Satellite observations of Mt Pinatubo ash clouds

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Satellite imagery currently available from the Japanese Geostationary Meteorological Satellite (GMS) is of great benefit to operational meteorologists responsible for the provision of warnings for volcanic ash clouds for aviation in the Asian region. However, on visible and single channel infrared satellite data it is frequently not possible to discriminate volcanic ash clouds from water/ice clouds. This is a particular problem in the volcanically active southeast Asian region where there is a high frequency of thunderstorms which can produce extensive areas of cloud. It has previously been demonstrated that National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) satellite data can be used to improve the discrimination of volcanic ash clouds from water/ice clouds. This is based on identification of areas where the brightness temperature difference, T(10.8 μm)−T(11.9 μm), is negative. In a study of GMS and AVHRR satellite data for the Mt Pinatubo eruptions of 12 June 1991 this paper confirms the operational availability of AVHRR data should enable a significant improvement in our ability to identify volcanic ash clouds.

Introduction

A major responsibility for operational meteorologists is the provision of forecast and warning services for the aviation industry. This now includes warnings for volcanic ash clouds. Since 1982, when two Boeing 747 aircraft encountered volcanic ash clouds over Indonesia from Mt Galunggung (Hanstrum and Watson 1983), the hazard presented to aircraft from such clouds has been well recognised. Both aircraft suffered engine failure and severe damage to wings and fuselage and were forced to make emergency landings at Jakarta.

If notification of a volcanic eruption is received and little or no cloud is present in the area it is possible to identify the eruption plume on visible and infrared satellite imagery. The horizontal extent of the resultant ash cloud can then be monitored and by assuming the ash cloud radiates as a black body the cloud-top height can be estimated. With knowledge of the upper winds it is further possible to determine the direction in which the cloud will be dispersed. Hanstrum and Watson (1983), Matson (1984), Prata et al. (1985) and Malingreau and Kaswanda (1986) all describe cases where satellite imagery and upper wind data have been useful for describing the location and movement of volcanic ash clouds. The techniques described in these reports are used in the operational warning services provided by meteorological authorities. In the Asian region the hourly satellite data currently available from the Japanese Geostationary Meteorological Satellite (GMS) are of considerable benefit to operational meteorologists responsible for the provision of volcanic ash cloud warnings for the aviation industry.

The discrimination of volcanic ash clouds from water/ice clouds on visible and single channel infrared satellite data is often difficult. This is a significant problem in the volcanically active Asian region where there is a high frequency of thunderstorms which can develop rapidly to great heights and produce extensive areas of cloud. In an examination of GMS images over the Asian region for the period 1977–1985, Sawada (1989) was able to detect an eruption cloud for only 14 per cent of a total of 227 volcanic eruptions, although all strong eruptions where the ash cloud reached higher than 10 km were detected. The cruise altitude of most passenger aircraft is in the range 7.5–13 km and so it is the stronger eruptions that are of primary concern. The Australian Bureau of Meteorology provides a Volcanic Ash Cloud Advisory Service for areas to the near-north of Australia which relies on identification of
the ash cloud on GMS imagery following notification of an eruption or report of an ash cloud. For the period 1985–1990 it was possible to identify an ash cloud on GMS imagery in only 20 per cent of cases (Potts and Whitby 1993).

Several studies have shown that Advanced Very High Resolution Radiometer (AVHRR) data from National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites can improve the discrimination of volcanic ash clouds from water/ice clouds (Hanstrum and Watson 1983; Prata 1989a; Prata 1989b; Holasek and Rose 1991; Barton et al. 1992). Prata (1989a and 1989b) and Barton et al. (1992) distinguish ash clouds by identifying areas where the brightness temperature difference $T(10.8 \mu m) - T(11.9 \mu m)$ is negative. Holasek and Rose (1991) use a ratio of raw AVHRR Channel 4 (10.8 $\mu m$) and Channel 5 (11.9 $\mu m$) counts to monitor the movement of ash clouds from the 1986 Augustine eruption. Although Holasek and Rose were able to effectively discriminate the ash cloud, their approach made no allowance for the non-linear response characteristics of the radiometer which can introduce corrections of 3K or more to the observed brightness temperatures for each channel (Weinreb et al. 1990).

The availability of real-time AVHRR data to operational meteorologists in the Australasian region is increasing and hence the feasibility of using these data for the provision of operational warnings for volcanic ash clouds is also increasing. The operational utility of these data is yet to be evaluated and further studies of eruption events are required. This paper examines the utility of GMS and AVHRR satellite data for the detection and monitoring of volcanic ash clouds from the initial Pinatubo eruptions of 12 June 1991.

The detection of volcanic ash clouds on AVHRR satellite data

NOAA AVHRR data are recorded at the visible wavelengths 0.58–0.68 $\mu m$ (Channel 1), and 0.725–1.1 $\mu m$ (Channel 2); and the infrared wavelengths 3.55–3.93 $\mu m$ (Channel 3), 10.3–11.3 $\mu m$ (Channel 4), and 11.5–12.5 $\mu m$ (Channel 5). The resolution at the satellite sub-point is 1.1 km for both the visible and infrared data.

For the infrared channels the noise equivalent differential temperature (NE$\Delta T$) is 0.12K at 300K. For the infrared channels the radiance $R_{i}$ measured in a narrow band centred on wavelength $\lambda_{i}$ for a uniform cloud layer overlaying a non-reflecting surface, assuming no scattering and no angular dependence, can be approximated by:

$$R_{i} \approx (1 - \varepsilon_{i})B_{i}(T_{c}) + \varepsilon_{i}B_{i}(T_{e})$$

where $(1 - \varepsilon_{i})$ and $\varepsilon_{i}$ are the transmissivity and emissivity for the cloud, $B_{i}(T)$ is the Planck function, $T_{c}$ is the cloud-top temperature and $T_{e}$ is the temperature of the surface (Prata 1989a and 1989b). The brightness temperature of the cloud is calculated from the radiance assuming blackbody radiation (i.e. $\varepsilon_{i} = 1.0$). If the cloud is optically thick ($\varepsilon_{i} < 1.0$), the brightness temperature provides a good estimate of the cloud-top temperature. Alternatively, for an optically thin ($\varepsilon_{i} < 1$) cloud overlying a relatively warm surface the brightness temperature will be warmer than the true cloud-top temperature. In practice $\varepsilon_{i}$ is a function of $\lambda$ in addition to the microphysical and chemical properties of the cloud and since $\varepsilon_{i} < 1$ always, then the observed brightness temperature will depend on the wavelength at which it is measured. Consider then the brightness temperature of a cloud of given optical depth, observed by satellite and measured at $\lambda_{1}$ and $\lambda_{2}$ where $\lambda_{1} < \lambda_{2}$. From Eqn 1 it follows that if $\varepsilon_{1} < \varepsilon_{2}$, then $T_{1} > T_{2}$ where $T_{i}$ is the brightness temperature in channel i. Conversely, if $\varepsilon_{1} > \varepsilon_{2}$, then $T_{1} < T_{2}$.

In the atmospheric window region (10–12 $\mu m$) the emissivity for water/ice clouds increases with wavelength such that $\varepsilon(10.8 \mu m) < \varepsilon(11.9 \mu m)$. Consequently for a thin cloud overlying a warmer surface, the difference in brightness temperature, $\Delta T$, between Channel 4 (10.8 $\mu m$) and Channel 5 (11.9 $\mu m$), where $\Delta T = T_{4} - T_{5}$, will be positive (Inoue 1985; Yamanouchi et al. 1987).

The composition and evolution of volcanic plumes following an eruption are variable and complex (Hobbs et al. 1981; Inn et al. 1981), and consequently the variation of $\varepsilon_{i}$ with wavelength is difficult to evaluate. In general the volcanic plume contains a large percentage of silicates, SO$_{2}$ and water vapour. The SO$_{2}$ is converted to sulphuric acid photochemically, with an e-folding time (1/e decrease in total load) of the order of a month (Pinto et al. 1989; Bluth et al. 1992; Hoff 1992). The concentration and size distribution of particulates vary considerably with time due to changes in the emissions together with subsequent dispersion, deposition, coalescence and precipitation scavenging. Studies by Chuan et al. (1981) of aerosols from the Mt St Helens eruptions of 1980 showed that in the eruption cloud immediately above the crater, over 90 per cent of the mass had radius larger than 10 $\mu m$ and it was essentially monomodal. Further from the volcano the size distribution is such that there may be more than one modal maximum, typically with radius in the range 0.1–10 $\mu m$ (Chuan et al. 1981; Farlow et al. 1981; Knollenberg and Huffman 1983; Valero and Pilewskie 1992). Larger particulates will settle within hours or days while the e-folding time for submicron-sized particles in the stratosphere is 6–12 months (Hofmann and Rosen 1984). The greatest hazard to aircraft occurs within the first few hours when the ash concentration is high.
Potts: Satellite observations of Mt Pinatubo ash clouds

GMS observations of Mt Pinatubo ash clouds

The Japanese GMS visible and infrared spin scan radiometer (VISSR) collects data in one visible channel (0.5–0.75 μm) and one infrared channel (10.5–12.5 μm). The resolution at the satellite subpoint for the visible data is 1.25 km while the resolution for the infrared data is 5.0 km. The NEΔT for the infrared sensor is 0.5K at 300K increasing to 1.5K at 220K. Both visible and infrared data are available hourly.

Figure 1 shows a series of GMS infrared images over the South China Sea covering the period 0130 UTC to 1623 UTC, 12 June 1991. There was relatively little water/ice cloud over the area and in Fig. 1(a) the volcanic ash cloud associated with the initial eruption at 0051 UTC is clearly evident.

Following the eruption the ash cloud drifted to the west and southwest and gradually dispersed, becoming elongated in a northeast–southwest direction as it moved. By 1623 UTC the ash cloud from the initial eruption is quite thin and the boundaries are difficult to discern from the GMS imagery. Near 11°N, 111°E, the ash cloud has moved into an area of water/ice cloud and it is not possible to discriminate the ash cloud. The hazard presented to aircraft when the ash cloud has dispersed to such an extent is unknown and this is an area that requires further study.

On this day there was a second major eruption of Mt Pinatubo at 1450 UTC. There was significant thunderstorm activity over Luzon at this time and it is not possible to discern the ash cloud associated with this eruption from the storm clouds in the GMS image (Fig. 1(d)). This highlights the difficulty in discriminating volcanic ash clouds from water/ice clouds on single channel infrared satellite imagery as little useful advice concerning the location of the ash cloud could be provided to aircraft based on this image.

Assuming the ash cloud radiates as a black body and the temperature of the cloud quickly reaches equilibrium with the environment, the cloud-top height can be estimated. From the satellite-derived brightness temperature and the 0001 UTC vertical temperature sounding from the nearby Clark Air Force Base, the cloud top in Fig. 1 is between 130 and 100 hPa (15–16 km). For the period shown the highest levels of the ash cloud from the eruption at 0051 UTC moved to the southwest at approximately 15–20 m s⁻¹, consistent with upper wind analyses. Figure 1(c) shows the ash cloud has become elongated in a northeast–southwest direction. The ash cloud in the northeast has a top around 500 hPa (∼5.6 km) and moved west at approximately 6 m s⁻¹, also consistent with upper wind analyses.

Prata (1989b) calculated extinction coefficients for model ash clouds comprising volcanic pumice, quartz, sulphuric acid, acid coated particles and a mixture of acid coated particles and ice. Log-normal and modified gamma size distributions were assumed with modal maxima for radius in the range 0.2 μm to 100 μm. These showed that for ice-free ash clouds with particles of mean radii less than 3 μm the extinction coefficient β(10.8 μm) > β(11.9 μm) and hence emissivity ε(10.8 μm) < ε(11.9 μm). Consequently ΔT will be negative. Conversely for mean radii equal to or greater than 3 μm then ΔT will be positive. As the fraction of ice in the cloud increases then ΔT tends more positive.

It is clear that the microphysical properties of any ash cloud are critical to the observed value of ΔT. Nevertheless, the identification of areas where ΔT < 0 should significantly improve the discrimination of ash clouds from water/ice clouds when compared to visual inspection of single channel satellite imagery.

Pinatubo eruption

After a relatively short period of increasing seismicity, deformation and emission of small plumes, Mt Pinatubo (15.1°N, 120.3°E) on Luzon, the main island of the Philippines, erupted violently at 0051 UTC on 12 June 1991, sending a tephra column to around 20 km. This initial eruption was the start of an active phase which culminated with the climactic eruptions of 15 and 16 June when the eruption column reached altitudes around 40 km. Following the climactic volcanic episode of 15–16 June the activity of Mt Pinatubo gradually decreased (Wolfe 1992).

The social impact of the Pinatubo activity was devastating and it was further exacerbated by heavy rain and strong winds from typhoon Yunya which crossed Luzon on 15 June. There were over 700 deaths and major property losses from the eruption, the associated pyroclastic flows and from lahars in the period following the eruption (Smithsonian Institute 1991a).

There was also considerable disruption to aircraft operations in the region during the active volcanic period. Manila Airport was closed for several days and a number of aircraft were stranded at the airport unable to depart because of the risk of ash ingestion into jet engines. Clouds of volcanic ash from successive eruptions of Pinatubo moved across the South China Sea and over Vietnam with the resultant closure of several air routes.

A total of 15 aircraft suffered damage to varying degrees from the ash, primarily from the climactic eruption of 15–16 June (Smithsonian Institute 1991b). Fortunately, there was no loss of life from any aircraft encounters with the ash cloud but the damage costs were considerable.
AVHRR observations of Mt Pinatubo ash clouds

For this study NOAA 11 AVHRR full resolution Local Area Coverage (LAC) data in 1B format (Kidwell 1991) were obtained from the NOAA National Environmental Satellite, Data and Information Service (NESDIS) and converted to McIDAS format (LeMarshall et al. 1987) for analysis. The infrared channels (Channels 3–5) are calibrated in-flight with data acquired when the AVHRR views space and an internal calibration target. This determines two coefficients of a linear calibration equation and enables the calculation of radiance for the earth view. The brightness temperature is then calculated from the inverse Planck function (Kidwell 1991). A further correction to the brightness temperature is required as the response of the AVHRR is non-linear for Channels 4 and 5 and this can result in errors in excess of 3K in scene temperature (Weinreb et al. 1990).

Figure 2(a) shows a NOAA 11 AVHRR Channel 4 image of the ash cloud at 0600 UTC, 12 June and Fig. 2(b) shows AT for the same time with positive differences coloured blue and negative differences coloured red. The temperature range extends from $-10$K to $+15.5$K. The ash cloud is largely associated with negative differences except for the region in the southwest where the ash cloud is coldest and thickest. Remaining areas of the image, showing water/ice clouds, sea surface and land show positive differences which vary from 0K to $+12$K.

The area A shown in Fig. 2(a) encloses an area $41 \times 41$ pixels which includes both water/ice clouds and sea surface. For each element within the area $AT$ was determined and plotted as a function of $T4$ on a scatter diagram (Fig. 3). This shows differences of $+1$ to $+9$K and has an arch shape similar to that reported by Inoue (1985) and Yamanouchi et al. (1987). The warmest pixels, where $T4 \approx 294$K, are associated with the sea surface and the positive values for $T4-T5$ can be
Fig. 2  NOAA 11 AVHRR image for 0600 UTC, 12 June 1991, showing Mt Pinatubo ash cloud. (a) Shows infrared Channel 4 image while (b) shows ΔT(T4–T5). For the area coloured red ΔT is negative and for the area coloured blue ΔT is positive. Temperature scale extends from −10K to +15.5K. Latitude and longitude grid at 2 degree intervals. (See text.)
largely attributed to atmospheric moisture (McClain et al. 1985). The coldest pixels, where T4 ≈ 230K, are associated with the coldest and thickest regions of cloud. Extensive thick clouds will tend to act as a black body and ΔT will tend towards zero. Intermediate values for T4 are associated with pixels covered by semitransparent cloud or with fractional cloud cover and are associated with larger values for ΔT.

The area B shown in Fig. 2(a) encloses an area of the ash cloud and a scatter plot of ΔT vs T4 shows differences of −2 to −12K, (Fig. 4) with an arch shape similar to that expected from Prata (1989b). The coldest values for T4 will be associated with the coldest, thickest areas of the ash cloud within area B while the warmer temperatures may have a warm bias due to the transmission of radiation from the surface or from lower regions of the cloud.

For the coldest and thickest region of the ash cloud (Fig. 2(a), area C) the effective cloud-top temperature is in the range 194 to 204K. Examination of visible imagery suggests the ash cloud is quite thick in this area and the measured temperature should be a reasonable estimate of the actual temperature. The difference ΔT is in the range +1 to −0.8K (Fig. 5). There are a number of possible reasons for the small positive differences observed rather than negative differences. Prata (1989b) showed that for an ash cloud comprising large particles of pumice or quartz and large sulphuric acid coated pumice particles, that ΔT may be positive. Also there may be ice within this area of the ash cloud. This would be associated with a positive difference and may cancel any small negative difference associated with ash particles (Prata 1989a). At temperatures less than 200K non-linearity corrections to the derived brightness temperatures are not well known and these may be significant when measuring small temperature differences between Channels 4 and 5.

Figure 6(a) shows the NOAA 11 AVHRR Channel 4 image for 1830 UTC, 12 June 1991, and Fig. 6(b) shows the corresponding image for ΔT with negative differences coloured red. The area of thunderstorms immediately west of Luzon shows negative differences within. As discussed earlier the second eruption of Mt Pinatubo occurred at 1450 UTC when this area of thunderstorms was over the volcano. In the coldest area of the cloud, the effective brightness temperature is in the range 195 to 205K and ΔT is in the range −0.5 to −2.5K. The negative differences suggest the presence of volcanic ash within and near cloud top.

West of 115°E the ash cloud from the initial eruption at 0051 UTC is well dispersed and not clearly visible. From GMS imagery the ash cloud extends from 11°N to 16°N. In Fig. 6(b) only the area near 14°N, 112°E, shows negative ΔT. The scatter diagram of ΔT vs T4 for this area (Fig. 6(a), area A) shows T4 is in the range 266 to 286K and ΔT has negative differences to −2.5K (Fig. 7).

As previously discussed, the GMS imagery showed the main area of the ash cloud moved over an area of water/ice clouds near 11°N, 111°E, and was quite thin. Figure 6(b) shows ΔT is positive in this area suggesting the expected negative differences associated with the ash are cancelled by the positive differences associated with the water/ice clouds.
Fig. 6  NOAA 11 AVHRR image for 1836 UTC, 12 June 1991, showing Pinatubo ash cloud. (a) Shows infrared Channel 4 image while (b) shows ∆T. For the area coloured red ∆T is negative and for the area coloured blue ∆T is positive. Temperature scale extends from −10K to +15.5K. Latitude and longitude grid at 2 degree intervals. (See text.)
more, for the area associated with Fig. 8 it is suggested that the positive differences associated with the atmospheric moisture are greater than the negative differences associated with the ash cloud. The change to $\Delta T$ due to the presence of volcanic aerosols has in fact been responsible for negative biases of sea-surface temperatures derived from AVHRR satellite data (McClain et al. 1985; Walton 1985).

Although the discrimination of volcanic ash cloud from water/ice clouds can be improved by identifying areas where $\Delta T$ is negative on NOAA AVHRR imagery, Figs 2 and 6 also show that further research is warranted before this can be done uniquely. When the ash cloud is very thin, small negative differences can be overcome by positive differences associated with underlying water/ice cloud or atmospheric moisture. The hazard which such a thin ash cloud presents to aircraft is unknown at this time. Also, when large ash particles or ice are present in the cloud, $\Delta T$ may be positive. Presumably in most such cases, areas where $\Delta T < 0$ will be observed in the vicinity which will alert those responsible for the preparation of warnings.

In the equatorial regions the ground track of the NOAA polar-orbiting satellites and the scan width of the AVHRR sensor is such that with two satellites there are only four scans per day at intervals of approximately six hours for any given location. This limits the operational utility of AVHRR data as an ash cloud can move a considerable distance in this time.

Despite these limitations, the NOAA AVHRR data currently available should be a valuable complement for the hourly GMS imagery and facilitate a significant improvement in the current ability to identify volcanic ash clouds.

Moreover, the geostationary satellite GMS5 due to be launched in 1995 will have two split window channels and 11 $\mu$m and 12 $\mu$m data will then be available hourly. If the available data are sufficiently accurate to detect small temperature differences between these channels at the cold brightness temperatures observed near cloud top, these data should prove most beneficial.

**Conclusion**

Volcanic ash clouds present a significant hazard to aircraft and appropriate warnings of such clouds must be provided to the aviation industry in a timely manner by meteorological authorities. Satellite imagery enables the movement of ash clouds to be monitored and if it is assumed the ash cloud radiates as a black body, estimates of the cloud top can be made. Single channel visible and infrared imagery available hourly from GMS is of great benefit to operational meteorologists responsible for the provision of warnings for vol-
canic ash clouds in the Asian region. However, in this volcanically active region there is also a high frequency of thunderstorms and on present GMS satellite imagery it is frequently not possible to discriminate volcanic ash clouds from water/ice clouds.

This study examines the utility of NOAA AVHRR infrared satellite data for discriminating the volcanic ash clouds emitted by Mt Pinatubo on 12 June 1991. It is shown that volcanic ash clouds can be discriminated from water/ice clouds by identifying areas where ΔT is negative on the AVHRR imagery. When the ash cloud is well dispersed, small negative differences can be cancelled by positive differences associated with underlying water/ice clouds or atmospheric moisture. The hazard which such a dispersed ash cloud presents to aircraft is unknown and warrants further study. Also ΔT may be positive when the ash cloud contains a significant proportion of water and ice or immediately after an eruption when large particles may be present in some parts of the cloud. Presumably in such cases, areas where ΔT is negative will be observed in the vicinity which will alert operational meteorologists responsible for the preparation of warnings.

Although AVHRR data are currently only available at intervals of approximately six hours in equatorial regions, these data should complement current hourly GMS imagery and enable a significant improvement in the current ability to identify volcanic ash clouds. Moreover, the implementation of appropriate systems at satellite data receiving stations located in high risk areas would enable largely automated, near real-time monitoring for ash clouds. With the recent installation of AVHRR receiving stations in Darwin, Australia, and Manila, Philippines, there is now full coverage over the volcanically active Asian region. These data should be made available in real time to operational meteorologists responsible for the provision of warnings for volcanic ash clouds.

Furthermore, the geostationary satellite GMS5 due to be launched in 1995 will have two split window channels and 11 μm and 12 μm data will then be available hourly. If the available data are sufficiently accurate to detect the small temperature differences between these channels at the cold brightness temperatures observed near cloud top, these data should prove most beneficial.

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References


