

Monitoring Volcanic Eruptions in Indonesia and the Southwest Pacific

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インドネシアと南西太平洋の火山噴火の監視

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要旨

ダーウィン火山灰情報センターにおいて現在実施しているリモートセンシング操作について述べる。担当地域の火山は、2002 年後期に特に活発であり、GMS-5 や NOAA/AVHRR-16, Aqua/MODIS による Raung (インドネシア, ジャワ)や Ruang (インドネシア, Sangihe 島)の衛星画像を示す。また、1999 年パプアニューギニア・ラバウル火山からの‘火山性雷雨’について示す。極軌道衛星のより高い分解能は、小さい噴火の細部の検出に重要であるが、静止衛星の高い時間分解能は、有効な警告サービスのために決定的である。窓分割法は火山灰検出において主要な方法である。GMS-5 は、Ruang の噴火など窓分割法を用いた火山灰の検出に有効である。成層圏の温度逆転や不十分な較正によってもたらされる‘誤報’はダーウィン火山灰情報センターで使っている強調処理法で最小に抑えることができる。極軌道衛星の各スペクトルバンドの利用は、噴煙の性質を理解するのに役立つ。Aqua/MODIS の 0.415 μm 反射バンドは Ruang の噴火を明瞭に検出し、NOAA-16/AVHRR の 1.6 μm バンドは、Ruang の噴煙と氷雲をはっきりと区別した。

Abstract

We briefly describe current operational remote sensing at the Darwin Volcanic Ash Advisory Centre. The region has been particularly active during the second part of 2002, and we show GMS-5, NOAA/AVHRR-16, and Aqua/MODIS data from eruptions of Raung (Java, Indonesia), and Ruang (Sangihe Islands, Indonesia). We also show a possible ‘volcanic thunderstorm’ from Rabaul, Papua New Guinea, in 1999. The higher spatial resolution of polar orbiting instruments is important for examination of eruption details and detection of small eruptions, but the high temporal resolution of geostationary satellites is critical for an effective warning service. The ‘split-window’ method is the primary method of volcanic ash detection. GMS-5 can be effective at detecting ash with the split-window method, particularly in the eruption at Ruang. ‘False alarms’ caused by the stratospheric temperature inversion and poor instrument calibration can be minimised with the enhancement techniques used in Darwin. The availability of more spectral bands in polar orbiting satellites can help us understand the nature of eruption clouds. The 0.415 μm reflective band on Aqua/MODIS observed the Ruang eruption distinctly, and the 1.6 μm band on NOAA-16/AVHRR clearly distinguished the Ruang eruption cloud from glaciated meteorological cloud.

1. Introduction

Volcanic eruptions in the southwest Pacific and Indian Ocean area pose a danger for aircraft because of the hazardous effects of volcanic ash (JOHNSON and CASADEVALL, 1994). Volcanic Ash Advisory Centres issue advisories of volcanic clouds to aviation and meteorological authorities as well as commercial airlines, under the International Airways Volcano Watch (ICAO, 2000). In the western Pacific and eastern Indian Ocean, four Volcanic Ash Advisory Centres are responsible for forecasting the dispersion of volcanic ash cloud (Fig. 1).

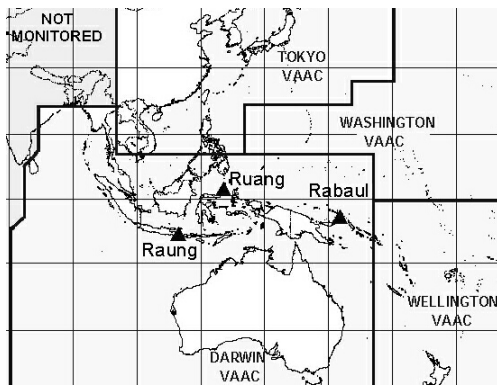


Fig. 1 Boundaries between the areas of responsibility of Volcanic Ash Advisory Centres (VAACs) in the region, after ICAO (2000). The locations of the volcanoes discussed in this paper are also shown.

VAAC 航空路火山灰情報センターの担当地域間の境界 (国際民間航空機関による)。Raung 火山・Raung 火山・Rabaul を▲で示す。

TUPPER and KINOSHITA (2003) describe aircraft and ground observations of volcanic eruptions in the region, the necessity for resourcing ground-based observations, and also show many images of eruptions in the region. Here we explore the operational remote sensing techniques currently used in the Darwin Volcanic Ash Advisory Centre, and show three recent eruptions. Indonesian volcanoes had been relatively inactive since the eruptions of Rinjani (Lombok) and Merapi (Java) in 1994, so the recent activity in the region provides a good opportunity to evaluate current techniques.

2. Satellite observation methods

The ‘split-window’ method (PRATA, 1989a,b) is the primary tool for discriminating volcanic ash from meteorological cloud. The introduction of the GMS-5 satellite in 1995 provided the first opportunity to use this technique on a geostationary platform in the western Pacific. Despite lower resolution and band separation than the NOAA/AVHRR satellites, GMS-5 was shown to have potential for ash discrimination with the Ruapehu eruptions in New

Zealand (POTTS and TOKUNO, 1999). TOKUNO (2000) compared the effectiveness of GMS-5, NOAA/AVHRR, and the (at that stage) forthcoming MTSAT for theoretical cases.

The limitations of the split-window method are well known and are important in the moist tropics (ROSE *et al*, 1995, POTTS and EBERT, 1996, SIMPSON *et al*, 2000, PRATA *et al*, 2001). To supplement the split-window method, visible and infrared imagery is used extensively. The skill of the satellite analysts is extremely important for proper imagery interpretation. The complexity of, and variation between, volcanic clouds has so far precluded the development of a functional, automatic detection system.

The Darwin Volcanic Ash Advisory Centre is co-located with the Darwin Regional Specialised Meteorological Centre in the Bureau of Meteorology's Northern Territory Regional Office. GMS-5 and NOAA/AVHRR data are received locally and displayed using the University of Wisconsin's 'McIDAS' system, which is the standard operational display system in the Australian Bureau of Meteorology.

The implementation of the split-window method at the Darwin Volcanic Ash Advisory Centre has two important features. Firstly, the split-window imagery is combined with infrared imagery to provide a display that shows 'normal' clouds in the standard infrared enhancement, but shows negative brightness temperature differences in varying shades of green to red. Secondly, the tendency of the technique to show false alarms with high tropical thunderstorm tops, due to convection penetrating the tropopause and calibration errors at very cold temperatures (Potts and Ebert, 1996), has been almost eliminated. This is achieved by imposing a more negative detection threshold at very cold temperatures. Ash detection using the split window technique requires semi-transparent cloud that does not have very cold brightness temperatures, so this modification does not reduce the probability of ash detection.

To supplement operational imagery, additional imagery is used for post-analysis, such as SPOT Quicklook data from the CRISP facility (CARN and OPPENHEIMER, 2000), and MODIS and TOMS data from NASA.

3. Examples of operational methodology

3-1. Rabaul, Papua New Guinea, 21 September 1999

One of the difficulties in the tropics is that small eruptions or even just hot volcanoes can interact with the moist atmosphere to produce convective activity, which may or may not

include volcanic ash. OSWALT et al (1996) observed this phenomenon repeatedly during the post-paroxysmal eruptions of Pinatubo in the Philippines in September 1991. Fig. 2 shows a possible example of this at Rabaul in 1999. In this event, the volcano was known to be unusually active, with a vent opening on the Tavurvur cone on 17 September and giving continuous emissions of dark grey ash clouds for the next eight days (SMITHSONIAN INSTITUTION, 1999).

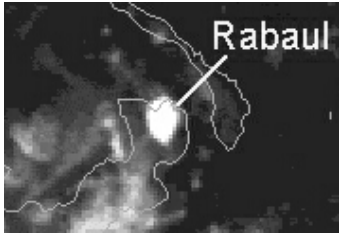


Fig. 2 Possible ‘volcanic thunderstorm’ from Rabaul, Papua New Guinea, GMS-5 IR1, 21 September 1999, 0730 UTC.

パプアニューギニア・ラバウル火山からの‘火山性雷雨’と思われる雲。1999年9月21日0730 UTC(世界時)、GMS-5赤外1バンドの画像。

The cloud in Fig. 2 has the exact appearance of a cumulonimbus. Ash was not detected using the split-window technique, and there were no ground reports of explosions relating to this event. Visual observations of volcanic clouds are always restricted during the night, so the event could not be verified from the ground. The Darwin Volcanic Ash Advisory Centre inferred that the cloud was associated with the volcano based solely on the location of the isolated cloud exactly over Rabaul, and the unusual timing of the thunderstorm.

3-2. Raung, East Java, Indonesia, 25 August 2002

A NOAA-16/AVHRR image of an eruption from Raung is shown in Fig. 3. The eruption generated an ash cloud reported to approximately 30,000 feet (approx. 9000 metres) by an international passenger aircraft.

Height estimation is a critically important factor in understanding the evolution of clouds from each eruption. SAWADA (1987, 2002) has highlighted serious problems in reliable height estimation, and TUPPER and KINOSHITA (2003) give more examples and discuss the reasons for some height estimation errors. It is often problematic to use blackbody temperatures when estimating the height of volcanic clouds (OPPENHEIMER, 1998). Note that observations are usually reported to a round number in the unit that the observer is most familiar with – so aircraft reports will tend to be 15,000, 20,000, 25,000 feet and so on above mean sea level, while volcanological reports might be 500, 1000, 2000, or 5000 metres above the summit height. Often precise eruption heights reported in literature may

be the result of a literal conversion of an approximate measure in another unit. In this case, no ground report of the eruption was made, as the observatory 7 km to the southeast was covered in cloud. The eruption cloud was very dark on visible images (3 a), and moderately cold on infrared imagery (3 b), with a minimum brightness temperature of about 259 °K.

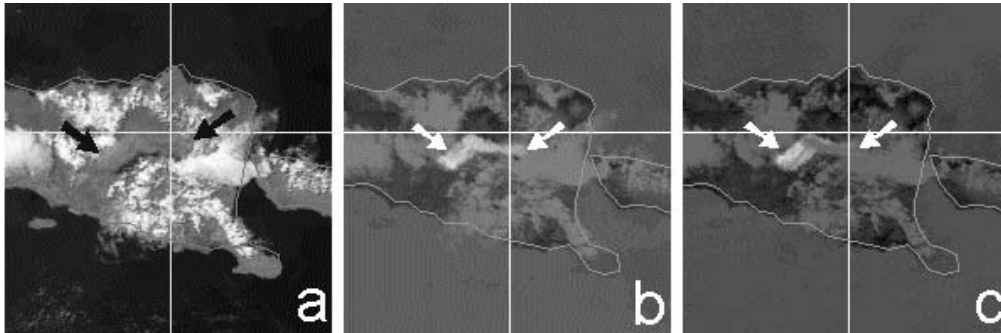


Fig. 3 Eruption of Raung, east Java, Indonesia. NOAA-16 / AVHRR image, 0612 UTC, 25 August 2002. a) Band 2, b) Band 4, c) split-window image, white indicates negative. The right hand arrow indicates the location of the volcano, the left arrow indicates the maximum plume extent at this time. The observatory for this volcano is 7 km to the southeast, covered in cloud.

2002年8月25日06時12分UTC インドネシア・東ジャワの Raung 噴火の NOAA-16 / AVHRR 画像。それぞれ a) 2バンド, b) 4バンド, c) 4バンドと5バンドの差画像(白い部分は負)。各画像中の右側の矢印は火山の場所を示し、左の矢印はこのときの噴煙の最大の広がりを示す。Raung 火山観測所は南東7kmに位置するが、雲に覆われている。

Fig. 3 (c) is a split-window image, with negative 11-12 μm brightness temperature differences ($T(11\mu\text{m})-T(12\mu\text{m})$) shown in grey to white shades. The western part of the eruption cloud shows brightly because it is diffusing, and the split window technique detects the ash easily. Because the cloud is still dense close to the volcano, the split window technique is ineffective and the ash is not detected there (PRATA *et al*, 2001).

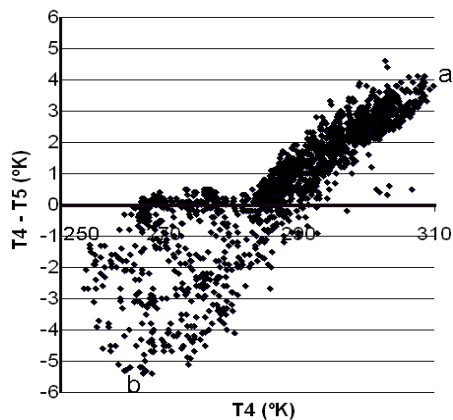


Fig. 4 Scatter diagram over area of Fig. 3. $T(11\mu\text{m})-T(12\mu\text{m})$ is plotted against $T(12\mu\text{m})$. The distinctive 'U' shape of an ash cloud is evident, as is the positive $T(11\mu\text{m})-T(12\mu\text{m})$ bias from low level water vapour.

Fig. 3 に示した地域の、4 バンドー5 バンドの輝度温度差と 4 バンドの輝度温度の散布図。火山灰雲に特有の U の形がはっきりしている。低高度の水蒸気は $T(11\mu\text{m})-T(12\mu\text{m})$ が正の傾向を与える。

'Scatter diagrams' are used in operations in Darwin to examine the results of the split-window method over a suspected eruption cloud (Prata et al, 2001). In Fig. 4, the main body of the ash cloud is visible as a 'U' shaped curve of $T(11\mu\text{m})-T(12\mu\text{m})$, with the strongest difference of -5.5°K (marked with 'b'). At higher temperatures, the effect of absorption by water vapour near the ground is strongly evident (marked 'a') – in fact the positive difference of $T(11\mu\text{m})-T(12\mu\text{m})$ is commonly used to estimate the amount of water vapour in the atmosphere. The operational use of scatter diagrams enables instant diagnosis of the effect that water vapour is having upon volcanic ash detection (Prata et al, 2001). Examination of the diagram also suggests that a representative black body temperature to use for the cloud top would be about 255°K , consistent with an altitude of approximately 7500 metres based on temperature sonde data.

3-3. Ruang, Sangihe Islands, Indonesia, 25 September 2002

This eruption has many interesting aspects that are under investigation. TUPPER and KINOSHITA (2003) noted how well the dispersing ash and gas clouds were observed by the MODIS instruments, and also discussed the difficulty of ground based height estimation for this eruption. Fig. 5 a) shows another interesting MODIS observation, from the Aqua/MODIS pass over the young eruption cloud. The cloud has a low albedo in all of the visible bands on MODIS, to varying degrees. However, in the $0.415\ \mu\text{m}$ band, normally used for ocean colour measurement, all clouds in the surrounding area appear quite saturated, giving a very high contrast with the eruption cloud. The response in this band will be worth exploring for other eruptions, although if it only occurs for clouds with an obviously low albedo in other visible channels, then it will have limited operational benefit. Fig. 5 b) is a NOAA-16 pass over the eruption cloud shortly afterwards, shown with channel 3A ($1.6\ \mu\text{m}$), which is normally used for snow and ice discrimination. This band is already known to be useful for plume identification (KINOSHITA *et al*, 2002). In the figure some of the many glaciated thunderstorm clouds are marked with arrows, and all appear dark coloured because of the response of the channel to the ice in the clouds. The eruption cloud, however, actually shows brighter in the central and highest part, although slightly darker around the edges where it is thought there is a higher ice content. Using this channel, we may be able to objectively measure the relative ice content in the tops of optically thick eruption clouds.

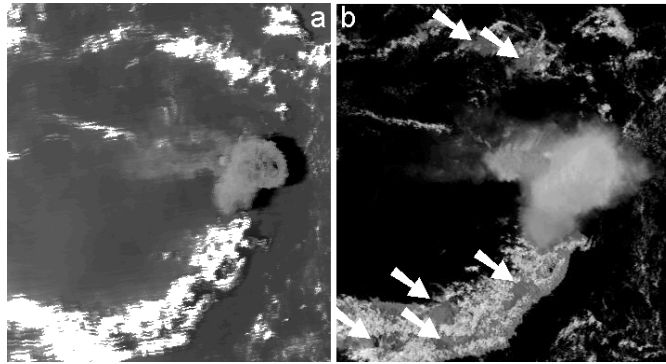


Fig. 5 The eruption of Ruang, seen in a) 0.415 μm band of Aqua/MODIS at 0450 UTC, 25 September 2002, and b) NOAA-16/AVHRR 3A (1.6 μm) at 0531 UTC, 25 September 2002. Glaciated thunderstorm clouds, appearing dark, are indicated by arrows in b).
 2002年9月25日の Ruang 噴火。a) 0450 UTC の Aqua/MODIS (0.415 μm)による画像、b) 0531 UTC の NOAA-16/AVHRR (3A 1.6 μm). b)では矢印で示すように、氷粒の雷雲は暗く見える。

An abbreviated GMS-5 sequence from the eruption is shown in Fig. 6. The enhancement shown here is the operational infrared and split-window enhancement discussed earlier. In the greyscale reproductions, a weak split window signal appears white and a strong signal appears dark grey. Five different levels of cloud are shown here, with ‘A’ lowest (near ground level) and ‘E’ highest (perhaps over 20 km high). In visible imagery, the ‘A’ level can be subdivided further with a sheared, bifurcating plume evident before the major eruption. The speed of movement varies from approximately 60 km/h towards the west for the ‘B’ level cloud in the mid-troposphere, to 60 km/h eastwards for the ‘E’ plume which is presumed to be moving with stratospheric winds. The ‘D’ level cloud, probably at just above tropopause height, is drifting slowly westwards with an average speed of 9 km/h.

The ‘B’ and ‘D’ clouds give very strong ash responses in the split window algorithm. ‘A’ is small and low and is not detected, and ‘C’ appears to be a shallow cloud with high ice content as well as ash, with no ash detected using the split-window algorithm. ‘E’ is thought to have contained SO_2 (from GOME imagery, <http://www-iup.physik.uni-bremen.de/gomenrt/>), but ash was not detected with the split window algorithm. TOMS imagery detected SO_2 and ash from the westward moving clouds, but not cloud ‘E’ (S. Carn, personal communication). In operational work, all volcanic clouds are assumed to contain ash, but certainly in this case the movement of the ‘B’ and ‘D’ clouds determined the main warning strategy.

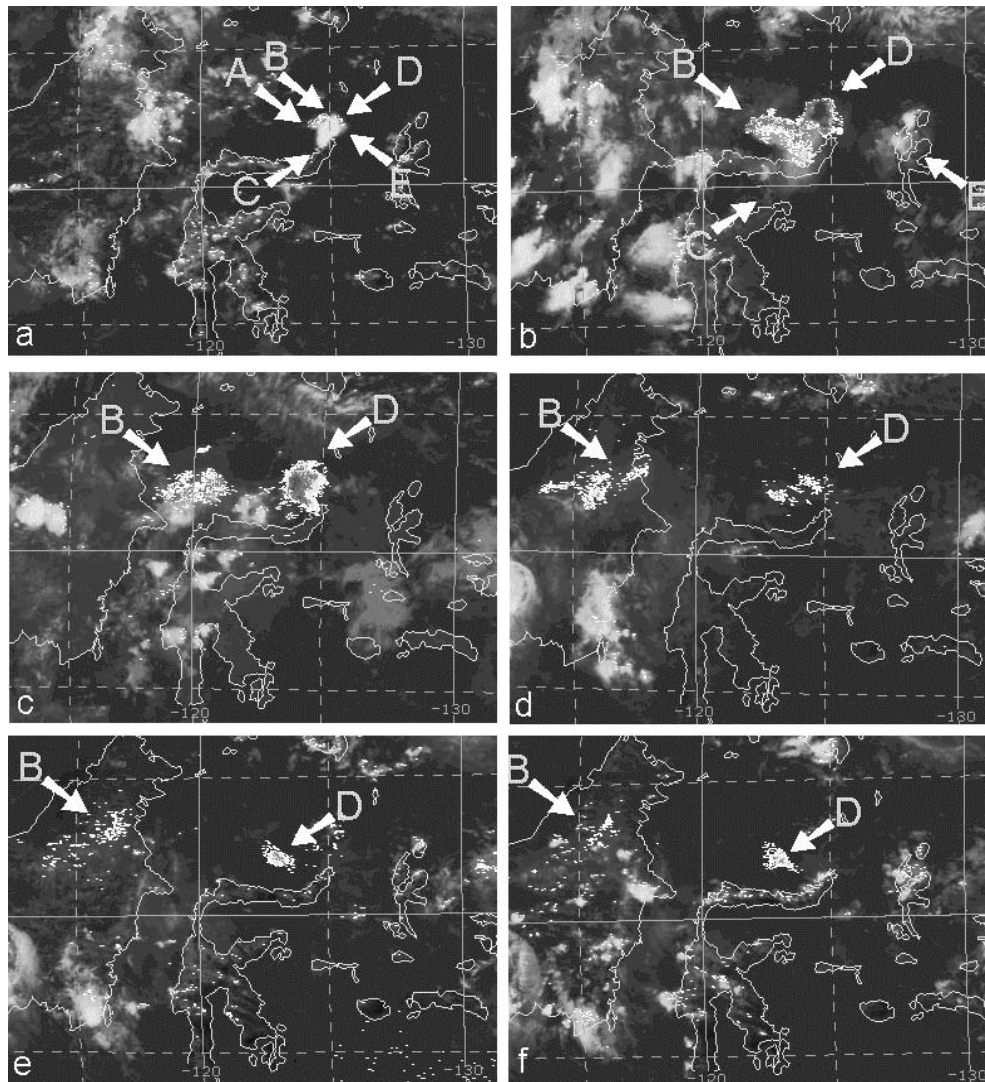


Fig. 6 GMS-5 images of the Ruang eruption, with frames a-c at 0545 UTC, 1040 UTC, and 1640 UTC respectively on 25 September 2002, and frames d – f at 0045, 0440, and 0640 UTC on 26 September 2002. This is the combined IR / Split-window enhancement from Darwin Volcanic Ash Advisory Centre, shown in greyscale. Five different altitudes of eruption cloud are identified here, with ‘A’ lowest and ‘E’ highest.

Ruang 噴火の GMS-5 画像。a~c は 2002 年 9 月 25 日の 0545・1040・1640 UTC であり、d~f は 2002 年 9 月 26 日の 0045・0440・0640 UTC である。これはダーウィン火山灰情報センターによる赤外と split-window 法を組み合わせ強調の、グレースケール表示である。ここで噴煙の高さは、最も低い A から最高の E まで 5 段階で区別されている。

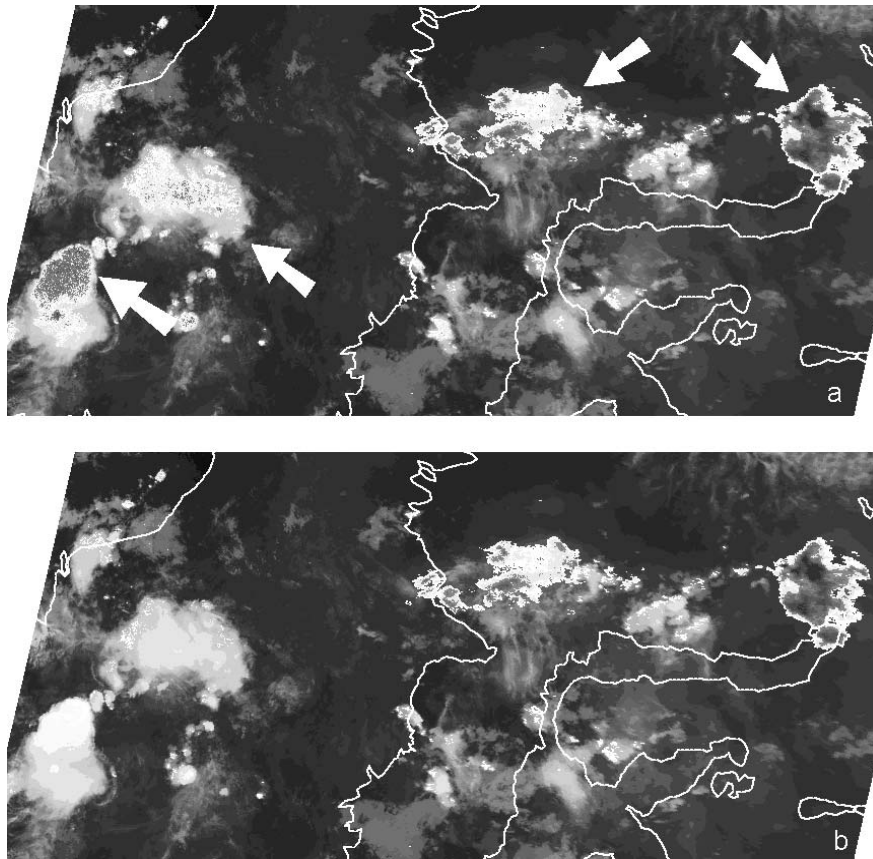


Fig. 7 NOAA-16/AVHRR image from 1830 UTC, 25 September, 2002, showing Ruang eruption clouds and 'false alarms'. Frame a) shows the combined IR / split-window without filtering out false alarms. The ash clouds are arrowed on the right, and the 'false alarms' are arrowed on the left. Frame b) shows the same image after filtering for false alarms.

Ruang 火山の噴煙と"誤報"を示す 2002 年 9 月 25 日 1830 UTC の NOAA-16/AVHRR 画像。
 a) 誤報除去のフィルターをかけていない、赤外と split-window 法を組み合わせた画像。右側の矢印は火山灰雲で、左側は誤報。b) は誤報除去フィルターをかけたもの。

Fig. 7 shows the 1830 UTC NOAA-16 pass over the area, with two slightly different enhancements shown. Fig 7 a) is the infrared / split-window combination previously used at Darwin Volcanic Ash Advisory Centre, without the filtering of false alarms from high meteorological cloud tops. The deep convection on the left of the image erroneously shows ash in the central, cold areas. Fig 7 b) is the same area after cold cloud false alarms are filtered out. The area identified as ash in the known volcanic clouds has not changed, but the thunderstorm tops now appear normally.

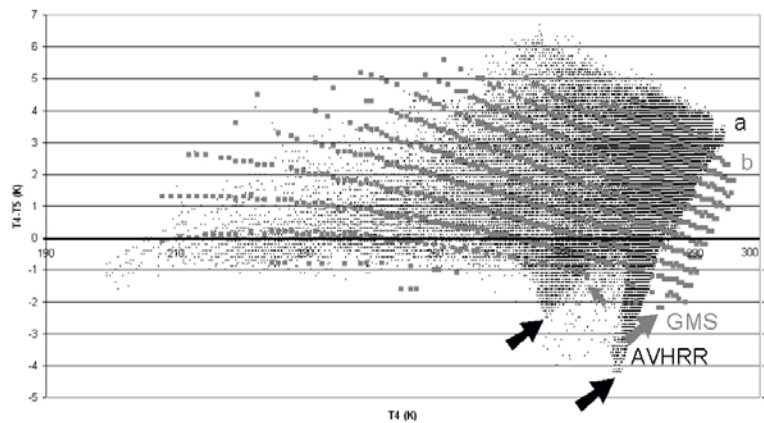


Fig. 8 Scatter diagrams as in Fig.4 for NOAA-16/AVHRR, 1830 UTC, (black, small dots), and GMS-5, 1840 UTC 25 September 2002 (grey, large dots), over the region of the eruption and the surrounding meteorological clouds. The arrows indicate diagram features characteristic of volcanic ash clouds.

2002年9月25日のNOAA-16/AVHRR(1830 UTC, 黒点で示す)とGMS-5(1840 UTC, 灰色の大きなドットで示す)の、噴煙と周囲の氷雲の地域について、図4と同様の散布図。矢印の部分は火山灰雲に独特なグラフの特徴を示している。

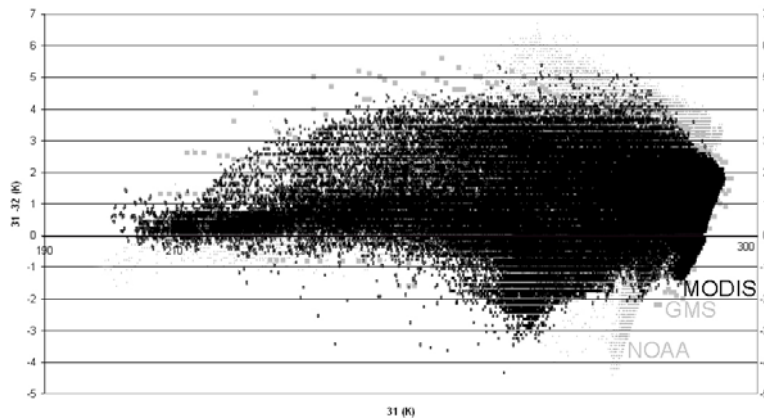


Fig. 9 Scatter diagram for Aqua/MODIS, 1710 UTC, 25 September 2002, over a similar area to Fig. 8, and overlaid (in black) on the data from Fig. 8 (in grey).

2002年9月25日のAqua/MODIS 1710 UTCの散布図を図8と同様な地域の散布図を黒く表示し、図8を灰色について重ねたもの。

Fig. 8 is a scatter diagram for the area, with the NOAA-16 data in black, and the lower resolution GMS-5 data overlaid in grey. Both satellites identify the ash clouds (arrowed) very well. The AVHRR data has a higher water vapour response (a) than GMS-5 (b), which is expected because the two infrared channels have greater separation on AVHRR. The calibration problems at cold temperatures are evident from the negative values near 210 °K.

Fig. 9 is another scatter diagram of Aqua/MODIS data from 80 minutes earlier, using the 11 and 12 μm channels. The MODIS channel response is not quite equivalent to the AVHRR channels. $T(11\mu\text{m})-T(12\mu\text{m})$ for MODIS data also appears to be less negative than AVHRR for very cold temperatures.

4. Discussion and Conclusions

The performance of the split window technique using GMS-5 during the eruption of Ruang in particular, illustrates how important geostationary instruments are for Volcanic Ash Advisory Centre operations. The relatively high temporal resolution allows the tracking of rapid cloud evolution, and more than compensates for the reduced sensitivity of the instrument. With careful application of the split-window algorithm, false alarms can be minimised, and meteorologists can use their skills in satellite analysis to identify volcanic clouds not identified by the split-window algorithm. Thorough training of meteorologists in volcanic cloud identification and behaviour is very important to support operational work.

Smaller eruptions can only be effectively observed by higher resolution, high temporal resolution satellites. The need for high temporal resolution exists mainly in the close vicinity of the volcanoes, as older, drifting ash clouds usually evolve slowly compared to fresh eruption cloud. During the night or in cloudy conditions, many small eruptions will not be identified using current meteorological satellite systems, and ground based observations are the only effective way to warn for ash cloud. ‘Volcanic thunderstorms’ will also be difficult to identify in most circumstances.

Height measurement of volcanic clouds remains a difficult and important issue.

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