. Prata *et al.* (2000) begrudgingly concede this possibility when they state "the fundamental incapability of the algorithm to detect early hazard events, while possibly true, …" Note, the algorithm does well as originally stated by Simpson *et al.* (2000a) in detecting the plume/cloud but only 12 hours after the eruption. Unfortunately, the false detection rate also is higher. (see Simpson *et al.* 2000a, Figure 5i). It is interesting to note, that Yu *et al.* (2000), even with their new atmospheric correction to the $T_4 - T_5$ split-window technique, only show results for Mt. Spurr/Crater Peak twelve or more hours after the eruption (their Figure 3).

Finally, it is unlikely that the $T_4 - T_5$ split-window technique would have produced any discernable and useful plume signature in the early hours of this eruption (0-6 hours) if the usual cloud cover, Arctic haze and atmospheric moisture had been present and contaminated the AVHRR imagery. This interference is supported by recent experience with the Hekla eruption, which will be discussed in detail below.

c. Mt. St. Augustine

We are confused by the remarks of Prata *et al.* (2000) when they state "The crucial image frame is shown as Simpson *et al.* Figure 7b. Simpson *et al.* fail to detect a plume, while the $T_4 - T_5$ method identifies a small plume over the volcano vent." Figure 7b in Simpson *et al.* (2000a) is a T_4 image only; no attempt was made to classify volcanic ash pixels in this frame. Figure 7f is the $T_4 - T_5$ image and it clearly shows the plume as well as false alarms. We do not understand their point.

Prata *et al.* (2000) again state we are using our own method for $T_4 - T_5$ and our results cannot be tested against Holasek and Rose (1991). As clearly stated in Section III above, this is not the case. We used the technique espoused by Prata (Prata 1989a, b; Wen and Rose, 1994; Schneider *et al.*, 1995) for evaluation and our results are consistent with Holasek and Rose (1991).

Prata *et al.* (2000) criticize our identification of all negative $T_4 - T_5$ pixels as one color. Again we used a zero threshold fully consistent with the above and other references (see Table 1, and Section III). We are disturbed by the very recent use of different negative and positive threshold values to classify pixels within a scene. Such an exercise has little academic value because the use of such static thresholds (*e.g.,* "magic numbers") is inconsistent with modern theories of scene classification (Haralick and Shapiro, 1992; 1993). Moreover, they are not useful in the operational environment of split-window volcanic ash detection because of numerous inherent errors (see section VIII. Independent Evidence from functioning VAACs). It is known that the calibrations of the AVHRR thermal channels have errors of order 1.3K (NOAA Polar Orbiter Users Guide, TIROS to NOAA-14, 1998). Additional errors in the BTD values can come from many sources (*e.g.,* water vapor attenuation (Harris and Mason, 1992); thermal temperature inversions). Thus, any attempt to establish numerous static thresholds to classify ash and other environmental parameters will be scene specific if it works at all. Indeed, this has proven to be the case in Alaska. The Forecast Techniques Development Meteorologist at the Anchorage VAAC attempted to adjust the threshold to separate ash in scenes captured daily. The effort resulted in the inability to automate the ever-changing thresholds. This partially results from the different types of volcanoes in Alaska (*e.g.*, plumes/clouds with typical values of $T_4 - T_5$ near –1K for Mt. Bogoslof and others which are as negative as –11K for Mt. Spurr). Finally, Simpson *et al.* (2000a, p.212) discuss in detail results from Potts and Ebert (1996) and Ebert and Holland (1992) which show that under many common circumstances, negative $T_4 - T_5$ differences can cause meteorological cloud to be wrongfully identified as volcanic cloud. Simpson *et al.* (2000a) specifically note this appears to have occurred in the imagery of the Mt. St. Augustine eruption.

d. Ruapehu

The GMS Pathfinder Project has clearly shown problems associated with the GMS-5 instrument. However, in the spirit of Prata *et al.* (2000), namely, that one must use whatever information is available, we have used GMS-5 imagery because it is the best available geostationary satellite that covers the Ruapehu Volcano.

Ash was not detected well at the initial stage of the eruption (Figure 9j). About 4 hours later a good plume definition is finally detected (Figure 9l), as stated in Simpson *et al.,* (2000a) on p. 202. Again some meteorological clouds give false alarms very far from the plume/cloud in the scenes. It is of interest that Potts and Tokuno (1999) had problems with ash detection of the 19-20 July, 1996 Ruapehu eruption using the $T_4 - T_5$ algorithm on GMS-5 and NOAA AVHRR imagery.

The initial inability to detect an ash plume in GMS-5 data deserves some comment, since the lack of a strong ash signal in the GMS-5 data for over four hours is consistent with the presence of a large amount of water vapor in the plume. We had estimated on the order of several times 10^6 m^3 of water vapor released during the eruption, with about 30-40% of that amount coming from surface or phreatic water. Although Prata *et al.* (2000) assert that "…earlier eruptions had emptied Crater Lake, changing the style of eruption from phreatomagmatic to magmatic in style (Bryan and Sherburn, 1999)…" it is clear from on-site field reports that as early as November 1995, the summit lake was refilling and lahars were reported as a significant geologic hazard at that time (INGS, 1995). The lake continued to fill, as noted in field reports during the following March and April (INGS, 1996 a, b), eventually submerging the intra-crater lava dome that had formed. In addition, fumarolic activity was noted as "water rich" and fumaroles were most likely cooled by “near-surface quenching by shallow groundwater.” (GVNB, 1996). Both observations suggest an intensely phreatic local environment, as one would expect. Finally, April 1996 observations of the Ruapehu summit lake show that it had refilled to cover about 30% of the surface area of the pre-eruption lake (GVNB, 1996), and although bathymetric data are less certain, it appears that Crater Lake was not empty. Thus even a somewhat diminished Crater Lake could contribute a significant phreatic component (along with magmatic water) to the eruption, consistent with the difficulties encountered in GMS-5 data. Finally, we would like to concur with the Prata *et al*. (2000) suggestion that perusal of “independent data … are required for careful validation” and would encourage their efforts in this area, as well.

We are curious how Prata and Grant (2000) determined very thin ash layers using the $T_4 - T_5$ method. Ash fall will only provide retrospective information. It indicates what has rained out from the atmosphere, not what is left in the atmosphere (*i.e.,* the thickness of a volcanic cloud layer) or what was in it at the beginning of the eruption. Our participation in the NASA funded effort to obtain real-time ash samples in the atmosphere should further our understanding of aerosol types, concentration and distribution. This information should help improve algorithm design and validation.

e. Popocatepetl

Prata *et al.* (2000) again state that one can use some kind of static threshold value to classify the image scene and minimize false detections. This is their response to the false alarms seen over the land and the identification of offshore meteorological cloud as volcanic plume/cloud by the $T_4 - T_5$ procedure. They suggest that land in the scene is on the order of –1K and that misclassifications in the scene should be of no great surprise.

As stated above we are intrigued by these magic numbers used for classification. If these threshold numbers for Popocatepetl are used for a relatively wet atmosphere or even in another region (*i.e.,* the polar regions), evidence indicates that there would be either an increase in the false alarm rate or missed events (*e.g.,* the Alaskan volcano Bogoslof, personal communication C. Baur, Anchorage VAAC). Such static thresholds are scene/volcanic event specific and useless under an operative imperative (see further discussion below).

Prata *et al.* (2000) repeatedly emphasize the utility of animation of geostationary imagery to aid in its interpretation. We agree that animation can be very useful but not under all conditions, especially if a volcanic ash plume/cloud is embedded in overcast meteorological clouds. In addition, the time required to collect/process data and prepare the animation loop generally will compromise the operation response time requirement. Animation can be highly useful for further downstream tracking of the plume/cloud if it lasts several hours and/or days.

When one conducts a case study, one must be careful in generalizing the results. Hufford *et al.* (2000) provided a hypothetical operational example using the *Popocatepetl volcano* to demonstrate the atmosphere water vapor effect. Their Figure 6 shows ash encounter probabilities (AEPs) based on the VAFTAD numerical volcanic ash transport and dispersion model output with “climatological” forcing 48 hours after the simulated eruption (Stunder and Hefter, 1999). AEPs are the percentage of time in which a particular cell will experience ash from a hypothetical eruption during a period of interest. In this simulation, the eruption column from Popocatepetl is assumed to reach flight level 40,000 ft. The VAFTAD model output for a layer between flight level 20,000 and flight level 35,000 ft for a winter (Dec-Jan-Feb) and a summer (Jun-Jul-Aug) season is given by Hufford *et al.* (2000). Each season represents a 2-year average of winds. The flight path charts are included in the figure and they provide seasonal AEPs along a specific track. The AEPs for the winter season move eastward from Popocatepetl into the Gulf of Mexico and the western Atlantic, under the influence of the prevailing seasonal westerlies. The AEPs for the summer period now occur west of Popocatepetl, over the eastern tropical Pacific. This change is due to prevailing easterlies in the summertime. Simpson *et al.* (2000c, in review) have examined the space-time variability of the global distribution of atmospheric total column water vapor using the NASA NVAP dataset. Analysis of the seasonal variability over and around Mexico showed, that in general, the winter atmosphere over Mexico is much drier then summer and that the atmosphere over the ocean near Mexico is much moister than over the land. In summer the land-sea contrast is more pronounced. The seasonal variability in the regional wind field can advect a relatively dry volcanic ash plume into a moist atmosphere. The atmosphere-volcanic plume/cloud interaction can, in turn, compromise the use of the operational $T_4 - T_5$ volcanic ash algorithm as clearly stated in Simpson *et al.* (2000a). Thus, a case study may show that the $T_4 - T_5$ performs reasonably well under a specific set of conditions, but had the eruption occurred under different conditions (wet vs. dry season), then the results can be dramatically different. Under scenarios such as these, a continuously varying set of thresholds would cause operational havoc.

f. Rabaul

We do not understand why Prata *et al.* (2000) question the use of the term "failure". For this case and throughout their paper, they agree that the $T_4 - T_5$ method did not show any significant $T_4 - T_5$ negative differences for the Rabaul eruption. Unfortunately, the operational forecaster would be looking for negative ΔT not positive ΔT! We clearly stated that the reason for "failure" in this case was the presence of ice coating the particles (Simpson *et al.*, 2000a, p. 212). We also carefully cited the work of Ebert and Holland (1992) and Potts and Ebert (1996) on their observations of extremely cold cloud tops in the tropics (Simpson *et al.,* 2000a, p. 212).

We do thank Prata *et al.* (2000) for pointing out a typographical error for the height of the Rabaul plume. The height should have been 11-17 km, not 1.1 to 1.7 km, which is consistent with the mean value of 15 km given by Prata *et al.* (2000).

We do not understand the relevance of GMS-4 data for evaluation of the $T_4 - T_5$ algorithm. GMS-4 has a single infrared channel. Therefore, although we were aware of these data, we chose not to cite them (how does one form a difference from a single channel?). As an additional tool for the operational forecaster to use, we agree that GMS-4 data may be useful on occasion.

We are amused by the use of the "arch" and "inverted arch" for discriminating meteorological clouds from volcanic ash plumes/clouds. Prata *et al.* (2000) refer to our Figure 13a as "exactly" what is expected to show the arch distribution. We ask where is this arch in Figure 13b and c? See additional comments below about "arch" and "U" shapes for use in detection.

VI. Other Considerations/Discussion

Prata *et al.* (2000) state "Scattered negative $T_4 - T_5$ pixels that are upwind of a known eruption are generally of no concern." We disagree. Such pixels only can be excluded as an aviation hazard if the forecaster knows the vertical profile of wind at the remote location and the distribution of cloud height. Unfortunately, these usually either aren't known or are known with insufficient accuracy and spatial resolution for the aviation application. In fact, lack of this specific type of information played a critical role in the aircraft encounter with volcanic products from the Hekla eruption (see below).

Prata *et al.* (2000) again cite the usefulness of seismic data (*e.g.,* the Spurr eruption). As noted earlier in our reply, less than 20% of the world's active volcanoes have adequate seismic networks around them and even those that are instrumented do not provide unambiguous evidence for all eruptive events (Miller and Casadevall, 1999).

Prata *et al.* (2000) state that "image animation is a very powerful interpretive tool". The time required to downlink and process data for use in a animation loop, however, often is inconsistent with the real-time warning requirements of the aviation industry cited above. Moreover, the theory of optical flow (Hildreth, 1983; Horn and Schunck, 1981) and its application to satellite data (Wahl and Simpson, 1991) clearly show that flow visualization requires the presence of gradient in the scene. If, for example, a volcanic cloud with high optical thickness is embedded and/or surrounded in meteorological cloud with high optical thickness, then the gradient difference may be insufficient for good feature recognition in an animation loop (*e.g.,* try to spot a polar bear on an ice flow!).

Prata *et al.* (2000) state that volcanic ash causes a distinct "U" shaped $T_4 - T_5$ vs. T_4 scatter plot whereas other phenomena cause an "arch" shape in the scatter-plot! The Montserrat $T_4 - T_5$ vs. T_4 scatter plots (Simpson *et al.*, 2000a Figure 4) show little or no evidence of either an "arch" or a "U" shape. Similar scatter plots for Mt. Spurr (Figure 6), Mt. St. Augustine (Figure 8), Mt. Ruapehu (Figure 10), Mt. Popocatepetl (Figure 12) and Rabaul (Figure 13) generally do not show either an “arch” or “U” shape. On occasion, such a shape does occur in the scatter plots of a particular scene for a given eruption (see Simpson *et al.*, 2000a, Figure 6b, Figure 13a). However, of the 28 scatter diagrams shown in Simpson *et al.* (2000a) 2 or perhaps 3 at best, exhibit a “U” or “arch” shape readily ameanable to this shape identification. We infer that Prata *et al.* (2000) would have operational meteorologists resort to the use of “magic shapes” in addition to “magic numbers” to help sort out the deficiencies in the $T_4 - T_5$ split-window volcanic ash detection algorithm. Finally, we note that the Mt. Spurr image at 17:19 (Simpson *et al.*, 2000a, Figure 5e) and its corresponding $T_4 - T_5$ vs. T_4 scatter diagram (Figure 6e) contain 119,213 plume pixels. Of these, 3,620 are positive (meteorological cloud), the remaining are negative (115, 513) and indicate ash cloud. Yu *et al.* (2000) analyzed the same eruption using data taken about 1 hour later at 18:57. **Their Figure 1 shows a scatter diagram of selected pixels only** (about 200) plotted as $T_4 - T_5$ vs. T_5. They show about 87 pixels as volcanic ash and 105 as meteorological cloud. We question how they can postulate a valid “U” or “arch” shape when they have greatly sub-sampled the population of pixels using undefined criteria. Subsampling can produce almost any desired distribution from a parent population. The subsampled distribution, however, may or may not represent the parent population well. The base AVHRR data (their Figure 3) indicates a plume/cloud comparable in size to the one shown in Simpson *et al.* (2000a). We also wonder why Yu *et al.* (2000) chose an image nearly 19 hours after the eruption to demonstrate the robustness of their new atmospheric correction. Surely, the August 19, 1992 image at 01:26 GMT would provide a more rigorous test. We are willing to supply the data.

Prata *et al.* (2000) state that “the physical basis of algorithm not discussed or challenged by Simpson *et al.* (2000a)…” This is incorrect. Simpson *et al.* (2000a), starting on p. 210 under their section heading “Failure Modes of Detection”, state “Limitations of the $T_4 - T_5$ algorithm in discriminating volcanic and meteorological cloud have been recognized by others. Prata (1989a, b) found that, for ice-free ash clouds with particles of mean radii less than 3 μm, the $T_4 - T_5$ difference will be negative. This discussion continues to p. 212 and cites several other authors who have found failure modes of the $T_4 - T_5$ approach.

As stated in both Simpson *et al.* (2000a, p. 192) and herein, TOMS data definitely are extremely useful for identifying volcanic ash. For reasons already cited, however, their use in present operational VAACs is extremely limited.

We are pleased that Prata *et al.* (2000) acknowledge, without direct reference, the success of our radiative transfer sensitivity study (Simpson *et al.*, 2000a p. 209-210 Figure 15). It clearly shows that a wavelength near 8.6 μm would be a better discrimination of volcanic ash than either the currently used 11 or 12 μm data. Moreover, we are pleased that they agree with our suggested use of new (MODIS) and anticipated data (ASTER, ENVISAT data – see detailed discussion Simpson *et al.*, (2000a) p. 214-215). We anticipate using the new X-Band downlink in Alaska for this very purpose. Their unwillingness to cite us correctly in Prata *et al.* (2000) is consistent with their lack of citation in Yu *et al.* (2000) which attempts to make a water-vapor loading correction to their original split-window $T_4 - T_5$ method. The central theme of Simpson *et al.* (2000a) is that water vapor contaminates the $T_4 - T_5$ volcanic ash retrieval obtained with the original split-window method of Prata (1989a, b) and as used by various authors (Table 1). We assert that the need to write the Yu *et al.* (2000) manuscript vindicates the correctness of the scientific position in Simpson *et al.* (2000a).

VII. Radiative Transfer Issue

Prata *et al.* (2000) state we are unfamiliar with the physics (*i.e.,* radiative transfer) underlying the $T_4 - T_5$ split-window technique (*e.g.,* Prata, 1989a, b; Wen and Rose, 1994). **This is not so.** The actual problem isn't with the radiative transfer modeling itself. Rather, the problem is with the assumptions made for the volcanic ash properties which were used as input for the radiative transfer model. The general applicability of the Prata (1989a, b) radiative transfer modeling is based on the general validity/applicability of his several assumptions to a specific eruption:

1. Plane-parallel volcanic cloud layer with homogeneous physical properties;
2. Assumed chemical composition for the volcano clouds;
3. Assumed, instead of measured, particle size distribution;
4. Spherical particle size shape assumed in Mie scattering formulation;
5. Assumed certain cloud and surface temperatures.

Scattering is small for thermal infrared wavelengths. Any error introduced by ignoring scattering should be smaller than from uncertainties introduced in any of the parameterizations/assumptions cited above. **The critical question is: How representative are the assumptions made by Prata (1989a, b) for an arbitrary volcanic event?** The data presented by Simpson *et al.* (2000a) and independent evidence (see section VIII below) indicate that more often than not these assumptions simply aren't representative of arbitrary eruption events. Perhaps the new aerosol observations to be taken as part of our recently funded NASA field program will help. Clearly, we'll share these with Prata *et al.* (2000) and the entire community.

Wen and Rose (1994) also raise questions about the assumptions of particle size, aerosol composition, particle shape, and the single-layer parallel cloud with homogeneous properties. They state that equivalent spheres may overestimate the $T_4 - T_5$ temperature difference and that until shape effects on the scattering are addressed, exact $T_4 - T_5$ temperature difference will elude computation. Shape also plays an important role in the settling times of particles out of the volcanic cloud/plume, which in turn, may have a significant influence on the time after eruption required to get an unambiguous volcanic ash signal from the $T_4 - T_5$ split-window algorithm. Rose partially acknowledges this when he states "the development of a retrieval method to obtain the mass of ash in a drifting volcano cloud as well as its position has greatly expanded the utility of the two band infrared method because it gives us the ability to measure the mass of hazardous silicate "as the cloud dissipates" (Rose, Volcanic Ash Clouds and Hazards, http://www.geo.mtu.edu/departement/classes/ge404/gcmayber/intro.html). **The time required for "dissipation," however, appears inconsistent with the aviation community's insistence on rapid detection and early warning (< 5 minutes)**

Simpson *et al.* (2000a) choose not to criticize the Prata (1989a, b) work because it made a valuable, initial contribution towards solving a very complex problem even though it used many simplifying assumptions as discussed above. Many agencies, however, have seized upon this simple formulation in the hope of a quick fix to a very complex issue. Moreover, some scientific workers have labeled the five-minute warning time requirement as unrealistic. This is, however, the aviation community's expressed operational need. Unfortunately, accurate detection of volcanic ash within the 5 minute time frame is not likely with a split-window $T_4 - T_5$ retrieval scheme due to particle size restrictions (and other assumptions) inherent in the retrieval scheme developed by Prata (1989a, b). In fact, the largest particles generally are most abundant during the early stages of the eruption when detection is so important. Moreover, unpredictable atmospheric motions may keep these larger size particles (≥ 3 μm) aloft much longer than anticipated from simple settling velocity estimates. Nonetheless, all agencies involved in volcanic ash detection must strive to meet the aviation community's stated requirement. We acknowledge this is a difficult task requiring time, talent, and resource.

VIII. Independent Evidence

a. Hekla Eruption

1. Nature of Encounter

A highly instrumented NASA DC-8 research aircraft studying arctic ozone inadvertently flew through the fringe of an airborne volcanic ash plume generated by the eruption of Hekla Volcano (Iceland). The eruption occurred 26 February 2000, 1830Z. The crew knew of the eruption and adjusted their flight plan according to avoid the predicted positions of the plume. During the encounter, pilots noticed nothing unusual. There was no visible exterior manifestation (*e.g.*, St. Elmo's fire, windscreen abrasion), and there was no abrasive damage to other aircraft exterior flight surfaces. Research instruments on board the aircraft registered increased SO_2 and decreased O_3 abundances. The particulars of encounter are: i) approximately 700 nautical miles north of the predicted position of the ash plume; ii) location of Hekla: 64°N 19.7°W; iii) farthest predicted location of plume above 18,000 feet ASL (Flight Level 180): 73°N 05°W at 27

Feb 0900Z; iv) position of the DC-8 at plume encounter: 76°N 00°W at 37,000 feet ASL (FL 370); and v) time of encounter: 28 Feb 0510Z.

Damage: (information courtesy of Tom Grindle and Bill Burcham at NASA Dryden Flight Center) There were two main discoveries that affected the operational readiness of the DC-8: i) upon arrival at Kiruna, Sweden, an analysis was done of the aircraft engine oil for all four engines. In every case, about 500ppm elemental sulfur was indicated (normal range <1ppm). As a result fluids were changed and the aircraft experienced approximately one week of downtime; and ii) upon return to Edwards AFB, California, (68 flight hrs later) engine borescope analyses indicated ash-clogged cooling air passages in the #4 engine. The engine was removed and sent to the General Electric Corporation facility in Kansas. Similar damage was discovered in the other three engines and they were removed and sent to GE. Essentially the damage consisted of plugged cooling holes in turbine rotor blades, erosion of leading edge coatings on turbine blades, and the build-up of ash inside interior engine ("bleed air") passages; iii) ash was also discovered in the air filters of the air conditioning system and samples of that material are being analyzed at JPL and at Michigan Tech; and iv) during the 7 minutes in which the DC-8 traveled through the plume, engine EGT ("exhaust gas temperature") appears to have risen slightly, then decreased slightly, along with an indication of slightly increased fuel flow. These findings are still preliminary and under investigation. *Costs:* (information courtesy of Dr. Cheyl Yuhas, NASA Code YS): initial estimate of $3M for the overhaul of all four engines. An additional 3000 hour check of the entire airframe also accomplished during this time. The NASA funded PacRim 2000 airborne campaigned had to be postponed to accommodate the 3000 hour overhaul procedure, which was originally scheduled for November 2000.

2. London VAAC Analysis

David Smith of the London VAAC provided information via Dr. A. Harris of the U.K. Meteorological Office. Smith says that an initial plume height of 35,000 feet was input into the trajectory model, based on radar measurements from Iceland. Note that such measurements will only pick up the large particles. Early satellite passes showed the plume in both $T_4 - T_5$ and TOMS data for the SO_2, but cloud cover meant that no satellite data (at least AVHRR) were interpretable for the days following the eruption. After a few days the model was switched from modeling the initial plume to the continuos emission (the model is not currently set up to cope with more than one event at a time). The height of the continuous emission plume was lower (as might be expected) and therefore followed a different trajectory from the initial eruption. It was a couple of days after this that the DC-8 had its encounter with remnants of the initial plume in the lower stratosphere.

Thus, the root cause of the problem was the error in initial height assignment, with 35,000 feet not quite enough to get the plume into the stratosphere. After a few days, the decision was made that the modeling should concentrate on continuous emission, based on the erroneous assumption that material would have dropped out of the northerly plume by this time. The absence of any interpretable satellite data meant that there was little else to guide the forecasters.

3. Relevant Comments

David Smith states "Our only tool was IR imagery which was of little use". Andrew Harris (U.K. Met. Office) states "There is no doubt that improved techniques which permit the reliable detection of volcanic plume above lower-lying cloud from AVHRR would be welcome."

4. Summary of Hekla event

This report of the Hekla eruption and subsequent DC-8 encounter with volcanic material far from the predicted position is not a criticism of the London VAAC. These highly competent forecasters did the best they could with the little information available. Contrary to the assumption of Prata *et al.* (2000), an abundance of information for VAAC forecasters often does not exist. The Hekla eruption clearly demonstrates this unfortunate situation. This makes the requirement for a stand alone, more robust volcanic ash retrieval algorithm from satellite data self-evident.

b. E-mail from Dr. Arlin Krueger, VOLCAM Principal Investigator at NASA Goddard Space Flight Center to Mr. William Alexander, National Volcanic Ash Program Leader for the National Weather Service

Bill,

"I feel strongly that NWS should have a requirement for SO_2 detection in addition to the ash requirement. That is because all of the ash detection methods are subject to interference or ambiguous…"

c. Washington VAAC

Marcia Weaks, chief of the Synoptic Analysis Branch (SAB) at NOAA-NESDIS, stated in discussions on volcanic ash detection at the 1999 Dallas annual meeting of the American Meteorological Society that the SAB found that the $T_4 - T_5$ technique, using both GOES-8 and NOAA POES imagery on the September 1996 eruptions of Montserrat, was ambiguous. The staff had to use other resources such as visible and single channel IR to aid in detecting the airborne ash. Marcia Weaks also has recently asked the Anchorage VAAC "Have you had much progress in finding a technique or two… to mitigate the moisture problems we typically encounter in moist tropical atmosphere?"

This group also has been evaluating a suggested improvement to the $T_4 - T_5$ technique developed by Dr. Bill Rose and colleagues (Yu *et al.,* 2000). Gary Ellrod of the SAB concludes, "Bill Rose has come up with a scheme to improve the $T_4 - T_5$ in moist conditions, although there are some false detection areas added from clouds. To me, it doesn't seem to work much better than current three channel techniques." (Note, SAB has implemented a three channel technique in addition to the $T_4 - T_5$ technique). Again, all this independent operational evidence supports the earlier conclusions of Simpson *et al.* (2000a). Moreover, this operational experience of the Washington VAAC supports the conclusion made herein that the use of "magic numbers" and "magic shapes" in this application is dubious at best.

d. Wellington VAAC

The Wellington VAAC has been concerned about White Island eruptions for some time. White Island is just off the Bay of Plenty coast, North Island, New Zealand (U.S. Geol. Survey #401-04 at S 37-31.1 E 177-10.5). The volcanic ash is emitted from near sea level to heights of 3,000 to 5,000 feet in conjunction with gas and steam. Plumes typically are 20-50 km in length and generally reach a height no greater than 7,000 feet. Forecasters at the Wellington VAAC have reported mixed usefulness with the split-window ($T_4 - T_5$) technique applied to NOAA data. Problems with the technique are especially serious for low level (low altitude) emissions. This summary was provided by Mr. James Travers. He is Operations Manager – Aviation Services Division, Meteorological Service of New Zealand.

e. Darwin VAAC

Dear Gary,

I noticed in the report of the Volcanic Ash Work Session on January 11 that you have been working on false alarms related to water content in processed imagery. We have been worrying about false alarm problems here at Darwin VAAC for some time (Rod Potts may have mentioned something to you since he was at the meeting?) as well as the masking effect of water vapour (we have quite a lot of moisture in the atmosphere here!). Would you be able to send any information about your project?

Regards,

Andrew Tupper, Senior Meteorologist

Darwin VAAC, Australia

We have problems reconciling Andrew Tupper's request for help with accurate volcanic ash detection in his e-mail to Gary Hufford and his co-authorship of the Prata *et al.* (2000) comment on the Simpson *et al.* (2000a) paper which clearly identifies the problem Mr. Tupper needs to solve.

f. Anchorage VAAC

Craig Baur, lead techniques development forecaster for the Anchorage VAAC, provided an overview of his operational experience with the $T_4 - T_5$ algorithm in Alaska at the request of NWS management. His views, based on several years of experience, are quoted below.

"About 3 years ago I tried to look at the AVHRR $T_4 - T_5$ imagery for purposes of setting up an automatic scan of each image for volcanic ash. I immediately ran into problems with false indications of ash in the atmosphere. This was especially pronounced in NOAA14 images. Cumulonimbus clouds and some cirrus features are especially troublesome in false ash indications."

"Rod Potts of Australia has also been trying to set up a volcanic ash auto detect system using AVHRR $T_4 - T_5$ imagery. In conversations with Rod, he indicated that he was unable to implement the system because of the frequent false alarms. As I recall, Rod discovered that the problem was with the channel calibration near the tropopause. NOAA 14 (polar orbiting satellite with the AVHRR instrument) in Alaska, however, gives false ash indications in clouds with tops much below the troposphere."

"I have not looked at GOES imagery for automatic scanning for ash. But about 3 years ago Rene Servanchkx of the Canadian Met Center sent me an e-mail that contained $T_4 - T_5$ GOES image of the western Bering that had a strong ash signature. I looked at the area with either NOAA12 or 13. It ended up to be a cluster of cumulonimbus clouds with no ash indication. So I suspect that some of the same problems exist with GOES."

g. Other Significant Recent Volcanic Activity

These are preliminary reports for two very recent eruptions (August, 2000):

1. **Arjuno-Welirang eastern Java, Indonesia 7.73°S, 112.58°E; summit elev. 3,339m**

On 14 August 2000 a pilot report to the Darwin VAAC stated that an ash plume from Arjuno-Welirang was observed at an altitude of about 10 km. **The plume appeared to be stationary and was not visible in satellite imagery.** Source: Darwin VAAC

2. **Miyake-jima Izu Islands, Japan 34.08°N, 139.53°E; summit elev. 815 m; All times are local (+ 9 hours = GMT)**

At 0659 on 9 August 2000 an ash cloud producing eruption occurred at Miyake-jima. **At 0750 the ash cloud was not visible in satellite imagery**, but the Tokyo, Japan VAAC received a report that the ash cloud was at an altitude of 3.8 km. **By 0802 the cloud was visible in GMS 5 imagery** and was estimated to be at 10.7 km altitude. **(Note, this is about 1 hour later than the 5 minute notification time mandated by the aviation community).** The ashfall from the eruption prompted officials to evacuate about 600 residents from the NE part of the island of Miyake-jima. According to a Reuter's article, an airport spokesman said the eruption forced the airport on the island to close and commercial flights between Tokyo and Miyake-jima were canceled. On 15 August an air report sent to the Tokyo, Japan VAAC stated that an ash cloud was at 5 km altitude. **The ash was not visible in GMS 5 imagery.** Reports indicate that a Boeing 747 aircraft executed a decent through a volcanic cloud for about two minutes. The crew reported that the cabin filled with dust. Sources: Tokyo, Japan VAAC, Reuters, Associated Press.

All the independent evidence provided in this section is fully consistent with the conclusions of Simpson *et al.* (2000a).

IX. SUMMARY

The overwhelming preponderance of data, as well as independent evidence, supports the original conclusions of Simpson *et al.* (2000a) in their analysis of the multiple failure modes in the split-window $T_4 - T_5$ volcanic ash detection algorithm currently in use by many (Table 1, the VAACs). Recent "improvements" to the split-window $T_4 - T_5$ algorithm (*e.g.,* Yu *et al.,* 2000) do not correct the deficiencies noted. We conclude that Prata *et al.* (2000) have not carefully evaluated either their own algorithm or protocols. Moreover, continued insistence that this technique is a sound one within the context of the airborne volcanic ash aviation hazard creates a false sense of security for agencies charged with maintaining aviation safety. We view the safety of the flying public as more important than any particular academic exercise.

In spite of our justified criticisms of the split-window $T_4 - T_5$ volcanic ash detection algorithm developed and used extensively (Table 1), we do acknowledge the significant contribution which Prata, Rose, Schneider and colleagues have provided over the years to the important area of airborne volcanic ash. It is time, however, to move forward.

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Table 1: Summary of prior use of the T_4-T_5 algorithm by some of its developers. Value of threshold is the number used to distinguish volcanic ash plume/cloud from meteorological cloud in a given study. Prata (1989b) states "The radiative transfer calculations show that the temperature (ΔT) between the brightness temperatures at 10.8 μm and 11.9 μm at a particular optical depth is positive for ice and water clouds [Yamanouchi *et al.*, 1987], whereas for volcanic pumice, quartz and the acid droplets ΔT is negative provided the mean particle size is less than 3 μm or so" (page 1295, column 1, lines 12-17).

Reference:	**Davies and Rose, 1998**	**Krotkov *et al.*, 1999**	**Schneider *et al.*, 1995**	**Holasek and Rose, 1991**	**Rose and Schneider, 1996**	**Rose *et al.*, 1995**	**Schneider and Rose, 1994**
Volcano(s) Studied:	Montserrat	Mt. Spurr/Crater Peak	Mt. Spurr/Crater Peak	Mt. St. Augustine	Popocatepetl	Rabaul, Klyuchevskoi	Redoubt
Identification of ash plume/cloud region in scene	T_4-T_5	T_4-T_5	T_4-T_5	T_4-T_5, T_4/T_5	T_4-T_5	T_4-T_5, T_4/T_5	T_4-T_5
T_4-T_5 Cutoff Used (0 K unless otherwise specified)	Rose and Schneider, 1996 (pg 506, column 2, line 37 through page 506, column 3, line 1).	Prata 1989a; Wen and Rose 1994 (pg 455, column 2, lines 17-21). Figure 1 caption states cut off of –0.5 K used.	Prata 1989b, Schneider and Rose, 1994 (pg 28, column 1, lines 47-50). Tested cut off of –0.5 K to better define edges.	Prata 1989a (pg 424, column 1, lines 1-5).	Prata 1989b, Schneider *et. al*, 1995 (pg 530, column 3, lines 19-24).	Prata 1989b (pg 477, column 2, lines 7-10).	Prata 1989a, Holasek and Rose, 1991 (pg 406, column 2, line 13 through pg 407, column 1, line 2).
T_4-T_5 Validation Method:	Results of T_4-T_5 are compared with radiosonde data to provide a cloud height estimate (pg 506, column 3, lines 31-43). No validation of the areal extent of the volcanic event detected.	They visually compare a T_4-T_5 result with a TOMS pattern and conclude that there is good agreement between the areal extents of the ash cloud derived from the two methods (pg 456, column 1, line 18 on).	No method presented.	No method presented.	No method presented.	No method presented.	The results of these mathematical operations were visually evaluated to determine their ability to enhance volcanic clouds (pg 407, column 1, lines 23-25)
Eruption Time(s):	1) September 22, 1997 14:46 UT 2) November 6, 1997 18:30 UT	~August 18, 1992 00:00 UT	1) ~18 August 1992 00:00 UT 2) ~17 September 1992 09:00 UT	There were several explosive events from 27 March 1986 to 7 April 1986 that took place. Not very precise.	~ March 10, 1996 11:00 GMT	18 Sept, 1994 20:06 GMT	1) 8 January 1990 19:09 GMT 2) 15 February 1990 13:10 GMT 3) 23 March 1990 13:04 GMT
First available image(s):	1) September 22, 1997 15:15 UT 2) November 6, 1997 19:15 UT	August 18, 1992 18:57 UT	1) 18 August 1992 01:26 UT 2) 17 September 1992 12:40 UT	See table 2 in Holasek and Rose (1991).	March 10, 1996 17:15 GMT	19 Sept, 1994 09:00 GMT	1) 8 January 1990 19:28 GMT 2) 15 February 1990 13:17 GMT 3) 23 March 1990 13:25 GMT
Time of first scene analyzed after eruption:	1) 30 minutes 2) 45 minutes.	19 hours	1) 1.5 hours 2) 3.7 hours	N/A	~6.25 hours	13 hours	1) 20 minutes 2) 7 minutes 3) 20 minutes