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Remote Sensing of Environment 78 (2001) 341–346

Remote Sensing of Environment

www.elsevier.com/locate/rse

Comments on "Failures in detecting volcanic ash from a satellite-based technique"

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Received 7 July 2000; accepted 7 April 2001

Abstract

The recent paper by Simpson et al. [Remote Sens. Environ. 72 (2000) 191.] on failures to detect volcanic ash using the 'reverse' absorption technique provides a timely reminder of the danger that volcanic ash presents to aviation and the urgent need for some form of effective remote detection. The paper unfortunately suffers from a fundamental flaw in its methodology and numerous errors of fact and interpretation. For the moment, the 'reverse' absorption technique provides the best means for discriminating volcanic ash clouds from meteorological clouds. The purpose of our comment is not to defend any particular algorithm; rather, we point out some problems with Simpson et al.'s analysis and re-state the conditions under which the 'reverse' absorption algorithm is likely to succeed. © 2001 Elsevier Science Inc. All rights reserved.

1. Introduction

The basic premise of the paper by Simpson, Hufford, Pieri, and Berg (2000) is to demonstrate to its audience that a particular satellite-based algorithm (the $T_4 - T_5$ method)[1], used for detecting hazardous volcanic ash clouds, often fails. The paper also notes that the algorithm is fundamentally incapable of providing prompt detection of the explosive event itself. The fact that the algorithm does not detect ash under certain conditions has been known for a long time (Prata, 1989a, 1989b; Prata & Barton, 1994; Rose et al., 1995), and most of the reasons for this are already well known among the research and operational aviation/meteorological community. The fundamental incapability of the algorithm to detect early ash hazard events, while possibly true, is not shown by Simpson et al. To understand how the authors have reached their conclusions, it is worth scrutinising their methodology.

They must show that, against some independent "truth" concerning the existence or non-existence of volcanic ash in a plume, the $T_4 - T_5$ method misclassifies pixels within the plume. The misclassification can occur in two modes: the algorithm can miss pixels that are *known* to be ash, or it can classify pixels as ash that are *known* not to be ash. Either way, the authors must demonstrate that they know the *true* nature of the pixel under question. Their methodology for 'truth' is as follows.

(1) Using the same satellite data, the authors use an arbitrary threshold on pixel brightness temperature or manually determine the location of a plume in the image.

(2) They assume, without justification, that all pixels in the plume are volcanic ash.

(3) They 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. Ash clouds, as distinct from plumes, are perhaps more hazardous

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[1] It is conventional to refer to the AVHRR 11 and 12 μm brightness temperatures as T_4 and T_5, respectively.

PII: S0034-4257(01)00231-0

to aviation and while these clouds start out as plumes, their evolution to clouds depends on the time scale for dispersion and transport, which in turn depends on the three-dimensional wind structure of the atmosphere.

In their attempt to show the failures of the technique, the authors have unwittingly presented an alternative technique for detecting ash in plumes — a technique based on pattern recognition and assumed to be 100% perfect. At the most pedantic level, it could be argued that neither do they know the *truth* nor can they assume that the pixels in a plume are volcanic ash. As an independent test, it is generally not good practice to compare algorithms using the same data, although sometimes this may be the only choice. Thus, at the start, we can see that the basic methodology has some serious problems and certainly should not be used to invalidate a second approach.

The authors also give the impression that the $T_4 - T_5$ method is the main satellite technique used for operational ash cloud warnings. This is not the case. Geostationary satellite imagery, AVHRR visible imagery (if available), TOMS sulphur dioxide and aerosol index maps, pilot reports (PIREPS), dispersion and transport model forecasts, information from volcanological observatories, and direct observations are consulted in the process of issuing a volcanic ash advisory. Given that this work is directed toward serious hazards, it may also seem irresponsible to some to ignore the existence of drifting volcanic clouds that may not resemble plumes. In September 1992, such a volcanic cloud drifted across Milwaukee and Toronto, causing severe restrictions to air traffic for many hours. This cloud was tracked without any split-window information being used, although it could have been elegantly tracked in real time using the $T_4 - T_5$ algorithm as shown by Schneider, Rose, Coke, and Bluth (1999). In this note, it should become clear that the $T_4 - T_5$ difference is one piece of information among many, including non-satellite information, that are used to warn of the volcanic ash hazard to aviation.

We question the use of the word "failure" in the context of the use of the algorithm for detecting volcanic ash. The algorithm is physically based and does exactly what it is supposed to do. The user of the algorithm is responsible for its application and for interpreting the results — Simpson et al. have not recognised this. We summarise here the conditions under which the algorithm gives negative differences in the absence of volcanic ash plumes.

(1) Over clear land surfaces at night. In the presence of strong surface inversions in temperature and moisture, it has been shown by Platt and Prata (1993) that $T_4 - T_5$ can be negative.

(2) Clear desert surfaces. Barton and Takashima (1986) demonstrated that negative differences may occur over soils with a high quartz content (e.g., deserts). This is thought to be due to the restrahlen effects mentioned in the Simpson et al. paper.

(3) Over very cold surfaces (temperatures less than 220 K). Two reasons have been noticed for causing negative differences in these conditions. Potts and Ebert (1996) suggest that negative differences occur at the tops of very cold clouds because of overshooting, which causes a temperature inversion at the cloud top. However, negative differences also occur over ice-covered surfaces (see Yamanouchi, Suzuki, & Kawaguchi, 1987) and it is possible that the cause may be due to errors in the nonlinearity corrections used in the calibration procedure (see Steyn-Ross, Steyn-Ross, & Clift, 1992 for a discussion of the AVHRR-2 nonlinearity correction; see also Potts & Ebert, 1996).

(4) At the edges of clouds. This effect has been noticed in AVHRR data for a long time and is due to misalignment of the centres of the fields-of-view (FOV) of the infrared channels. If the radiance field changes sharply within the instrument FOV, then the nonlinearity of the Planck function is sufficient to introduce spurious effects when a difference is taken. The differences can also be very high and positive.

We have studied the examples presented in Simpson et al.'s paper in some detail and illustrate the basic problems with their methodology below.

2. Analysis

2.1. Soufrière Hills (Montserrat)

This eruption occurred in the tropics with quite high amounts of precipitable water (48 ± 5 mm — quoted in inches in their paper, which we have converted to SI units). Fig. 3 of their paper shows several timeframes of GOES imagery obtained during eruptive activity. The authors assume that the plume is identified perfectly and it is surrounded by a rectangular box on the imagery. The actual location of the plume is anything but clear, and perhaps the only general agreement about the imagery is that there appear to be cloud-like features near the island of Montserrat. These could be volcanic in origin. They are not identified as volcanic by the $T_4 - T_5$ method and the authors thus conclude up to 99% false classification rates for the algorithm.

Montserrat volcanic clouds have been studied in great detail using the split-window technique (Bonadonna et al., 2001; Davies & Rose, 1998; Mayberry, Rose, & Bluth, 2001; Rose & Mayberry, 2000). It is very important to realize that these Montserrat eruptions are all very small in scale. Even the largest Montserrat eruptions, such as that on December 26, 1997, are an order of magnitude smaller than the 1992 Spurr eruptions. In the studies cited above, the larger Montserrat events were studied in the most detail. The September 18 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 1000 tons of fine ash of 1–25 μm in diameter) to overcome the effects of water vapor (Rose & Mayberry, 2000). Besides the problem of high atmospheric water vapor, the Montserrat eruptions include volcanogenic meteorological clouds, derived from the interaction of volcanic material with the ocean surface[2] (Mayberry et al., 2001), and these features must also be realized by an interpreter. The reader is referred to the studies above for much more detail on Montserrat volcanic clouds, which have been very informative for improvement of the split-window algorithm for volcanic clouds. The Montserrat example used by Simpson et al. is poorly selected as representative of a tropical event.

2.2. Mt. Spurr/crater peak

This eruption occurred in arctic conditions in a dry atmosphere (6.4 mm of precipitable water according to Simpson et al.). Data used are from the AVHRR-2 a polar orbiting instrument with poorer temporal resolution, but better calibration than GOES. Simpson et al.'s failure rates for this eruption vary from 3% to 89.3%. A close inspection of the spatial pattern of the $T_4 - T_5$ negative differences shows that the algorithm identifies the edges of the plumes in all five cases shown.[3] Panels g and h of Fig. 5 are particularly revealing because they show that the so-called failures occur at the centre of the plume. This is anticipated from the theory of the algorithm (see Prata, 1989b) and is in complete accordance with the underlying physics of the algorithm. Regions classified as negative outside the edges of the plume may, or may not, be volcanic ash. The 'truth' or an acceptable validation protocol approximating truth has not been demonstrated by the authors.

The Spurr example shown by Simpson et al. has also been highlighted in several papers already and thoroughly explained (Andres & Rose, 1995; Schneider, Rose, & Kelly, 1995). The high optical depth of the young volcanic cloud can be easily interpreted from the low brightness temperatures and this allows valuable information to be inferred in real time, e.g., that this volcanic cloud is still in its early development. The ash clouds from the Mt. Spurr eruptions were tracked for more than 3 days over thousands of kilometers using the $T_4 - T_5$ technique, and may be one of the very best examples to date on how well the technique can work. Thus, rather than a failure, this example is already widely known to depict some of the values of the $T_4 - T_5$ algorithm for interpreting hazards to aircraft over the known hazardous lifetime of the clouds.

2.3. Mt. Augustine

This is also an arctic eruption in a very dry atmosphere. It seems that the authors are arguing that there was sufficient water available from other sources (e.g., snow, juvenile water in the magma chamber) to provide a volcanic source of water to the atmosphere. The analysis for this case is interesting because this example shows the great value of the $T_4 - T_5$ method. The crucial image frame is shown in Fig. 7b. Simpson et al. fail to detect a plume, while the $T_4 - T_5$ method identifies a small plume over the volcano vent. Holasek and Rose (1991) report that an eruption occurred at 20:22 GMT, roughly 2 h prior to the AVHRR image (see Table 5 of their paper), based on local observations (non-satellite). Thus, in all likelihood, this plume was volcanic and the $T_4 - T_5$ method suggests that there was ash in the plume. Holasek and Rose also suggest that some of the other negative $T_4 - T_5$ differences are due to volcanic ash clouds. These regions cannot be tested against the Simpson et al. method because according to their methodology, only plumes are volcanic. There are many parts of this image that show negative differences, and it is evident that the $T_4 - T_5$ method is giving results that could be wrongly interpreted. However, the causes for these negative differences are known.

Finally, it is worth pointing out that Simpson et al. show all pixels with negative $T_4 - T_5$ as one colour. This can be misleading and does not utilise the information content of the technique. In fact, the ash cloud has negative differences as low as -5 K and the vast majority of the regions unlikely to be volcanic ash have differences of about -1 K. Furthermore, this noise (over land) exists as isolated speckles that are easily removed with a 3×3 mean filter, whereas the same filter technique only serves to improve the spatial homogeneity of the ash cloud.

2.4. Ruapehu

This eruption may be classified as mid-latitude with moderate atmospheric water vapor. Simpson at al. utilised GMS-5 data to study this eruption. The infrared channels of the GMS-5 instrument are not well adapted to the $T_4 - T_5$ method. This is because the data are 8-bit, poorly calibrated, and there is significant overlap of the split-window channels that introduces correlation between the channels (Prata & Cechet, 1999; Tokuno, 2000). The digitisation error is evident in the frames of Fig. 10. Simpson et al. quote a 1992 reference that the 1996 Ruapehu ash clouds contained large quantities of surface and ground water. While this is clearly in error, the GMS-5 image frames shown in Fig. 9j–r are remarkable in their excellent consistency in identifying the plume. Prata and Grant (2001) concluded that the ease of identification of the ash cloud was in fact due to the absence of water vapor either in the atmosphere or available from within the crater. Earlier eruptions had emptied Crater Lake, changing the style of eruption from phreatomagmatic to magmatic in style (Bryan & Sherburn, 1999). Prata and Grant also show that the $T_4 - T_5$ method identified very thin ash layers in parts of the North Island of New Zealand where ash falls were reported. These are the kind of

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[2] Volcanologists on Montserrat have confirmed to us that pyroclastic flows were entering the sea during September 17–18.

[3] Panel (f) is ambiguous because edges of water/ice clouds sometimes appear to have negative differences due to instrumental effects; see the earlier discussion.

independent data that are required for careful validation of any objective ash detection method.

2.5. Popocateptl

This is another tropical eruption, but in a relatively dry atmosphere. Panels j–r of Fig. 11 of Simpson et al. show that the $T_4 - T_5$ method successfully identifies a small plume extending southwards from the volcano location. There are large areas of cloud-free land and other regions away from the plume that have negative $T_4 - T_5$ differences. These occur mostly at night (cf. panels n–r; local times 17:15 to 01:45 h). Again, Simpson et al. show only one colour for all negative $T_4 - T_5$ differences. The magnitude of the negative differences for the land values is of the order -1 K and the magnitude of the ash differences is smaller than -3 to -5 K.

Armed with knowledge that there are likely to be $T_4 - T_5$ differences over land at night, and that the GOES is an imperfect instrument, these misclassifications are of no great surprise and can be handled easily by a proficient meteorologist. The great utility of the geostationary satellite instruments is of course the high temporal resolution (up to 15 min for the GOES). Imagine then that these static frames are animated and highlighted using the $T_4 - T_5$ algorithm and now show a plume moving southwards. This is excellent, current, and useful information for volcanic plume detection, and valuable for the aviation industry.

2.6. Rabaul

This last case, also in the tropics, is used to demonstrate a catastrophic failure of the $T_4 - T_5$ algorithm. The AVHRR-2 data did not show any significant $T_4 - T_5$ negative differences for the Rabaul plume. The reason for this has been elegantly shown by Rose et al. (1995) and was due to the ash particles being coated by ice. The source of the water for the copious amounts of ice produced in the plume is thought to derive from seawater that gained access to the vent, which was located at sea level. We would argue that the failure to detect negative pixels in this case provides strong support for the basic physics of the algorithm. For ice-covered particles, radiative transfer theory shows that $T_4 - T_5$ should be positive (Prata, 1989b; Yamanouchi et al., 1987). The arch-shaped distribution in the scatter plot (Fig. 13a) is *exactly* what is expected from the theory. It is also interesting to note that Prata (1989b) calculated a scenario for a volcanic cloud with a high fraction of ice-covered particles mixed in with ash particles. His results (see Fig. 3, solid curve of Prata, 1989b) show a striking resemblance to Fig. 13a of Simpson et al. An important point to note here is that Simpson et al. report that this plume was 1.1–1.7 km above sea level. In fact, this plume was higher than 15 km above sea level and most likely reached the stratosphere.

Simpson et al. state that satellite and radiosonde data were limited for this eruption. In fact, there is a complete GMS-4 record of the Rabaul eruption and the animation of these images of the early stages and evolution of the plume makes it very evident that this is an eruption plume (see ⟨http://www.bom.gov.au/info/vaac/rabaul.shtml⟩).

3. Other considerations

Simpson et al. fail to recognise or acknowledge that the majority of operational work using this technique involve the context of the satellite information. Scattered negative $T_4 - T_5$ pixels that are upwind of a known eruption are generally of no concern. Likewise, if there is seismic evidence of a strong eruption in progress and a circular cold cloud appears above the volcano (i.e., Spurr), the information provided by its split-window signature is of secondary importance. Furthermore, the Alaska Volcano Observatory has several examples of good detection of eruptions using the $T_4 - T_5$ method, including the last two eruptions of Bezymianny. There are also many examples of plumes extending from a vent with negative values, including the 1994 eruption of Klyuchevskoi that had a more or less continuous plume for more than 1000 km. Aviation meteorologists are experts in interpreting weather patterns and have used satellite imagery for several decades. Their experience has taught them that the atmosphere is a very dynamic place and that image animation is a very powerful interpretive tool. Volcanic Ash Advisory Centres (VAAC) use satellite imagery routinely. These data are usually the first to be consulted in an armoury of data that are used to advise of volcanic ash hazards. The $T_4 - T_5$ algorithm has been used at the Darwin VAAC since 1994 and the operational meteorologists have gained experience from using it, including occasions when the signal should not be interpreted as a volcanic ash plume. The Darwin VAAC also scrutinises the shape of the distribution of pixels in the $T_4 - T_5$ vs. T_4 scatter plot whenever an eruption plume is suspected. This is because, as explained by Prata (1989b), Rose, Bluth, and Ernst (2000), Wen and Rose (1994), and Yu and Rose (2000), volcanic ash causes a distinct "U"-shaped scatter plot, whereas other phenomena cause an "arch" shape in the scatter plot. Even though the differences may be positive, the "U" shape is a fingerprint for ash particles in the atmosphere. Conversely, negative differences occurring in an arch or other distribution shape are not due to volcanic ash particles. The method remains the most useful, currently available tool for operational tracking of volcanic plumes and clouds.

The physical basis for the algorithm (not discussed nor challenged by Simpson et al.) also makes it a powerful method and suggests when the algorithm works best and when it fails. For example, the effects of viewing geometry can be assessed. Prata and Barton (1994) have shown that the size of the negative difference observed for ash clouds is diminished at high zenith viewing angles (long atmospheric paths). This is due to increased water vapor absorption, which introduces positive temperature differences. Simpson et al. did not discuss this effect in their paper. We emphasise that these effects do not constitute failures of the algorithm — they are what is expected from the physics of the problem and users should be aware of them.

To settle the question of the probability of detection of the $T_4 - T_5$ algorithm, independent information on volcanic ash concentrations in plumes is required. Schneider et al. (1999) have compared TOMS retrievals of SO_2 with ash retrievals from the AVHRR-2 $T_4 - T_5$ algorithm for the largest El Chichon eruptions in 1982. Their results indicate a high degree of coincidence between the locations of the volcanic clouds determined by both sensors (see Plate 1 of their paper). They also show that because these algorithms are sensitive to different volcanic constituents (the TOMS to SO_2 and the AVHRR-2 to ash), gravitational separation can be inferred when the algorithms indicate different dispersal patterns. Bluth et al. (1995), Constantine, Bluth, and Rose (2000), Krotkov et al. (1999), and Schneider et al. (1999) have used TOMS-based data to study clouds of volcanic origin. Krotkov et al. used the TOMS Aerosol Index algorithm to show that particulates in the drifting August 1992 Spurr volcanic cloud, as seen in ultraviolet reflectance by TOMS, matched the simultaneously observed pattern determined by the AVHRR-2 $T_4 - T_5$ algorithm, providing an important validation.

4. Discussion

Our analysis has shown that the example eruption cases given by Simpson et al. do not demonstrate catastrophic or gross (their words) failures in the algorithm. Rather, they show that the algorithm is quite robust when used and interpreted in the correct manner. Misclassifications do occur and the reasons for these are known. The radiative transfer theory outlined by Simpson et al. demonstrates a poor understanding of the physical basis for the algorithm. A complete explanation of the physical mechanism for negative differences observed for volcanic ash clouds has been given by Prata (1989b), Prata and Barton (1994), and Wen and Rose (1994). The physics of the problem involves scattering, and neglect of this process (as was done by Simpson et al.) yields erroneous results. In addition, it is not clear from their paper what aerosol extinction coefficients they used in their MODTRAN calculations. The sulphate aerosol model contained within MODTRAN is inappropriate for modelling ash clouds because the optical constants used do not represent the high quartz content of volcanic ash. They also conclude that the results demonstrate that *neither* the 11-μm nor the 12-μm channel is ideally suited for volcanic ash detection. Prata and Grant (2001) show that channels at 8.6 and 12 μm are better suited to volcanic ash detection — such channels are available on MODIS and will be available on the ADEOS-II GLI.

Simpson et al. have assumed that they can provide an ash plume detection technique that purports to be the "truth" and against which other algorithms can be tested. Readers of their paper should note this and consider their conclusions appropriately.

Despite the above, the paper raises good points about the effect of water in volcanic plumes and the likelihood that this will be a problem in the future. Completely accurate detection of volcanic ash in the atmosphere remains an unsolved problem. More work is necessary to improve the techniques available to operational centers, and also to ensure the effective application of those techniques.

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