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EXECUTIVE SUMMARY

This purpose of this report is to evaluate an automated volcanic ash detection routine (VOLCAT) for operational use in the Bureau of Meteorology. This software has been provided to the Bureau by the National Oceanic and Atmospheric Administration (NOAA). The algorithm uses multi-spectral satellite images to detect ash boundaries and provide quantitative estimates of cloud top height, mass loading and effective particle sizes. The full technical details of the scheme are available in Pavolonis et al [2013] and Pavolonis et al [2015a, b]. The adaptation of VOLCAT in the Bureau will upgrade operations in its Volcanic Ash Advisory Centre (VAAC) to include these state-of-the-art methods, as well as help manage the increased data stream from Himawari-8 in mid-2015.

The evaluation is performed through case studies of four volcanic ash events that had significant impacts for the Australian aviation industry. These events are examined using both traditional analysis techniques and VOLCAT. The analyses from these two methods are then compared to evaluate performance. By design, this report is critical; it identifies both strengths and weaknesses of the scheme with the intention of assisting in the implementation of the scheme into operations at the VAAC.

In the case studies here, we find that the algorithm performance is comparable to that done with traditional methods and a human analyst. The Kelut case from February 2014 gives a preview of what how a significant eruption will appear with 10 minute imagery like that expected from Himawari-8. From the May 2014 Sangeang Api eruption, a detailed examination of the quantitative estimates of the ash cloud properties shows that the different satellites yield qualitatively similar structures within the plume, building confidence in those retrievals. In the Cordon-Caulle event of June 2011, where ash circumnavigated the globe to impact Australia, VOLCAT complemented existing operational methodologies, providing a clearer delineation of the ash boundaries at night when the traditional BTD technique has more difficulty. In the Merapi eruption of November 2010, VOLCAT was able to identify ash in the Indian Ocean 2-3 days before warnings were issued by the VAAC, despite obvious calibration issues with the MTSAT-1R satellite.

In every case, the algorithm was unable to consistently detect the full extent of the ash cloud; this is the case with traditional methods as well and reflects the limitations of quantitative remote sensing methodologies. Human examination of satellite imagery containing ash is still required to confidently identify ash boundaries. Beyond the automation, a significant benefit of VOLCAT is that it provides quantitative estimates of ash cloud properties. With proper utilization, the measurements provide an important pathway to future dispersion modelling improvements, through better initialization and assimilation of the cloud properties into the model. However, the findings here suggest that validating and fully utilizing these estimates needs considerable work. With the ‘heritage’ MTSAT satellites, retrieved ash cloud top heights are poor; the retrieved height fields appear to be largely a ‘mask’ for the underlying brightness temperature fields. When data from MODIS are used, more representative of the instrumentation expected from Himawari-8, these issues are rectified to a large degree, although fields can still be noisy, difficult to interpret and subject to error. This behaviour is not fully understood at this time, but the algorithms occasionally show a high degree of sensitivity and produce significant errors in height, perhaps due to changes in the calibration of the radiometer. The other microphysical fields (i.e. mass loading and effective radius)
still require validation, difficult because proper ‘ground truth’ data to do this is rare. Encouragingly, a brief intercomparison of different satellites suggests some qualitative similarities in the broad structure of the fields, suggesting the estimates are reasonably robust despite differences in sensors.

It should be noted that this evaluation is performed on an earlier version of the software; several improvements from NOAA are included in the operational version that address some of the issues raised here. The algorithm is continually evolving and should continue to improve in the future as the techniques are refined and incorporated into future versions of the software. With these improvements and some research effort into better understanding the unique characteristics of volcanoes in the VAACs area of responsibility, the opportunity exists for the Bureau and its collaborators to create a 21st century volcanic warning system that is tailored to the specific needs of our region.
1. INTRODUCTION

Volcanic ash presents a significant hazard to the aviation industry. When blown through volcanic ash, jet aircraft engines become damaged and may fail, endangering lives and imposing large costs onto the industry to repair aircraft. From the 1950s, there have been aircraft encounters with volcanic ash plumes, with several significant events drawing attention to the issue in the 1980s [Miller and Casadevall 2000; Guffanti et al 2010]. The exact threshold of where volcanic ash becomes dangerous is the subject of ongoing debate [Schumann et al 2011]. Current guidelines suggest that flying through any ‘visible ash’ is not desirable [ICAO 2007].

To manage this risk, the International Airways Volcanic Watch was set up [e.g. ICAO 2007], a key component being the 9 global Volcanic Ash Advisory Centres (VAAC) that issue timely advice and warnings about the presence of volcanic ash in the atmosphere. The Bureau of Meteorology operates one of these VAACs, currently located in Darwin in the Northern Territory. The Australian VAAC has an area of responsibility that covers some of the world’s most volcanically active regions, including Indonesia, Papua New Guinea and the southern Philippines. The detection of volcanic activity in this region is a particular challenge, as the moist, conditionally unstable environment results in frequent deep convection that can hinder the detection of volcanic eruptions. This is particularly problematic in the local wet season [e.g. Tupper et al, 2004].

Several factors are leading to changes in the Australian VAAC’s operations. The first is the recent development of automated volcanic ash algorithms that rely on multi-spectral satellite imagery to identify areas of volcanic ash. These algorithms can significantly enhance the operations of the Australian VAAC, potentially leading to a more timely and efficient detection of volcanic ash clouds. A second factor is the launch of the Japanese Meteorological Agency’s (JMA) Himawari-8 satellite, which will greatly increase the temporal coverage and spatial resolution of routine remotely sensed data in the Australian region from mid-2015 when it becomes fully operational.

To take advantage of these developments, the Bureau has instigated the Improved Volcanic Ash Detection and Prediction Project. The aim of the project is multi-fold. The first aim is to update the Bureau’s satellite infrastructure to better handle the volume of data expected with Himawari-8. This is to be partially accomplished with the installation of the GEOCAT software suite, a flexible framework for general satellite data processing for both operational and research needs. With GEOCAT comes VOLCAT, a modern multi-spectral volcanic ash algorithm. This software provides a complex framework for integrating observations from both geostationary and low-earth orbiting satellite sensors in near-real time. An overview is given in Pavolonis et al. [2015 a, b]. The implementation and evaluation of the VOLCAT software for operational use is a second aim of this project, the one of primary concern in this report. The third aim of the project is enhance the Bureau’s dispersion modelling output for volcanic ash, in part using output from the VOLCAT software. This is reported on elsewhere.

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1 As this report is being finalized, the Volcanic Ash Advisory Centre is being permanently moved to Melbourne, VIC. It has generally been referred to as the ‘Darwin VAAC’ both in Australia and internationally. However, in light of the move, we will refer to it as the ‘Australian VAAC’.
The purpose of this report is to present a preliminary evaluation of the VOLCAT algorithm. The version of VOLCAT being evaluated here is an earlier version of the software; the algorithms are continually evolving and being improved. Hence, not all of the results presented herein will reflect the latest capability of the software. The algorithm has the potential to yield better, more consistent detections of volcanic ash and fully exploit the increased capabilities of Himawari-8. The algorithm also provides a path for improved guidance with dispersion models through assimilation of the quantitative results into those models. While this report will note positive aspects of the algorithm performance, much of the report is critical. How well does it perform compared to traditional methods? What are its strengths and weaknesses? When does it succeed? When does it fail? This tone is not taken to denigrate the intellectual achievements of this algorithm, which are substantial in addressing a difficult problem. Rather, asking and answering these questions provides a basis for evaluating the potential usefulness of the algorithm in an operational environment and provide some insights into its capabilities and shortcomings that won’t have to be ‘learned on the job’ in an emergency situation. This evaluation is done using multiple case studies of volcanic ash events that had a significant aviation impact on Australia.

After a brief summary of the relevant ash identification and measurement techniques, each case study is presented in its own section with the following format. The first subsection presents an overview of the eruption along with general comments on the significance of this event and the specific data sources used in the evaluation. The second subsection presents the highlights of the relevant VAAC reports, including the time frames of when the event comes to the attention of the VAAC. The third subsection represents the main focus of each case, namely a discussion of the satellite evolution of the eruption using the VOLCAT algorithm. The relevant comparisons, most often with the picture of ash from the BTD methodology, are also presented here. The final subsection concludes with a brief overview of the performance of the VOLCAT algorithm.

2. METHODS OF ASH DETECTION

The detection and identification of volcanic ash is a challenging problem. Several remote sensing techniques have been utilized to detect volcanic ash. A brief summary of the satellites used in this study is provided, followed by a quick overview of the techniques.

2.1 Satellites

The primary satellite data used in the study come from the JMA satellites MTSAT-1R and MTSAT-2. These are geostationary satellites that provide a full disk view of the Earth at hourly time resolution, with nominal image time at approximately half-past each hour. MTSAT-1R is centred at 140°E and MTSAT-2 at 145°E. These data are available from the archives at the Bureau of Meteorology.

Each satellite has 5 channels. One visible channel and 4 infrared (IR) channels centred at 3.7, 6.7, 11 and 12 μm. MTSAT-2 was a replacement for MTSAT-1R starting in 2011, with the latter being used as a backup in more recent times. MTSAT-1R data was also available in 10-minute ‘rapid scan’ mode for a period from December 2013 to March 2014 and this included the duration of the Kelut eruption (Section 3). Data from this eruption provided insight into the potential impact of Himawari-8 on future operations, as this will be the normal temporal resolution in the future.
In general, output from MTSAT-2 appears to be superior to that from MTSAT-1R. This can be seen directly in the Kelut eruption, where both satellites are used to view the same scene; the results from MTSAT-1R are generally noisier, with more apparent false alarms. The Merapi case, which primarily uses MTSAT-1R, also suggests poorer performance of the algorithm that is not seen in later cases. This is probably due to ‘calibration issues’ with MTSAT-1R. Regularly updated satellite inter-calibration data [Hewison et al 2013] for the MTSATs indicate significant temperature-dependent biases in the IR channels of MTSAT-1R that are not present in the MTSAT-2 data. See https://mscweb.kishou.go.jp/monitoring/calibration.htm for more detail.

The MTSAT data are supplemented with data from the NASA Terra and Aqua satellite, particularly the MODIS instrument. These satellites are polar orbiting satellites in sun-synchronous orbits at 705 km altitude that view each region of the Earth twice a day, once in the day and once at night. The MODIS is an advanced radiometer that has 36 channels ranging from the visible to the IR. Horizontal resolution is a maximum of 250 m with a swath width of 2330 km. To some degree, these data can be considered analogous to algorithm performance under Himawari-8, where the instrumentation will have similar channels and resolutions. The data from MODIS used here is at 1 km resolution and is downloaded as five minute ‘granules’ from the website at http://ladsweb.nascom.nasa.gov. Navigation data for the images comes from the same source.

2.2 Visual identification of plumes

The simplest way to identify ash in a satellite image is visually. On a visible image, ash often has a distinct colour and/or texture that distinguish it from other clouds. On IR imagery, ash can be identified as it extends from a source; a cloud arising from a fixed location, often with a distinct linear or triangular shape. These features can be often tracked even as they move away from their source. Access to multiple images or animations helps in identifying ash visually. No quantitative information is provided with this method, but ash boundaries can often be extended from what is available from more objective sources. Multiple examples where the plume is visually identified are presented in the figures of this paper.

2.3 Brightness Temperature Difference

One of the first (and most enduring) quantitative remote sensing techniques to be applied to volcanic ash is the brightness temperature difference (BTD) or ‘split window’ or ‘reverse absorption’ technique (Prata 1989a, b). Absorption by ash and water varies with wavelength in different ways, and these differences can be exploited by comparing brightness temperatures at two channels to discriminate between particle types. Typically for volcanic ash, this is done using channels around 11 and 12 μm. Here, BTD is defined as \( BTD = T_{11} - T_{12} \).

In general, negative values of BTD are suggestive of volcanic ash. However, IR radiative transfer calculations show that there are many subtleties that can affect the magnitude and interpretation of the returned signal (e.g. Prata 1989b). A major consideration is the amount of ash in the cloud; calculations clearly suggest there is an optimal level of ash for best detection. Idealized calculations by Pavolonis et al [2006] show that for pure ash particles, the peak BTD signal occurs when the optical depth of the ash cloud is between roughly 2 and 3. At higher optical depths (i.e. greater concentrations of ash), the signal rapidly drops off to zero, while drop in signal is more gradual at lower optical
depths, with no signal at an optical depth of 0.1. The size of the ash particles also makes a difference. The negative BTD signal is best seen when mean particle size in the ash is < 3 μm; with larger mean particle sizes, the effect is eventually reversed and a positive BTD signal may be observed (again varying with optical depth), similar to that observed with pure ice clouds.

In the real world, particularly in the region of concern to the Australian VAAC, pure ash clouds are not always observed. More common are volcanic clouds that are of mixed composition, ice and ash combined. Pavolonis et al [2006] suggest a reduction in the negative BTD signal that follows the same general pattern as for pure ash. However, the Prata [1989b] calculations show a more complex behaviour that depends on the relative fractions of ash and ice. In cases with higher ice contents, the signal can be positive or negative, depending on the optical depth. Rose et al. [1995] show for an eruption at Rabaul that ash may be completely encased within ice crystals and correspondingly have a BTD appearance with positive BTDs more characteristic of ice.

These results indicate that volcanic ash may be identified from negative BTD values from routine satellite imagery. However, Prata et al. [2001] summarized several situations where non-ash related negative BTD signals may be observed. These were: 1.) over clear land surfaces at night, related to the formation of nocturnal inversions; 2.) over clear desert surfaces, related to the high silicate composition of the soil; 3.) over very cold surfaces (i.e. < 220 K), due either to the overshooting tops of deep convective clouds or due to the non-linearity of calibration effects, and; 4.) at cloud edges, where sharp gradients may cause large positive or negative BTDs due to differences in the satellite field of view at different channels. Without due care, these misleading signals can lead to ‘false positives’ of ash or the obscuration of a legitimate ash signal.

### 2.4 GEOCAT algorithm

As noted in section 2.3, ash detection via the BTD methodology is subject to many shortcomings that may limit its effectiveness in certain situations. Further, detection of ash by visual methods or BTD methodology relies on the skill of the human analyst and the setting of somewhat arbitrary thresholds [e.g. Pavolonis 2010]. To attempt to overcome these limitations, considerable community effort has gone into producing objective ash detection algorithms that reduce the human uncertainty while simultaneously making better use of the improving remote sensing capabilities being developed to provide more information in a timely fashion. Two recent examples, not examined further here, are found in Klüser et al. [2013] and Mackie and Watson [2014].

The complete VOLCAT algorithm is described in Pavolonis [2015 a, b]. This algorithm has been developed by NOAA NESDIS for use with next generation of US-based geostationary satellites (GOES-R; Pavolonis and Seiglaff [2010]) and being currently used operationally by the VAACs in Washington DC, Anchorage and Tokyo. The algorithm consists of 4 components: 1.) the conversion of satellite measurements into robust spectral metrics; 2.) estimation of the probability that a given pixel contains ash; 3.) the construction of ‘cloud objects’, and; 4.) identification of objects that are consistent with volcanic ash. An important component is the volcanic ash retrieval algorithm as described by Pavolonis et al [2013]. This algorithm provides quantitative estimates of the properties of the ash cloud, including the height of the ash cloud top, the mass loading of the ash and the effective radius of the particles.
The key spectral methods used are based on ‘effective absorption optical depth ratios’ or ‘β-ratios’ (e.g. see Pavolonis [2010] and references therein). Conceptually, the upwelling radiance at IR frequencies is characterised by a combination of emissions from the cloud (either volcanic or meteorological) and the clear sky radiance. This clear sky radiance is modelled, based on atmospheric profiles of temperature, water vapour, ozone and the surface emissivity. A key variable determining the partition of cloud and clear sky radiance is the effective emissivity \( \varepsilon \) of the cloud, which varies spectrally depending on the cloud composition and microphysics. Comparing \( \varepsilon \) at different frequencies yields the β-ratio between the two frequencies in question, which is directly related to the single scatter properties of the cloud. β-ratios can be computed between any two wavelengths \( (\lambda_1, \lambda_2) \) and are notated as \( \beta(\lambda_1/\lambda_2) \).

To assign the probability of a whether a pixel contains ash, a range of frequencies across the IR spectrum can be used, including wavelengths in the near-IR (~3.9 \( \mu \)m), at SO2-absorption bands (7-9 \( \mu \)m) and in the atmospheric window (10-12 \( \mu \)m). Visible wavelengths (~0.6 \( \mu \)m) are also used in the daytime. Performance is better where SO2 absorption channels are available. At this stage, reflectance ratios (VIS/Near-IR) or β-ratios (SO2/window) using assumed cloud heights are calculated between many of the available channels. As MTSAT lacks these channels, only they are not used, and the algorithm is similar to that described by Pavolonis et al [2006]. A series of tests is performed using pre-calculated look-up tables derived from radiative transfer modelling that compare the responses of two variables being tested to determine the likelihood of ash being present. Pavolonis et al [2015a] fully describes how probabilities are estimated using this Naïve Bayesian approach, based on the examination of over 2700 5-minute MODIS granules to discriminate between the spectral characteristics of ash and non-ash clouds. The tests used vary between day and night, with daytime tests utilizing the reflectance ratio between near-IR and visible channels and a dependence on the ‘scattering angle’. Tests also vary with the underlying land surface, with snow, land and water yielding different tests. Tests with different assumptions, including changes in the assumed cloud height and a simple case of ash cloud overlying an elevated opaque ‘black’ cloud are also included. Positive detections from at least two tests must be present for ash to be identified.

Where pixels are determined to contain volcanic ash, retrievals of the ash properties are performed. Input from three channels is used in the retrieval: 11, 12 and 13.3 \( \mu \)m. Expressions for the radiance at these channels are reworked into a set of equations where the unknowns are the effective temperature \( (T_{\text{eff}}) \) and \( \varepsilon(11) \) of the cloud at 11 \( \mu \)m along with \( \beta(12/11) \), the β-ratio between the 12 and 11 \( \mu \)m channels. An iterative matrix calculation (‘optimal estimation’) which accounts for errors from multiple sources (e.g. instrumentation, clear-sky modelling, etc.) is performed to find the best solution for the 3 unknowns. From \( T_{\text{eff}} \), the cloud top height is computed. From \( \beta(12/11) \), the effective radius \( (r_{\text{eff}}) \) and extinction cross section are determined using fourth-order polynomial curve fits derived using the theoretical single-scatter response of the particles. These derived variables, along with \( \varepsilon(11) \) are in turn used to determine the mass loading of the cloud.

There are limitations to the retrievals. The ash cloud in question must be the highest cloud layer visible. Multiple layers of cloud are difficult to accurately retrieve, although it is possible in theory. If the lowest layer of cloud radiates as a blackbody, this problem is easier to solve. Multiple distinct translucent cloud layers cannot be identified in this approach. Another uncertainty arises with the mineral composition of the ash; different minerals have different optical properties that can lead to
significantly different retrievals [e.g. Pavolonis et al. 2013]. As the mineral composition of a particular eruption is generally not known beforehand, some error in real-time retrievals can occur from this source.

Retrievals where $r_{\text{eff}}$ exceeds 15 $\mu$m are less reliable. Here, the sensitivity to $\beta(12/11)$ is large and small errors in that parameter can lead to significant variations in the retrieved parameters. Further, it is more difficult to separate ash clouds from water/ice clouds in this range, making the interpretation of the retrieved signal more unclear. The retrievals over land are also less certain, as the surface emissivity there is poorly characterized. Other parameters associated with the clear-sky radiance calculation (e.g. temperature/water vapour fields) could contribute to errors in retrievals, although mostly if they are grossly unrepresentative of the actual situation.

The physical retrievals are also affected by the older-generation sensors in that radiances from a 13.3 $\mu$m channel are not available on the MTSAT satellites. With only two variables and three unknowns, the set of equations solved via the optimal estimation technique in this case is degenerate. As a consequence, $T_{\text{eff}}$ does not change much from its initial guess, potentially leading to significant errors in the retrieved properties if that guess is poor. For example, if $T_{\text{eff}}$ is too high (meaning the physical cloud height is too low), then $\varepsilon$ is overestimated (e.g. Heidinger et al [2009]), which leads to an overestimate of the mass loading.

After performing the retrievals, the results are grouped into ‘cloud objects’. A cloud object, as described in Pavolonis et al. [2015b], is defined as ‘…a collection of spatially connected satellite pixels that meet certain criteria.’ Identifying these ‘certain criteria’ extends beyond simply setting a simple probability threshold; a complex series of tests (see Appendix A of Pavolonis et al [2015b]) is used to identify whether a pixel should be included as part of a cloud object. These tests account for a variety of factors, including the spatial context, the measurement uncertainty and the physical plausibility of the pixel as ash. Once grouped into objects, an ash/no-ash determination is made for each object; essentially, if an object contains a specified number of pixels with an ‘unambiguous’ ash spectral signature, it is considered ash.

The algorithm described here is future-oriented in that it expects input from ‘next-generation’ satellites with radiometers that provide information across a wide range of frequencies with 10 or more channels. As such, performance may be degraded with ‘heritage’ satellite systems such as the MTSAT which have only a few channels available. One adaptation was noted in the volcanic ash detection algorithms; the effect from this on the detection of ash is not entirely clear.

### 2.5 Lidar

In atmospheric applications, one use of lidar is to identify regions of cloud and aerosol, highlighting their extent (usually vertical) and coverage. Volcanic ash is one such aerosol that can be detected. For this report, the focus will be on the space-borne lidar on board the NASA Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite. The narrow beam of the lidar (~100 m) and the satellite’s orbit (it follows the NASA Aqua satellite as part of the ‘A-train’) make sampling of a particular area very much a ‘hit-or-miss’ affair. Further, the CALIPSO lidar algorithms do not automatically identify volcanic ash; some guidelines for doing so are found in Winker et al [2012] and Vernier et al [2013]. This process can be ambiguous when only the lidar is used, as ash clouds have
many similar properties to cirrus clouds. Other sources of information are needed to confirm a possible ash cloud. In principle, other quantitative ash properties could be derived from lidar. Here, these data will generally be used, where available, as a ‘ground truth’ for the determining the presence of ash and the altitude at which it is found.

2.6 Sulphur dioxide

The major source of sulphur dioxide (SO2) in the atmosphere is from volcanoes. Hence, the presence of SO2 in the atmosphere can be indicative of volcanic eruptions. SO2 is detectable using remote sensing techniques operating in both the ultraviolet (e.g. Carn et al [2003]) and infrared (e.g. Prata et al [2003]) region of the spectrum. While volcanic ash often occurs with SO2, the presence of SO2 does not necessarily imply that volcanic ash is present. For this study, SO2-based detections are not examined; however data from external sources are used operationally by the VAAC to identify regions of ash.

3. KELUT – FEBRUARY 2014

3.1 General comments

The Kelut event was a large Indonesian eruption beginning on 13 February 2014 at around 1600 UTC. Figure 1 shows an IR image of the eruption from the Aqua MODIS and a CALIPSO lidar cross section through the umbrella cloud approximately 2 hours after the initial eruption. A significant ‘warm spot’ is identifiable in the IR imagery, suggesting a deep stratospheric intrusion by this eruption. A widespread layer of ash with tops at 18-20 km is identified in the cross section, with secondary layers with tops around 22 km and over 25 km, verifying deep penetration into the stratosphere. Below the top of the lowest ash cloud, the lidar is completely attenuated, suggesting a large amount of ash is present in the umbrella cloud.

This eruption had a significant impact across Java, with more than 75 000 people forced to evacuate. Seven major airports were closed in Indonesia and an aircraft encounter with the ash cloud was reported [e.g. Kristiansen et al. 2015], forcing emergency action on that flight and causing extensive damage to that aircraft’s engines.

The data available for this eruption are excellent. In addition to the standard MTSAT-2 operation, MTSAT-1R was also operating in ‘rapid scan’ mode for a meteorological field experiment operating in Darwin. This allowed 10-minute temporal resolution data to be available for this eruption from the beginning, providing an unprecedented view of the plume. Further, there were several nearby CALIPSO overpasses (e.g. Fig. 1) as well as good views from the Terra and Aqua MODIS. The abundance of data sources allows for several ‘three-way’ comparisons between the different satellites.
3.2 VAAC summary

The VAAC released its initial advice at 13/1712 UTC, approximately 75 minutes after the eruption began. Two mains areas of ash are identified in the VAAs; the main upper level plume moving to the west and an area of lower level ash to the north and northeast of the volcano. Much of this lower region is identified using SO2 data and visible imagery during daylight hours. While warnings persist for this lower region for some time, these appear to be largely based on expectations (i.e. ‘ash expected in the area’), rather than explicit identification of the ash. The last VAAs for this event were issued at 15/2050 UTC.

3.3 Satellite evolution

Figure 2 presents a sequence of images from the MTSAT-1R rapid scan data for the first 5 hours of the eruption. It is noted that the time MTSAT-1R actually samples the rapid scan domain is roughly 14 minutes past the nominal image time which is how the time here is discussed. At 13/1610 UTC, the eruption appears as a small cold spot near the location of Kelut. By 13/1620 UTC, it is quite distinct. Unfortunately, the satellite performs navigation manoeuvres until 13/1700 UTC, missing 40 minutes of the early growth of the umbrella cloud. Beginning at 13/1710 UTC, 4 images show reasonably high probabilities of volcanic ash (70-80% in some spots) near the leading edge of the westward moving umbrella cloud. Retrieved heights in these detections are on the order of 18-20 km (not shown). These detections are quite ephemeral. Similar detections are also noted at 13/1820 and 13/1850 UTC. At 13/1810 UTC, the time of the Aqua MODIS overpass seen in Figure 1, there are no ash detections.

A strong detection of ash is first noted at 13/1940 UTC in the immediate vicinity of the volcano, primarily to the north; volcanic ash associated with the umbrella cloud is not detected at this time. There are no further detections until 13/2040, when ash in the same general area was identified. These reports are consistent with the lower level ash reported to the north by the VAAC. At the same time, ash began to be identified on the edges of the umbrella cloud. From this time, ash was consistently
detected by MTSAT-1R until the volcanic cloud moved out of the area of satellite coverage on 14/0730 UTC

Figure 3 shows the evolution of the ash cloud top height field from the MTSAT-2 over a longer time frame and at a considerably lower temporal resolution. The first image is from 13/2032, approximately 4.5 hours after the eruption. The detection is similar to the MTSAT-1R detection at 13/2040 UTC noted in Fig. 2. Heights are indicated at around 12 km to the north of the volcano, touching on 18+ km on the edges of the canopy cloud. This is the second image where persistent detections of ash were made by the software, the first being at 13/1932 UTC. As with MTSAT-1R, the first MTSAT-2 detections were not made on the umbrella cloud, but rather the area of lower level ash to the north and northeast. The BTD data (not shown) indicate a similar pattern at this time, with values of -1 to -2 K, primarily around the outer edges of the umbrella cloud.

The next image is from 14/0232 UTC, with a significant detection of the umbrella cloud tops suggesting heights of 18-20 km. This images around this time are the best detections of the umbrella cloud made by in this case. Six hours later, at 14/0832 UTC, the detected area is quite small. Peak heights in the range of 14-15 km are indicated; these detections are not associated with the umbrella cloud, which has begun to dissipate. Its location is not readily obvious in this still image, but can be discerned in an animated loop; it lies to the southwest between the detected area and the region of met cloud further southwest. Also in this image, deep convection is observed to the north and west of Kelut; the cold IR feature is meteorological cloud, not another eruption.
In the final image of the sequence, at 14/1432 UTC, the detected area has significantly increased in size, and is closer to the volcano. The heights of the detected ash clouds are mixed; regions with heights of 12-13 km are interspersed with heights of 18+ km, suggesting the possibility of multiple ash layers in the area. The deep convection that was present in the previous image has dissipated by this time, but meteorological cloud is still present. The reality and extent of this ash detection is not clear at this time; the corresponding probability plot (not shown) indicate that while some of these regions have high confidence, the probabilities are quite low (i.e. < 5%) in others, including much of the region identified with tops at 18+ km.

Figure 3 shows the evolution of ash cloud top height from MTSAT-2, 13-14 Feb 2014. Images at 13/2032 (top left), 14/0232 (top right), 14/0832 (bottom left) and 14/1432 (bottom right).

Figure 4 shows the evolution of the BTD field during the eruption. As with VOLCAT, the strongest BTD signals were initially detected in the lower level plume to the north and northeast of the volcano, with values of approximate -3 K in this region. The edge of the umbrella cloud is also showing negative brightness temperature differences, as well as a few pixels in the centre. By 14/0232 UTC, the northern area no longer shows a BTD signal. However, the umbrella cloud, shows one that is quite
strong, in excess of -4 K (the ‘holes’ apparent on the image are a problem with the plotting routine not plotting the strongest values…) over much of the umbrella cloud, but not the entire visually identifiable cloud. At 14/0832, the area with the strong BTD signal has shrunk, but regions with differences of roughly -4 K are visible in association with ash from the umbrella cloud. In the last image (14/1432 UTC) of the sequence, wide spread pixels with BTD of generally –1 K (or greater) are seen around where the ash is known to lie. A small region with peak BTDs of -2 K is seen well to the WSW of the volcano. These pixels are increasing in number, just as the areas identified as ash are in Fig. 3.

Figure 5 shows a comparison of the MTSAT-1R and MTSAT-2 detections of the umbrella cloud and surrounding area at 13/2330 UTC. This time corresponds to the best detections of the umbrella cloud made by either satellite for this event. The MTSAT-2 detections are confined to the canopy cloud, while MTSAT-1R detects many additional areas of ash, believed to be false. The most obvious area is the large area of largely low probability to the east of the volcano; a similar signal appears in the three prior 10-minute images as well. These are suspected to be false detections. Comparing to the MTSAT-2 shows that these detections are clearly associated with the deep convective activity to the east. The low probability and lack of detection in MTSAT-2 suggests that these returns are probably related to the calibration issues with MTSAT-1R.
More difficult is the detected region to the south of the umbrella cloud. The detections here in MTSAT-1R have a ‘speckled’ appearance. This feature appears only in this image, although a considerably smaller, even more ‘speckled’ region, appears for one image in the same general area 20 minutes earlier (not shown). It is unlikely that this ash from the eruption as it is simply too far away for it to have travelled the required distance in the time available. The brevity of the detections suggests they are not a genuine ash cloud. Comparison with the MTSAT-2 indicates that this feature is associated with an area of relatively warm cloud. These features are likely a problem with MTSAT-1R; similar features are common in the Merapi case study (Section 6), where the primary observations platform is MTSAT-1R. Such features are not observed with other platforms.

A three-way satellite comparison with MTSAT-1R, MTSAT-2 and Aqua MODIS is shown for the retrieved ash cloud top height within five minutes of 14/0630 UTC (Fig. 6), approximately 14 hours after the eruption. Between MTSAT-1R and MTSAT-2, the fields are reasonably similar, with peak heights around 15 km, reducing to 6-9 km further south. In the same area as the MTSAT detections, Aqua-MODIS shows heights of 19-20 km lowering down to 9-12 km further south. Additionally, Aqua suggests a large region of ash with heights of 12-15 km extending to the east, well past the location of the volcano. Much of this detection is suspect; ash should not be present to the south and east of Kelut, upwind of the eruption. Inverse modelling studies support this view (M. Zidikheri, personal communication).
Fig. 6 Three-way intercomparison of ash cloud top height field within 5 minutes of 14/0630 UTC. Shown are VOLCAT retrievals from MTSAT-1R (left), Aqua MODIS (centre) and MTSAT-2 (right). Comparisons are centred on the island of Java but areas covered are not identical; the location of Kelut marked with red triangle in each image.

However, at least parts of this region appear to contain ash, as seen in the coincident CALIPSO overpass (Fig. 7) which shows two layers. The lower, patchier layer between roughly 13 and 15 km is likely composed of ice. The composition of the higher layer, located between 19 and 20 km, is unclear, but is interpreted as ash here. The morphology of the cloud’s appearance in the lidar imagery is laminar, as expected from an ash cloud. Further, the ‘colour ratio’ and ‘depolarization ratio’ in this layer are lower than those in the lower layer, consistent with ash based on the guidelines in Winker et al [2012] and Vernier et al [2013]. Unusually for ash, the backscatter of the layer is quite high, much greater than ash backscatter seen in either the Cordon Caulle (Section 5) or Merapi (Section 6) cases. This suggests either an abundant amount of ash is present or that the cloud is not entirely ash.

Outside of the ash areas detected by the MTSATs (Fig 6), VOLCAT indicates that ash probabilities in the Aqua MODIS image (Fig 7) are very low, on the order of $10^{-5}$ with the exception of a few high probability pixels. The cross section is located in this low probability area, and is not in a region of ash detected by the MTSATs. Looking closer at the VOLCAT retrievals of cloud top height from Aqua along the CALIPSO path, shown by the black line, indicates that they are not accurately capturing the height of ash layer, but rather are aligned with the tops of the lower-level met clouds.
This example highlights some of the limitations of the necessary automated approach. It is hypothesized here that the result in this example is probably due to the built-in assumptions (which are generally reasonable). This is a case of a multi-layered cloud, an ash layer over a lower ‘black’ cloud, which the algorithm can in theory handle. However, the default assumption is that this lower cloud is at approximately 2-3 km altitude ($\sigma=0.8$), instead of 13-15 km where it is actually found, possibly creating some significant errors in calculating the $\beta$-ratios that feed into the detection algorithm. When the retrievals are performed, the effects of the clouds (both ash and ice) are combined and assumed to come from a single layer. The ‘combined cloud’ that likely most affects the absorption of the clear air radiance is in all probability the cirrus, and so the algorithm identifies this height as the height of the ash cloud. The retrievals also indicate mass loading of between 40 and 60 g $\text{m}^{-2}$ and $r_{\text{eff}} \sim 15$ $\mu$m (not shown). While the lidar cross-section suggests a large ash concentration, the mass loading values are considerably higher than expected in an ash cloud, and the $r_{\text{eff}}$ is at the upper range of the reported sensitivity (Pavolonis et al [2013] and see section 2.4).

3.4 Performance summary

In some sense, this was an easy case in that the eruption was quite obvious. The volcano was not obscured by meteorological cloud at the time, and magnitude of the eruption and rapid growth of the umbrella cloud made it readily detectable and unlikely to be mistaken for tropical convection. Initial warnings were issued within 75 minutes of the actual eruption.
VOLCAT performed similarly to BTD methods in this case. Neither technique identified the ash cloud in its initial stages, with first reliable detections becoming apparent some 3-4 hours after the eruption, and these warnings were not earlier than that provided by the VAAC (which learned of the eruption through media reports). After the remote sensing methods identified the eruption, the evolution in VOLCAT is similar to the evolution of BTD both temporally and spatially. Neither VOLCAT nor BTD-based methods identified the extent of the ash cloud that would be chosen by a human observer, particularly in the dense umbrella cloud in the first few hours of the eruption. This is likely due to optically thick cloud (probably a combination of ice and ash) obscuring the radiative signatures (see section 2.3).

The 10-minute resolution data provided an intriguing view of the early evolution and these foreshadow the temporal resolution of the data available with Himawari-8. Some fleeting detections were made in the canopy cloud before the more consistent detections were made later on. While these detections suggest excellent performance of VOLCAT, the ephemeral nature of these detections makes them difficult to determine the source. Adding to the confusion, a deep convective cloud well to the east of Kelut (> 400 km) not seen in the close-up images shows a similar behaviour at the same time; fleeting signatures of ash at heights of 18-20 km. Given the location, these signatures are clearly not from the eruption. Given that these detections come from MTSAT-1R, a sensor with known calibration issues, it is strongly suspected that these do not represent genuine detections of ash.

Three-way comparisons between satellites, along with CALIPSO data providing a ground truth, clearly suggest that data from the MTSAT-1R and MTSAT-2 tends to underestimate the height of the ash cloud tops in this event. The superior MODIS instrumentation appears to better capture the heights observed by the space-borne lidar. The strong dependence of the height field on the initial guess of $T_{eff}$ with the MTSAT satellites, discussed more completely for the Sangeang Api case (section 4), may also contribute the indication of multi-layer ash clouds; however, the MODIS data also support the interpretation of ash in several layers, although this could also be flawed as ash may be being identified at the wrong height. More investigation is required. Other satellite intercomparisons indicate that MTSAT-1R data appears noisier and more prone to incorrect detections compared to MTSAT-2. This was also the case in the Merapi case study (Section 6) and is likely due to the calibration issues with MTSAT-1R noted in section 2. However, in regions that are likely ash, MTSAT-1R and MTSAT-2 (compared to each other) show no appreciative biases in either the quantitative properties retrieved or the areas detected.

Finally, there is some possible argument for diurnal variation in ash detections in MTSAT-1R and MTSAT-2, but the evidence is not entirely compelling. The detection of ash in the umbrella cloud is most widespread just before sunrise and tends to decay after that, reaching a minimum at 14/0832 UTC. However, how much of this loss of signal is due to the gradual dissipation of the umbrella cloud (apparent to visual analysis) is unclear. There is also a rise in the area detected around 14/1430 UTC, not long after sunset. Similar tendencies are also seen in the BTD picture of the eruption as well.
4. SANGEANG API-MAY 2014

4.1 General comments

Sangeang Api in the Lesser Sunda Islands of Indonesia experienced a major eruptive event beginning on 30 May at approximately 0800 UTC. The volcano erupted almost continuously for more than a week, with two additional significant high level eruptions reported in the first 18 hours or so after the initial blast. Even after these initial high levels eruptions were over, significant amounts of ash which extended far to the southeast were emitted. This ash is readily visible in Fig. 8, a true colour image from the Terra satellite. The main eruptive period on 30-31 May is examined here.

Fig. 8 Terra MODIS true colour image of Sangeang Api eruption from 31/0235 UTC.

The impact of this eruption was widespread for the aviation industry. The cloud extended into Northern Australia, shutting down operations at Darwin Airport and other regional centres for more than a day. Flights were resumed from Darwin from approximately 31/0600 UTC. The proximity to Bali meant that flights to and from Denpasar were also shut down, causing significant delays.

The primary data source for the analysis of this case study is the MTSAT-2. Further, there are several suitable Aqua and Terra MODIS overpasses. Unfortunately, the CALIPSO lidar did not unambiguously sample the ash during the eruption, so little in the way of ‘ground truth’ exists. However, the clear view and consistent eruptions and detection make this a strong case study for evaluation of the algorithm. In view of this, some additional analysis is undertaken further exploring some of the sensitivities of the algorithm. This includes extra material showing the dependence of
retrieved height on $T_{\text{eff}}$ and an extra subsection presenting a detailed analysis of the quantitative retrievals of the plume.

4.2 VAAC summary

The Australian VAAC issued its Initial advisory at 30/0954, approximately 2 hours after the initial eruption. A second high level eruption is reported based on the 30/1732 UTC MTSAT-2 image and a third based on the 30/2132 UTC MTSAT-2 image.

The VAAC identified several plumes of ash that impacted northern Australia, extending well into the interior. Ash reaching the Kimberley region was first reported in the 30/1945 UTC VAA, which pushed deep into interior Australia by the 30/2245 UTC VAA. From the 31/0245 UTC VAA, ash was indicated over the Top End of the Northern Territory.

After approximately 02/0000 UTC, VAAs were primarily low-level warnings for ash in immediate vicinity of volcano associated with relatively minor eruptions. The last advisory for this event was issued at 08/0230 UTC.

4.3 Satellite evolution

Figure 9 shows a sequence of images from MTSAT-2 summarizing the VOLCAT detections made during the eruption. The first frame at 30/0832 UTC, the first image available after the eruption, shows no detections, but cold umbrella cloud (brightness temperature ~200 K) is present in the image. Assuming the cloud is ‘black’, this temperature suggests the cloud top height is found at approximately 16 km, the height of the tropopause. While there is no ‘warm spot’ in the canopy suggestive of a deep stratospheric intrusion by the plume as was seen in the Kelut case (section 5.3), careful examination of imagery from 30/0832 to 30/1232 UTC (not shown) reveals a thin cloud feature associated with the eruption that inverse modelling techniques suggest is found in the stratosphere between 17 and 19 km based on the wind profile (M. Zidikheri, personal communication). This feature, partially characterized by strong positive BTD consistent with ice or ice-coated ash, moves generally towards the east and northeast, and becomes difficult to track after 30/ 1232 UTC when it begins to merge with other pre-existing cloud features.
Ash detections began on the umbrella cloud at 30/1032 UTC (not shown). The next image, at 30/1432, shows that the umbrella cloud has travelled about 550 km to the south-southeast. Peak heights of 14-15 km were noted at 30/1232 UTC by MTSAT-2; by the time of the image shown, peak heights had declined to approximately 12 km. In the vicinity of the volcano, a few lower level ash clouds are indicated. Careful examination of the image also shows a thick plume of undetected ash extending to the SSE from the volcano. Brightness temperatures in this feature are on the order of 269 K. By 30/2032 UTC, the remnants of the umbrella cloud are located over the Kimberley in northern Australia, over 1100 km distant from the volcano. Considerably lower peak heights are noted. Around the volcano itself, a second high-level eruption has occurred and the plume is evident, moving off to the southeast. At 31/0232 UTC, no ash is detected over northern Australia; however, the continuous low-level eruptions at the volcano are still producing an easily detectable plume extending to the southeast. At 31/0832 UTC, this plume has shrunk in size, but is still present. By 31/1432 UTC, the eruptions have ceased, with a few remnant plumes to the east of the volcano, generally moving slowly to the northeast by this time. Ash ceased being detected in this vicinity by 31/2132 UTC.

Figure 10 presents the same sequence of images as Fig. 9 but for the BTD field. Overall, the BTD images depict the same evolution as the VOLCAT, with some subtle differences. At 30/0832 UTC, one pixel with a negative BTD is indicated. At 30/0932 UTC (not shown), a few pixels on the edge of...
the umbrella cloud show negative BTD, an initial detection that is 1 hour earlier than the VOLCAT algorithm. However, the detection an hour later in VOLCAT is more extensive. By 30/1432 UTC, the remnants of the umbrella cloud racing towards the Kimberley show a strong BTD signal, with peak differences on the order of -3 to -4 K. At 30/2032 UTC, the plume from the second high-level eruption (and the ongoing low-level eruptions) is apparent; careful comparison shows that the plume as suggested by BTD is not quite as extensive as that from VOLCAT, but similar nonetheless. Only a small weak signal remains from the umbrella cloud in the Kimberley. The evolution of the BTD field in the umbrella cloud to this time is consistent with an initial optically thick ash plume that shows no BTD signals. As the ash falls out and/or disperses the BTD signal strengthens where the optical depth is at some moderate value. Further thinning of the ash lowers the returned signal until eventually it is gone. At 31/0232 UTC, the differences between VOLCAT and BTD are fairly significant, with VOLCAT detecting more of the thin ash farther away from the volcano. As the event winds down (31/0832 and 31/1432 UTC), VOLCAT continues to identify more areas as covered by volcanic ash, although there is broad similarity.

Figure 11 presents a comparison of the retrieved ash cloud top heights between the Terra and Aqua MODIS and MTSAT-2. Of particular interest is the umbrella cloud noted earlier. At 30/1405 UTC, Terra MODIS suggests cloud top heights in some areas to be 18-22 km altitude. While these heights cannot explicitly be ruled out at this time, it is suggested here that they are unrealistically high. Based on inverse modelling studies, most of the comparatively small amount of ash that entered the stratosphere should have moved in a different direction from the umbrella cloud, for which the best evidence indicates that peak ash cloud top was at 16 km. At 30/1710 UTC, the Aqua MODIS indicates peak heights of 15-16 km, with heights in large areas of the umbrella cloud identified between 10 and 13 km, much more consistent with earlier estimates of the peak height. Both MODIS instruments indicate higher cloud tops than those identified in the nearest-in-time MTSAT-2 images. In the 30/1432 UTC MTSAT image, peak heights are between 7 and 12 km; in the 30/1732 UTC image, cloud top heights are identified between 5 and 8 km.
Also apparent in Fig. 11, particularly in the earlier set of images, is the plume extending out of Sangeang Api towards the southeast. Terra MODIS makes a partial detection of this feature, with peak heights of 12 km indicated. At the northern end, just off the Flores coast, both satellites see an ash feature. The plume is still visible at the later time, but not as sharply defined. Aqua makes some partial detections again on the edge, while MTSAT-2 does not see it. Further east, both Aqua and Terra detect features that are not seen by MTSAT-2. Also, ash features to the west-northwest of the volcano are detected by all satellites at both times. The features towards the eastern edge of the Terra scene with heights between 18 and 22 km could conceivably be the remnants of the ash that entered the stratosphere.
Fig. 11 Comparisons of the retrieved ash cloud top heights between Terra MODIS and MTSAT-2 around 30/1415 UTC (top) and Aqua MODIS and MTSAT-2 around 30/1715 UTC (bottom). MTSAT-2 is on right in each case.

Figure 12 further compares the umbrella cloud in the MTSAT scenes with their MODIS counterparts in the form of scatterplots of the retrieved height against pixel brightness temperature. The initial guess of $T_{\text{eff}}$ (see section 2.4) is set as a constant offset (-25 K) from the 11 $\mu$m brightness temperature of the pixel under examination, and this implied height is shown by the blue diamonds, based on the nearby Surabaya sounding. For the MTSAT data at both times (red symbols), the identified heights are strongly related to the underlying brightness temperature and cluster near the initial guess points, highlighting the dependence of the retrieved height upon the initial guess of $T_{\text{eff}}$.

In the MODIS scenes, considerably more variation is seen in the heights, while the pixels show approximately the same range of brightness temperatures. However, there are considerable differences between Terra and Aqua. In Terra, the spread of heights is large, essentially filling the ‘area’ on the plot, plus there are a large number of points above the nominal maximum cloud top height as determined from the umbrella cloud at eruption (16 km, indicated by the dashed line). In Aqua, a wide range of retrieved heights is observed over a narrow range of brightness temperatures and the
distribution of points appears somewhat more ‘constrained’; there are only a few points above the 16 km limit here. The degree to which these variations are a realistic depiction of mesoscale variability in the structure of the ash cloud or a reflection of the inherent uncertainty in the retrievals remains to be determined.

Fig. 12 Scatterplots of pixel brightness temperature against retrieved ash cloud top height for the umbrella cloud at the times depicted in Fig. 25. The Terra/MTSAT-2 comparison is shown on the left; the Aqua/MTSAT-2 is on right. Red symbols are for MTSAT-2, green symbols are for the MODIS instrument. Blue diamonds represent predicted retrieved heights based on the Surabaya sounding from 30 May 2014 1200 UTC.

The lack of ground truth validation limits the conclusions that can be drawn here. The significant differences between the simultaneous scenes and their temporal evolution would suggest that one (or more) of the satellites is producing incorrect height retrievals. There are known problems with MTSAT-2, and the retrieved height field with MTSAT is effectively a mask for the pixel brightness temperatures. In general, the retrieved height field will be an underestimate of the actual height; if the initial guess is close to right, the heights will be more accurate. With the MODIS instruments, there are clear differences in the characteristics of the retrievals, with the data from Terra appearing more likely to be incorrect in this case. Subtle differences in the calibration of the instruments are one hypothesis to explain the differences. However, this is speculation at this time and additional investigation is needed to understand these issues.

4.4 Detailed analysis of Sangeang Api plume

This section will focus on a detailed comparison of near-contemporaneous images from MTSAT-2 and Terra MODIS of the Sangeang Api plume at approximately 31/0235 UTC; the true colour image of the plume in this scene is depicted in Fig. 8.

Figure 13 shows the retrieved ash cloud top height fields and accompanying 11 μm imagery of the plume, with Terra on the right. Much of the extensive plume identified at this time initiated around 30/1700 UTC, the second major eruption of this event. The exact timing of the second eruption is
The extent of the detected plume between the two platforms is largely the same, although subtle and not-so-subtle differences are apparent. The resolution of the satellites is different; nominally 1 km for Terra MODIS and 4 km for MTSAT-2, resulting in approximately 16 times the number of pixels in the Terra image. The Terra image shows an extension off to the north, with heights extending to 18 km and higher. The odd pattern of the high heights, along scan lines of the satellite and the rapid variations in height suggested indicate that this is probably a false detection. Brightness temperature fields do not suggest the eruption reached these stratospheric heights at any time. These probably erroneous heights are consistent with the behaviour of this satellite noted with Figs. 11 and 12. Further, the true colour image (Fig. 8) does not suggest that visible ash is present at this location. Other differences in detected area can also be identified, although none as significant. The detected area in MODIS is subtly larger. Differences in the height fields are also apparent, with MTSAT having lower heights. Despite this bias, the overall pattern of height variability is similar. Heights are highest near the volcano; further downstream heights are generally lower. However, the Terra retrievals have more subtle mesoscale variability, regions of coherent higher heights. Despite this variability and the obvious biases, the retrievals from the different satellites qualitatively depict similar broad-scale structures of the observed fields.

Fig. 13 Retrieved ash cloud top height and 11 µm brightness temperature fields from the Sangeang Api plume at approximately 31/0230 UTC from MTSAT-2 (left) and Terra MODIS (right). Numbered boxes indicate the averaging areas referred to in the text; shapes are different due to the map projections used.

To facilitate a closer comparison, 5 boxes within the plume are selected for closer inspection, as shown in Fig. 13. The boxes are identical for each satellite; the apparently different shape is due to the
different map projections used in the figures. The boxes are between 0.3 and 0.5° latitude on a side. Only pixels with valid ash retrievals are examined. The retrieved properties (ash cloud top height, effective radius ($R_{\text{eff}}$) and mass loading) and 11 μm brightness temperature are averaged within each box. These averages are used in the analysis.

Figure 14 presents the averages and standard deviations of the retrieved fields in the boxes as a function of distance from the volcanic source. Despite some significant differences between the satellites, the box analysis presents a broadly consistent narrative of the structure and evolution of the plume, in agreement with the qualitative assessment above. Box 1, in the immediate vicinity of the volcano, shows the largest values of mass loading and $R_{\text{eff}}$ and the highest variability. In this box, relatively more ash area is detected by MTSAT-2 and heights are on average higher, although the Terra true colour image (Fig. 8) clearly suggests multi-level ash clouds are present. This is partially seen in the Terra retrievals, but not in those from MTSAT-2. In Box 2, average values of mass loading and $R_{\text{eff}}$ decrease from Box 1, as does the spatial variability. Compared to Box 1, the retrieved height is higher in Terra and lower in MTSAT-2. In the Terra height field, the source of the increase as is in part due to a very high ‘streamer’ or plume of ash in the box with peak heights of almost 19 km; a similar feature is not apparent in MTSAT. A visual examination of the true colour image indicates that this streamer is whiter than the browner textures of surrounding ash, suggesting the possibility that this feature is high cirrus above the ash, resulting in a mixed ice/ash cloud or a situation where ash is not the top layer. Both of these circumstances can result in errors in the retrievals, as reported in Section 2.4. Mass loading and $R_{\text{eff}}$ are larger in MTSAT-2.
Box 3 has the largest discrepancies in height between the two satellite retrievals; average heights are 13.0 and 9.3 km in Terra and MTSAT-2, respectively. The Terra retrievals clearly show more mesoscale structure within this box, with regions identified at ~15 km altitude; this structure is not apparent in the MTSAT-2 retrievals. Mass loading is greater in MTSAT-2, while effective radii are approximately the same. Further away from the source in Box 4 and Box 5, the ash cloud is become thinner, as is apparent in the true colour image. Quantitative values of mass loading and $R_{eff}$, generally higher in MTSAT-2, decrease with distance from the source, supporting the interpretation of the cloud thinning. Cloud top heights are found to be still higher in Terra, but are closer in value than in Box 3. In general, spatial variability within Boxes 4 and 5 is comparatively low.

Taken together, the box analysis can be interpreted as the evolution of the plume and its microphysics as time increases from the eruption. Near the eruption source, there is greater mass, associated with larger particles and broader size distributions. Spatial variability is large, associated with the turbulent nature of the erupting plume. Much of the initial mass falls out relatively close (~50 km) to the volcano, with the larger particles being removed. As the plume moves away from the volcano, the
mass decreases at a roughly constant rate. The rate of mass loss and the decrease in the particle size
distribution are reasonably consistent across the two platforms examined here. The evolution of the
cloud top height of the plume is less clear, although in this case it appears to generally decrease with
distance from the eruption.

It should be strongly emphasized that this is an examination of a single satellite scene, subject to a
great deal of uncertainty. There is no ground truth with which to compare the retrievals and both sets
of retrievals in this case are subject to a great deal of uncertainty. Refer to earlier discussions in this
section (e.g. Fig. 12). Retrieved cloud top heights are the least consistent retrievals here, owing to the
fact that $T_{\text{eff}}$ is the least constrained variable retrieved. It should be remembered that the retrieved
cloud top height reflects a ‘radiative’ cloud top, some unknown weighted average of the radiances
within the clouds, and not the physical cloud top height. That makes interpretation of the height
difficult, especially in thin portions of the cloud where the emissivity is low. As noted, biases in $T_{\text{eff}}$
can lead to subsequent biases in the retrieved microphysical properties of the clouds.

4.5 Performance summary

As with the Kelut eruption, the evolution of this case was clearly evident in satellite imagery. The
initial eruption was large and occurred in an environment that was relatively free from meteorological
cloud, making its appearance easily identifiable. VOLCAT detections were perhaps slightly superior
to more traditional identification methods based on BTD, as they more often identified larger areas as
covered in ash. That these more extensive detections were actually ash and not false signals is seen by
comparing the visible plume with the retrievals (Figs 8, 11 and 12). Ash was detected by VOLCAT for
a longer period compared to BTD as well.

After the initial eruption, there was a delay in the detection of the initial eruption plume. Full
identification of the umbrella cloud was delayed by several hours, but was able to be tracked for at a
distance of over 1000 km away from its source. Some parts of the plume were only partially detected
in satellite imagery, others not detected at all. This was seen regardless of satellite, although the
MODIS instrument did provide the partial detections. Despite this apparently better performance, there
are regions of ash detected by MODIS that are uncertain as they don’t seem physically consistent with
predictions from dispersion models or inferences from brightness temperatures, particularly at the
height at which they are reported. This is particularly the case with the Terra satellite.

Much of the apparent volcanic ash that was noted further afield by the Australian VAAC, such as that
affecting the Top End, is not identified by VOLCAT. These detections are presumably based more on
the presence of SO2. As noted above, the initial umbrella cloud that travels into the Kimberley was
detectable for some distance. In the end, BTD methods were perhaps better in tracking this particular
feature for longer.

After the second high level eruption at around 1700 UTC, the ash streaming from the volcano is
readily identified for several hundreds of kilometres downstream. These identifications are consistent,
and do not show any apparent influence of the diurnal cycle on the detections; in fact, many of the
‘best’ detections occur during the daylight hours. A careful intercomparison of two satellite platforms
of this plume has provided some insight into evolution of the plume and provided information on the
reliability/consistency of the retrievals.
5. CORDON CAULLE – JUNE 2011

5.1 General Comments

Cordon Caulle is different from the case studies examined here in that it is not an Indonesian eruption. Instead, Cordon Caulle is a volcano in Chile that erupted on 4 June 2011. This ash subsequently circumnavigated the globe at least twice over the next three weeks. Volcanic Ash Advisories were issued for several weeks for large portions of the Southern Hemisphere mid-latitudes. Klüser et al [2013] describes the evolution of the ash trajectory over the first 2 weeks after the eruption. Vernier et al [2013] examine the ash using CALIPSO lidar data later on after it reaches Australia.

While the issued VAAs covered parts of southern Australia, particularly south-western WA and Tasmania around the period 10-15 June, the most significant aviation impact occurred on the single day we examine here, 21 June 2011. By this time, the ash was generally found at latitudes well to the south of Australia. However, this day saw a significant breaking Rossby wave event over south-eastern Australia (SEA) that acted to draw this area of ash equatorward into the region. Radiosonde data (not shown) indicate that a significant tropopause ‘fold’ was present ‘folded’, with heights down to 7 km at Melbourne Airport. Ash remained detectable offshore from eastern Australia on 22 June.

Figure 15 shows a composite true-colour Aqua MODIS image over southern Australia captured around 21/0445 UTC; careful examination clearly shows a ‘tendril’ of ash snaking northwards over SEA. The red outline highlights this otherwise subtle feature.

Fig. 15 Aqua MODIS ‘True Colour’ composite image of southern Australia on 21 June 2011. Western portion of the image is derived from the overpass around 21/0445 UTC. Location of visible ash (red outline) has been manually highlighted.

As the ash from this eruption was so spatially extensive by the time of this case study, there is excellent data to validate and compare with the output from GEOCAT. Data from MTSAT-2 is the
primary observational platform, with data from Aqua and Terra MODIS and the CALIPSO lidar also used.

5.2 VAAC overview

The Australian VAAC first identified ash from Cordon-Caulle as a potential region of concern on 8 June 2011, based on alerts passed on from the Toulouse VAAC. The first explicit VAAs (i.e. with ash boundaries drawn) were produced by the Australian VAAC on 9 June. From 10-15 June, VAAs which included portions of southern Australia, particularly south-western WA and Tasmania, were produced. These generally warn of ash between FL260 and FL360. After this date until the event, ash was generally observed south of Australia.

The first hints of the impact on SEA appearing in the VAAs were produced on 19 June, 18 hours out from the event which is the maximum time window for VAAs. These were remarkably prescient, and even the length of time the ash was expected to be over SEA was also well forecast. This was an extremely well forecast event, in a meteorological situation which is also has a lot of predictability.

Volcanic ash advisories were issued for Cordon Caulle through 7 July, although there was no significant impact to Australia after 21 June.

5.3 Satellite evolution of eruption and ash detection

Figure 16 shows the evolution of the BTD field across SEA over 21 June 2011 at six-hourly intervals beginning at 21/0432 UTC. In the first image of the sequence, a negative BTD signal with values of around -1 K is clearly associated with the ash plume as depicted in Fig. 15. The source of this region lies in to the south, in the Southern Ocean; a thin tendril of ash moves up into the interior of Australia, curving eastward as it reaches the continent. As a whole, this ash plume moves eastward as time progresses, while individual parcels move with the flow towards the northeast. By the last frame of the sequence (21/2232 UTC), the BTD signal is less spatially coherent, but still identifiable as a single entity located off the east coasts of Tasmania and New South Wales. During the middle frames of the sequence, the BTD signal over land becomes ‘contaminated’ by surface cooling, one of the drawbacks of the BTD methodology (see section 2.3). This makes discernment of the genuine signal over land areas more difficult, although operational techniques exist to reduce this effect.
Fig. 16 Evolution of MTSAT-2 11 μm brightness temperature and BTD field during Cordon-Caulle SE Australia ash event. Times shown are 21/0432 UTC (top left), 21/1032 UTC (top right), 21/1632 UTC (bottom left) and 21/2232 UTC (bottom right).
Figure 17 presents the same sequence of images for the retrieved ash cloud top height field from the VOLCAT software. The evolution is considerably different from that shown in Fig. 11. At 21/0432 UTC, the detected ash is confined to the Southern Ocean, at latitudes poleward of 44°S; the tendrils of ash apparent in Figs 15 and 16 is not observed. In the middle two images of the sequence, occurring during local night, the ash cloud is identified across a broad area, from the Southern Ocean to the interior of the continent. In the final image of the sequence, no ash is detected by VOLCAT.

Where retrieved by the VOLCAT software, ash cloud top heights are generally reported between approximately 2 and 6 km; a few exceptions are noted, particularly in the 21/1632 UTC image, where small regions of reported heights of 8-10 km are noted in the southern portions of the plume. Other images occasionally show heights of 12+ km, also in the south over small areas. The CALIPSO lidar cross section from the 21/0445 UTC overpass (Fig. 18 top) clearly shows that the ash layer is between 10 and 13 km. The observed differences in height are due to the same factors that were described in the Sangeang Api case (Section 4), namely the close relationship between the initial guess based on
the IR temperature-based first guess and the retrieved heights. Vernier et al (2013) suggested an ash layer at ~4 km based on the CALIPSO data at 21/1550 UTC (Fig. 18 bottom), extending for well over 1200 km across mainland Australia. Pilot reports suggested visible ash at these levels at earlier times to this observation; no ash is observed by VOLCAT in association with this apparent lidar-based detection.

Figure 19 presents a comparison of VOLCAT height retrievals between the Aqua MODIS (21/0445 UTC) and the MTSAT-2 (21/0432 UTC). There are considerable differences in the detections. The MODIS highlights a more northward part of the tendril extending into southeastern Australia, while the MTSAT detections occur at latitudes to the south of Tasmania (which is largely not part of the MODIS granule examined here). There are no congruous detections by MTSAT. A second difference lies in heights retrieved; the MODIS instrument, which includes a 13.3 \( \mu \text{m} \) channel, shows ash cloud tops at altitudes in excess of 12 km. However, this is not consistently observed throughout, and the errors remain large in some regions of the volcanic cloud. The reasons for this are not entirely clear; one hypothesis, requiring further investigation, is that this is related to the relatively low density of the ash cloud. Within MODIS data, there are also differences in the detection over land and water. With the exception of a small spot of northwestern Victoria, there no detections over land, although ash is clearly present there in the visible image (Fig. 15). This includes the location of the CALIPSO overpass. Extrapolating to the portions that are detected, the ash is primarily detected in the part of the ash cloud that is vertically thicker (see Fig. 18), which is denoted by the stars.

### 5.4 Performance summary

This is a very unusual case, perhaps unique, in that the eruption that was the source of this ash occurred at least 1-2 weeks before it arrival over SEA, several thousand kilometres downwind from the source. The ash, as seen from space, was located primarily in the stratosphere, although the VAAC advisories placed it much lower based on pilot reports from aircraft in the area. Vernier et al [2013] offered some support from this ash, but there are no detections made by the VOLCAT software or in the BTD field. Overall, the performance of the algorithm in this case was generally adequate; at times very good while at others less good. Several shortcomings are noted.
The first shortcoming is the strongly diurnal nature of the detections, with significantly larger areas of ash detected by VOLCAT at night. Over the land regions of SEA, ash was identified only at night. This is true of both MTSAT-2 and the more advanced instrumentation of the NASA satellites. After sunrise on the 22nd (local time), the ash was no longer detected. The reason for this is not clear, but a reasonable hypothesis would be that the differences in the day vs night automated ash detection noted in section 2.4 is a source of this discrepancy. Land/water differences also appear to play a role. For the latter, the source could lie in the detection algorithm or elsewhere; over land, the surface emissivity values that drive the clear-sky radiance calculations are subject to a great deal more uncertainty, which could reduce the effectiveness in the retrievals.
Fig. 19 11 μm brightness temperature and retrieved ash cloud top heights from MTSAT-2 at 21/0432 UTC (left) and Aqua MODIS at 21/0445 UTC. White outlines on MTSAT image denote locations of detected ash from the Aqua image.

While VOLCAT showed a strong preference for detection of ash at night, the BTD technique worked best during the day in this case. In some sense, the different methodologies complemented one another quite well and represent a useful synergy between observation platforms, suggesting that VOLCAT should be a part of an integrated observation platform rather than a replacement. However, with more advanced observation platforms like Himawari-8, these issues could potentially disappear.

Height errors in the retrievals were quite significant. As with other cases examined here, this is related to the older instrumentation on board the ‘heritage’ MTSAT-2. However, the height retrievals with the better MODIS instrument were highly variable in a spatial sense, and height errors of similar magnitude were also identified on the ash cloud here as well. Whether this spatial inconsistency is a peculiarity of this case or more general behaviour is unclear and requires further investigation.

6. **MERAPI – NOVEMBER 2010**

6.1 **General comments**

Mt Merapi, the most active volcano in Indonesia, underwent a major eruptive event during October and November 2010. Surono et al [2012] provides a vulcanological overview of this event, which was composed of a series of eruptions. The initial eruption occurred on 26 October, with explosive eruptions observed on that day, 29 and 31 October and 1 November. As the lava dome grew, seismic activity increased, and frequent explosions were observed from 3 November. The climactic eruption for this event occurred on 4 November at 1705 UTC, the largest since the 1870s. The volcano was in
its waning phase from 8-23 November. These eruptions had a significant impact in central Java, where 353 people were killed, primarily due to pyroclastic flows.

For the case study here, the focus is on the period from 3-8 November 2010, when the impacts of the volcano to aviation were most significant. The airport at Yogyakarta, 30 km from Mt Merapi, was closed for an extended period with many cancelled and re-routed flights [Picquout et al 2013]. International aviation was also affected, as ash and SO2 extended well into the Indian Ocean and over northwest Australia, requiring the alteration of long-haul flight paths.

A composite SO2 image from NASA acquired over the 4-8 November shows the general path of the gas from the eruption (Fig. 20). The background environment during the period of the case study is very humid, often saturated through a significant depth of the troposphere. Deep convective activity was frequently observed over region, producing copious amounts of meteorological cloud. The roundabout path of the ash in Fig 20 was partially the result of the remnants of TC Anggrek to the south. This storm reached a maximum of category 2 but was downgraded to a tropical low on 4 November.

The main observational platform in this case is MTSAT-1R, which is supplemented with Aqua and Terra MODIS data. Multiple overpasses from the CALISPO satellite lidar suggest that ash is apparent throughout the broader region over the analysis period here, although these are challenging to confidently identify.

### 6.2 VAAC overview

The Australian VAAC issued its initial Volcanic Ash Advisory (VAA) for this event on 28 October around 1200 UTC. Initially, these warnings were primarily for the area around Java, particularly west of the volcano. A significant high level eruption was reported on 3 November at 0830 UTC, with a VAA to FL300 issued; this helped determine the choice of start time for this analysis. Interestingly, the VAAC did not specifically identify the climactic eruption on 4 November, with only a routine VAA at 1845 UTC stating ‘VA not Identifiable on sat imagery due to meteorological cloud but expected to still be in area’

During the initial part of the time period analysed here, VAAs were largely confined to the Java area. However, from 8 November at 0800 UTC the area covered by VAAs significantly increased, extending well into the Indian Ocean and covering the northwest coast of Australia as well. This was based primarily on SO2 imagery, rather than an explicit ash signal. Warnings for ash extending to FL500 were produced over the Indian Ocean until 15 November. The last VAA for this event was issued on 22 November at 11 UTC.
Fig. 20 Composite image of SO2 retrievals from the Merapi eruption. Data acquired from 4-8 Nov 2010 using the NASA Aura Ozone Monitoring Instrument. Image taken from NASA Earth Observatory.

6.3 Satellite evolution of eruption and ash detection

Table 1 summarizes an analysis of volcanic activity visible from satellite in the immediate vicinity of Mt Merapi is performed, combining the automatic detections with a subjective assessment of activity at the volcano. The initial high level eruption reported by the VAAC (03/0830 UTC; Fig. 21 left) is not detected by the software.

In Table 1, this is marked as ‘possible’ or ‘ambiguous’. Visually, there appears to be a source of lower IR temperatures emanating from the volcano in the 03/0830 UTC image, which expands in area in the 03/0930 UTC image. Surono et al [2012] suggest explosive activity at the volcano at 03/0720 UTC with a larger explosion at 03/0840 UTC, which broadly agrees with the evolution of the satellite imagery. However, the detection of this initial eruption is challenging as deep convection is occurring simultaneously in the vicinity, and the volcano is obscured by meteorological cloud for several hours after the initial eruption. There is no automated identification of the plume until 03/2230 UTC (Fig. 21, right), and then only for a single image.
VOLCANIC ASH ALGORITHM EVALUATION

Figure 21 MTSAT-1R 11 \( \mu \)m brightness temperatures and VOLCAT ‘ash probability’ at 03/0830 UTC (left) and 03/2230 UTC (right).

Table 1. The timing of ash detections in the immediate vicinity of Merapi by UTC hour (columns) and date in November (rows). Local time is UTC+7 hours. Letters indicate the following: X=accurate detection, E=evident plume, but no detection, M=volcano obscured by met cloud, P=possible plume, but interpretation ambiguous, ‘?’ indicates a questionable detection. Red colour indicates the significant high level eruption, Grey indicates that no analysis is performed.

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Figure 22 shows a sequence of hourly IR satellite images centred on the time of the climactic eruption at 04/1705 UTC. In the first image (04/1130 UTC), a small cold IR signature appears to be emanating from the location of the volcano. Further north, the similar feature is visible, identified by the algorithm as a possible volcanic cloud, probably in error. Over the next several hours, this cold IR signature persists (and expands from 04/1430 UTC) at Merapi, consistent with repeated explosions from ~1430 UTC noted by Surono et al. [2012]. Further north, the IR signature varies as convective clouds form and dissipate; several apparently false detections are made before the climactic eruption. These features are generally tracking off towards the north and northwest. At 04/1730 UTC, the cold IR signature on Merapi is much larger, and the umbrella cloud shows evidence of a slight ‘warm spot’ suggestive of a stratospheric intrusion; interpreting brightness temperatures thusly indicates peak heights between 18 and 20 km. Over the remaining images of the sequence, the coldest IR tops of the umbrella cloud move towards the west and southwest; IR brightness temperatures suggest cloud top heights between 15 and 16 km for most of the umbrella cloud. A detection of ash is made in the
umbrella cloud at 1830 UTC (discussed more below), and some (presumably false) detections are made to the southeast of the eruption on top of unrelated convective clouds at 1930 UTC.

Figure 22 MTSAT-1R 11 μm brightness temperature and ash probability fields on 4 November 2010. Time resolution is hourly, beginning at 04/1130 UTC. Each image shows the same area. The location of Mt Merapi denoted by red triangle

Figure 23 shows the retrieved height field of the umbrella cloud and it surroundings from MTSAT-1R (left) at 1830 UTC and the Aqua MODIS (right) at 1840 UTC. Interestingly, the volcano appears to be in a slightly different place relative to the canopy cloud in the two images; this is likely due to parallax from the differences in the viewing position between the two satellite platforms, although navigation differences may also make a contribution. In the MTSAT-1R scene, a small detection (7 pixels) with a generally low probability is made by VOLCAT. Retrieved cloud top heights are suggested to be 20-21 km, considerably higher than expected from the IR brightness temperatures. As with the earlier cloud top detections in this event (Fig. 22), this detection is likely not valid. These detections are also reminiscent of those in the 2014 Kelut eruption (Section 3), where apparently correct detections were made in the volcanic canopy with MTSAT-1R for the wrong reason. There is no detection on the umbrella in the scene from the Aqua MODIS (right); instead, a significant retrieval is made to the northwest of the umbrella cloud. Examining the evolution of the cloud features (Fig. 22) indicates that this detected ash was ejected before the climactic eruption. The ash cloud top height retrievals with Aqua MODIS range from 11 km to 21 km (or more). In the undetected portion of the apparent ash cloud, IR brightness temperatures suggest that the cloud top height is approximately 10-11 km. Further, wind profiles from radiosondes at Jakarta and Surabaya (not shown) suggest that it is unlikely that ash at higher altitudes would travel in that direction. Hence, it is suspected that the detections on the upper end of this range are in error, although the immediate source of this error is not readily
apparent at this time. This behaviour of the algorithm in this scene is reminiscent of the errors suspected in the Terra MODIS retrievals during the Sangeang Api event (Section 4.2).

![Fig. 23 Retrieved height and 11 μm brightness temperature fields from MTSAT-1R (left; 04/1830 UTC) and Aqua MODIS (right; 04/1840 UTC) showing the climactic eruption plume.](image)

Table 1 indicates that volcanic plumes are apparent for the much of the remainder of the analysis period, most notably on 5 and 6 November. Activity decreases early on 7 November, before resuming later that day and into the 8th. This agrees with the activity discussed Suirono et al [2012]. The detection rate of these plumes by VOLCAT greatly increases, but still remains far from 100%. However, these plumes are generally small and likely do not pose a significant aviation threat outside of the immediate vicinity of the volcano.

Further west, over the Indian Ocean, the presence of ash was widespread. Fig. 24 summarizes an analysis of the CALISPO satellite lidar data, highlighting when and where ash was subjectively identified in the satellite overpasses of the region from 5-8 November. Early in this period, the ash is well out over the Indian Ocean, westward of 95°E. This ash is spatially extensive, extending for over 1300 km along the satellite track on the 5th, and in excess of 25° of latitude on 6 November. As time progresses, the ash moves close to Australia. This behaviour is broadly consistent with the behaviour of SO2 as summarized by Fig. 1. On the 5th and 6th, the is ash is located between 13 and 18 km with the layers often quite thick, particularly further afield over the Indian Ocean (Fig. 25). As the ash moves closer to the continent, the layers become thinner, but generally remain at 15 km and above (Fig. 26 left). Further south, the ash is very thin and is found as low as 12 km. In the daytime overpass on the 8th, there are two distinct layers of ash that overlap. (Fig. 26, right).
The volcanic ash noted on 5 November over the Indian Ocean was partially detected by VOLCAT between 05/1130 and 06/0330 UTC. The region of detection was centred near 10°S, 95°E. The detected ash is quite changeable, varying from one image to the next; the largest areas are detected between 05/1930 and 05/2230 UTC. One interpretation of the shifting signal is that different portions of a larger area of ash are being incompletely detected at different times. This interpretation is supported by Figure 27, which shows ash detections/retrievals at approximately 05/1930 UTC from MTSAT-1R (left) and the Aqua MODIS (right). This coincides with the CALIPSO overpass in the top panel of Fig. 25. The MTSAT-1R detection is near 10°S 92°E, at approximately the location given by the thick ‘blob’ of ash identified in the CALIPSO imagery. There are also numerous detections -- likely erroneous -- in association with deep convective clouds in the vicinity. The detections in error tend to have cloud top retrievals in the 15-18 km range, while the likely ash retrievals are between 8 and 12 km. As in the Sangeang Api case (Section 4), these heights are likely a ‘mask’ reflecting the underlying brightness temperature fields. No ash is identified at these levels in the CALIPSO imagery. The Aqua MODIS also detects ash in this general vicinity. There is very little overlap with the MTSAT-1R detections, although the areas are adjacent. The MODIS does not identify the convective cloud tops as ash. Retrieved heights in the Aqua image are generally on the order of 17-18 km, consistent with the height of the ash observed in the area. No other ash is identified along the CALIPSO ground track.
Fig. 25  Cross sections of CALIPSO lidar data on 5 and 6 November. See Fig. 24 for locations. Top: 05/1928 UTC. Bottom left: 06/0738 UTC Bottom right: 06/1834 UTC.

Fig. 26  Cross sections of CALIPSO lidar data on 7 and 8 November. See Fig. 24 for locations. Top Left: 07/0643 UTC; Bottom left: 07/0646 UTC; Top Right: 08/0551 UTC; Bottom right: 08/1824 UTC.
The detections of ash on 5 November are the clearest, most consistent instances of ash identified over the Indian Ocean during the period analysed. On the remaining days, detections are made that generally align with the picture suggested by the composite SO2 map (Fig 20) and the CALISPO ash detections (Fig 24). However, these detections by VOLCAT are weak and ephemeral. Figure 28 shows an example on 6 November, again comparing retrieved heights from MTSAT-1R with those from the Aqua MODIS. There are multiple false detections, associated with the higher retrieved cloud top heights here. Plausible ash returns are visible between 17-20°S and 91-94°E, with heights varying between 5 and 10 km. The MODIS image (right) also shows some plausible retrievals, with heights around 17 km, although some regions with much lower heights are also apparent. Despite the correspondence in space between the two images, the interpretation remains unclear, particularly in the MTSAT data. The probability fields (not shown) are very ‘speckled’ and some of the detections are clearly associated with clouds. In other MTSAT imagery from around this time (1330-2330 UTC), there are multiple detections in this general area with similar characteristics; some ash-like properties are apparent and ash is expected in this vicinity from the previous day. But there is a clear association of these detections with developing cloud activity, which makes the interpretations of this as being ash very uncertain. Where ash is known to be present from the CALIPSO data (see Fig. 25), no ash is detected anywhere along the satellite path at that time.
Over the period of 7-8 November, there are very generally few detections of ash over the Indian Ocean by either MTSAT-1R or the MODIS platforms. With MTSAT-1R, the detections that are observed are generally associated with cloud activity, reducing the confidence that is placed in the interpretation of ash. The overpasses from Aqua and Terra do not show any ash detection in this region across either day. This is despite of the identification of ash in CALIPSO overpasses (Fig. 26).

6.4 Performance summary

The 2010 Merapi eruption was a challenging case, in both the real time identifications and tracking of the ash, as well as in this post-event evaluation of the detection software. The multi-day composite satellite analysis of SO2 (Fig. 20) suggests a meandering path of volcanic effluvia and provides clear evidence of the regions affected. Ash clouds subjectively identified from CALIPSO lidar data indicate that ash was widespread over the Indian Ocean for several days after the climactic eruption, although the concentrations appear to be very low in the latter part of the analysis period. The poor calibration of the MTSAT-1R satellite and the frequent deep convection in the area hindered the identification of the ash clouds.

Detection of the plumes by VOLCAT near the eruption was poor in the initial stages of the event, but improved towards the end of the analysis period. In the initial high level eruption clouds, the ash is optically thick which hinders performance of the algorithm, as seen in the other cases in this report. Obscuration of the region by meteorological clouds also proved to be a hindrance to identification. Later in the period, detection of ash plumes by VOLCAT arising out of Merapi was more common, but still not as frequent as could be identified through visual analysis. VOLCAT detections showed strong diurnal characteristics, with automated identification of ash plumes more frequent at night and in the early morning.
Over the broader Indian Ocean, ash from the climactic eruption was detected on 5 November with a reasonable degree of confidence approximately 1600 km from its source. Both MTSAT-1R and MODIS detected this ash, albeit in slightly different (but adjacent) locations. The best detections occurred where CALIPSO lidar suggested the ash was its thickest. Neither platform detected the full extent of the ash apparent on the lidar. On 6 November, more tentative detections of the ash were made, although these were not coincident with CALIPSO lidar detections. On 7 and 8 November, no reliable ash detections were made over the Indian Ocean.

The analysis of the ash in this case is made more difficult by the numerous false detections. These are often associated with cold cloud tops of mesoscale convective systems. There was also some coincidence of these false detections with lower level stratocumulus clouds. These signals appear to be unique to MTSAT-1R; these were not seen in the MODIS data. The false detections are hypothesized to result from the strong temperature dependent biases in IR brightness temperatures (and radiance) noted in section 2.

From Table 1 and the examination of the satellite data over the 6 days examined here, it is clear that there is a strong diurnal tendency for detections in this event. Detections are preferentially made at night and in the early morning. One explanation is that deep convection, particularly over Java and other land areas, initiates in the early afternoon, obscuring the scene later in the day. This is not the whole story though; the detected areas are larger at night, and the night time bias still occurs even when convection is not present. It is hypothesized that this is related to the different tests and channels used between day and night for the automated detections for the MTSAT-1R (and MTSAT-2) data.

Despite the difficulties identified in this analysis, the great potential of the VOLCAT software to improve operational warnings issued the VAAC was demonstrated in this event. Namely, the ash in the Indian Ocean was consistently identified on 5 November, some 2-3 days before the VAAC warnings for this area were issued in real time. This is a significant positive outcome.

7. SYNTHESIS

This work has examined case studies of four high-impact volcanic ash events in the Australian VAAC’s area of responsibility with the purpose of evaluating the VOLCAT automated volcanic ash algorithm for use in the Bureau’s operations. This algorithm uses advanced remote sensing techniques from multi-spectral satellite data to automatically identify volcanic ash clouds and provide quantitative estimates of their physical properties, including the height of the cloud top, the mass loading and the size of the ash particles. For this report, the evaluation is primarily focussed on the questions of the identification of ash and the validity of the height retrievals. A brief comparison of the robustness of the effective radius and mass loading retrievals between satellites is also performed for a single scene.

Overall, this evaluation of the VOLCAT volcanic ash algorithm is positive. The evidence presented here indicate that its performance is comparable to existing methods and should be a useful addition to the existing operational toolkit of methodologies and approaches to the challenging problem of identifying volcanic ash. Like all tools, it has both positive and negative aspects.

Some of the shortcomings identified in this evaluation are:
The ash detections generally do not exactly correspond with what a human analyst would identify as ash cloud. There are many missed or partially detected features that are readily detectable to the trained eye. False alarms and incorrect detections also occur. Detections and alerts will require further evaluation to ensure they are valid and that the entire ash area is being captured. This is seen to some degree in all the cases examined here.

The identification of deep ash plumes from the high level erupting volcanoes by the algorithm is problematic. There is often a delay in the identification of the initial ash plume, and many of the missed detections occur in the first few hours after an eruption. This arises in part because high level eruptions can produce copious amounts of optically thick ash that obscure the subtle radiative signals required for detection. A related issue, particularly relevant to the Australian VAAC, is that the eruptions are often accompanied by deep convective clouds in the moist, conditionally unstable environment of Indonesia. These clouds can produce large quantities of ice that further confound the differential spectral absorption techniques used. For the eruptive events examined here, this is manifest as thick ‘umbrella clouds’ – extensive regions of cold cloud tops that often grow rapidly in area. Detection is delayed until after the ash clouds have thinned out and become semi-transparent to IR radiation or until the upper cloudiness has moved away from the volcano, exposing the thinner lower level ash below the canopy to detection. However, this limitation is not confined to the VOLCAT algorithm examined here; the traditional BTD methodology, which also relies on differential absorption, faces the same issues. Fortunately, these umbrella clouds are often readily identifiable to a human observer, distinguished by their rapid growth rate and/or the unusual timing of the growth. To that end, an experimental ‘Volcanic CB’ algorithm exists (not evaluated here) that algorithmically mimics the human approach that may be beneficial in some cases to the early detection of these clouds.

There is an apparent diurnal cycle in the detection of volcanic ash in the VOLCAT algorithm. In the Merapi and Cordon Caulle cases, detections were clearly better at night, with broader areas detected. There is some non-conclusive evidence of this in the Kelut eruption as well. In part this is due to the diurnal cycle of convection and the increased presence of meteorological clouds in the afternoon. Some of the issue is related to the way the detection algorithm works, particularly with MTSAT, where near-IR channels are used in the daytime, potentially making detection more difficult in the daytime. Himawari-8 will not be as reliant on these channels for detection, and this issue may be reduced or resolved when MTSAT-2 is retired. A similar, possibly related issue are the detections over land and water, as seen in the Cordon Caulle event. Detections over the land only happened after sunset in that case. This latter is perhaps related to the computation of clear-sky radiance and the surface emissivity which plays a crucial role. Surface emissivity values are much more uncertain over land compared to water. These issues could be partially related due to artefacts of the older, less-sophisticated instrumentation on board the MTSAT series of satellites. However, the better MODIS instrumentation also showed hints of these diurnal issues, although those data are too sporadic to fully evaluate the diurnal cycle. MODIS also showed the land/water discrimination in the Cordon Caulle case. Further investigation of these important issues is required.
• There were significant errors in the retrieved ash cloud top height, particularly with the MTSAT instrumentation, where the heights are often much lower than available ground truth data. Further analysis indicated that with this platform, the retrieved ash cloud top heights are directly related to the initial guess for $T_{eff}$, which is related to the pixel brightness temperature. This is due to the lack of the 13.3 µm channel which is available in MODIS. This channel acts to constrain the solution when performing the retrieval for $T_{eff}$, upon which the height is based. Differences were also noted in the heights retrieved using the MODIS data, most obvious when comparing the Aqua and Terra in the Sangeang Api case. In particular, the retrieved heights in Terra appear to be too high in many places and display a large amount of mesoscale variability that is difficult to explain. The source of these differences is not entirely clear in the case of the MODIS data; there are perhaps differences in the viewing angles of the scenes or differences in the calibration that lead to these results. These issues highlight the need to fully evaluate the performance of the height retrieval algorithm with the Himawari-8 data when it becomes available.

• The errors in height retrievals (i.e. the $T_{eff}$) with MTSAT data can also lead to biases in the retrieved microphysical properties, including the mass loading and effective radius. Examination of one scene from two different satellites suggested that while there were biases, the properties of the plume evolved similarly in a qualitative sense. This suggests that the microphysical retrievals may be relatively robust. Considerably more investigation is needed, particularly in cases with some ground truth, to have confidence in these findings.

• Based on comparisons with ash detections from the CALIPSO lidar, there is clearly a lower limit to the retrievals identified by VOLCAT. Detections are most easily made where the ash appears ‘thick’ or has high backscatter on the lidar imagery. Where the layers are thin, and/or with low backscatter, there is often no detection by VOLCAT. Winker et al. [2012] suggested that ash is detectable by CALIPSO at optical depths of 0.01 or less, below levels where differential absorption effects are discernible to satellite [e.g. Pavolonis et al. 2006]. Further, Winker et al. [2012] showed that mass concentrations in these low optical depth clouds was on the order of 0.01 to 0.1 mg m$^{-3}$. Schumann et al. [2011] suggested that aircraft may be able to safely fly in areas with these mass concentrations for at least an hour without engine damage. Hence, while there is some lidar-detectable ash being missed by the satellite retrievals, it may pose minimal risk to aircraft operations. Nonetheless, this lower threshold of detection by VOLCAT needs be established.

Despite these shortcomings, there are many positive benefits with using the VOLCAT algorithm. These include:

• The automated detection works reasonably well in many cases and is on a par with conventional BTD techniques with a human observer. This has enormous potential for managing the higher frequency data expected with Himawari-8, as automatic detection will eliminate the need to manually examine every image.

• In the difficult case of the November 2010 Merapi eruption, ash was detected far over the Indian Ocean several days before warnings were issued by the VAAC for the same area. This highlights the possibility that otherwise undetectable ash could be identified,
particularly in difficult cases, which would allow warnings to be issued in a more timely fashion.

- The provision of quantitative estimates about the ash clouds (height, mass loading and effective particle size) offers significant potential for improvements in dispersion modelling. Although there is a need to further evaluate and refine the estimates, this is sufficient reason to utilize the VOLCAT algorithm. Initializing the dispersion model with the correct height of the ash cloud should provide better solutions to the position of the ash in the future. However, more effort is needed to understand the retrievals for this use.

8. CONCLUDING REMARKS

In this report, the performance of VOLCAT, an automated volcanic ash detection algorithm installed as part of the broader GEOCAT software suite, has been investigated. GEOCAT/VOLCAT is a complex framework for integrating observations from many different geostationary and low-earth orbiting satellite sensors in near-real time. It is currently unique in this capability. With increasing satellite data volumes, near-real time automation is becoming more and more critical to fulfilling the Bureau’s mission to provide timely warnings of volcanic ash hazards to the aviation industry. This software has been implemented as part of the Improved Volcanic Ash Detection and Prediction Project, which aims to improve the operational capabilities of the Australian VAAC. This implementation is a key outcome of this project, as it allows the Bureau the experience to quickly adapt to the influx of data expected with Himawari-8. Further, we have developed some insight into the operation and inner workings of the software, which could (if desired) be exploited to produce a unique Bureau capability for volcanic ash.

This report provides a preliminary evaluation of the software and algorithm for use in the Bureau. It finds that while there are some shortcomings, the software provides a powerful tool for the detection of volcanic ash. It is noted that the system evaluated here represents an earlier version of the software. A newer version, to be implemented operationally, has seen several major improvements. These include: 1.) The detection of volcanic eruptions using vertical growth rate anomalies (i.e. an algorithm to identify volcanic plumes during the initial ‘optically thick’ growth phase); 2.) The use of analyses of earlier images -- regardless of source -- to improve ash detection and cloud property retrievals; and 3.) Greatly improved detection of commonly observed small-scale ash plumes and puffs.

The effort presented here does not necessarily represent a complete evaluation of the software. This work is based on only 4 case studies involving major aviation-related volcanic ash incidents. These events are quite large and represent the ‘high profile’ side of VAAC operations. In many cases, these events are well captured by traditional methods of ash detection and VOLCAT only marginally improves on the detection methods currently available. In these types of cases, the bigger payoff with this software will lie in using the available quantitative information to produce better initializations of dispersion models, presumably leading to more accurate forecasts of future ash position, allowing the aviation industry to better manage its risks to this hazard. A key component for building confidence in this is determining the accuracy of the quantitative information and its uncertainty. Given the sparsity of available ‘ground truth’ information, how this verification is to be done is unclear. What is clear is that the Bureau’s efforts in this regard will need to be as part of the broader international effort. A
second question is how the adaptation of this quantitative information will be done, particularly in an operational environment, given the uncertainties and limitations with the algorithm and its output as identified in this report. Some aspects of this are being covered in other portions of this project, for example through inverse modelling, and these efforts are expected to continue in future projects.

Another challenge for evaluating the algorithm and its performance lies in the detection of the more frequent small and medium eruptions that are often more difficult to identify in a timely manner. These events are more common in VAAC operations. While these events may not have the large-scale, international impact of the major events, they can affect local and regional scale operations. The impression here, from looking at other cases not explicitly mentioned in this report, is that VOLCAT has a more difficult time of these smaller cases. Later versions of the software noted above may rectify some of these issues, but this is not clear, particularly in the tricky operational environment of the Maritime Continent covered by the Australian VAAC.

9. REFERENCES


