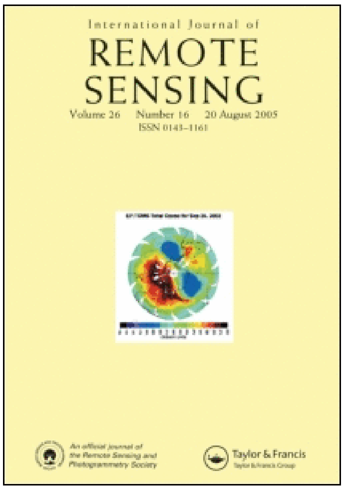

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Experiences from near-real-time satellite-based volcano monitoring in Central America: case studies at Fuego, Guatemala

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Over the past decade, remote sensing has been used increasingly in the study of active volcanoes and their associated hazards. Ground-based remote sensing techniques, such as those aimed at the analysis of volcanic gases or fumarole temperatures, are now part of routine monitoring operations with additional satellite-based remote sensing methods. It is likely that the use of satellite-based systems will be most beneficial for volcano monitoring in developing country regions and remote areas. In such situations, an operational real-time satellite remote sensing system could provide rapid assessment of volcanic activity levels and potentially be used to derive crucial information for disaster prevention. This would allow key at-risk areas to be rapidly and appropriately targeted. An operational test of such a system has been carried out in the past 3 years in Central America, based on local reception and analysis of Advanced Very High Resolution Radiometer (AVHRR) imagery. Here we analyse the performance and data quality for recent activity of Fuego volcano (Guatemala). We assess the ability of the system to detect, quantify and monitor periods of heightened activity and consider the benefits of such information being available in near-real time to local geoscientists and for hazard mitigation. We show that the system is able to detect significant changes in volcanic activity (November and December 2004, February and December 2005). There are good comparisons for these events with large-scale monitoring systems using additional remote sensing data. This paper provides one of the few evaluations of the direct application of operational AVHRR data to volcanic hazard monitoring and disaster management in developing countries.

1. Introduction

Developing countries can have logistical, political and budgetary constraints that may be so severe as to prevent the adequate implementation of traditional

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high-technology ground-based volcano-monitoring systems (Stoiber and Williams 1990). Furthermore, there is the problem of the sheer number of potentially active volcanoes whose monitoring needs to be addressed. On average, more than 50 eruptions occur annually and most occur in developing countries. With such a large number of potentially active volcanoes, traditional forms of monitoring require assistance if all these targets are to be kept under surveillance. This is particularly the case for developing countries, where there are often insignificant resources available for the purpose. Thermal measurements are one of many techniques used for volcano surveillance and for the monitoring of ongoing activity. *In situ* devices are widely used for this purpose, but remote sensing-based methods generally offer more adaptability and repeatability while minimizing exposure to potential volcanic hazards. Remote sensing is one of the key methods by which this limitation may be tackled, particularly when carried out using Earth-orbiting satellites, which provide data routinely at low recurrent cost, rather than by aircraft campaigns, which are usually somewhat experimental and certainly much briefer.

Francis and Rothery (2000) provide a recent and comprehensive review of the variety of satellite remote sensing methods used to investigate active volcanoes. They show that satellite remote sensing can yield an improved understanding of volcanic processes, simply by providing an enormously enhanced monitoring capability. They also indicate that remote sensing can provide qualitatively different kinds of insights from anything previously possible because of the 'new ways' that satellite-based instruments provide for looking at individual volcanoes. This paper provides an introduction to thermal remote sensing and shows how an Advanced Very High Resolution Radiometer (AVHRR) remote sensing system has been used successfully to monitor and detect volcanic activity in Central America. Four cases are shown for thermal activity at Fuego volcano, Guatemala during 2004 and 2005. The AVHRR data collected locally are compared to those from other remote sensing data sources to assess the usefulness that locally controlled near-real-time data would have within Central America.

1.1 *Review of basic principles of remote sensing*

To measure temperatures remotely requires an instrument sensitive to thermally emitted radiation, which for Earth-surface features is mostly found in the infrared region of the electromagnetic spectrum. The theoretical basis for the measurement is Planck's radiation law, which governs the relationship between the absolute surface temperature (T) of an emitter and the emitted spectral radiance (essentially a measure of the thermal energy output per unit time, per unit area and per unit solid angle) at any particular wavelength (commonly measured in $\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$):

$$L(\lambda, T) = \frac{2hc^2 \times 10^{-6}}{\lambda^5 \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} \tag{1}$$

where λ is wavelength (m), h is the Planck constant ($6.62 \times 10^{-34}\,\mathrm{J\,s}$), T is temperature (K), k is the Boltzmann constant ($1.38 \times 10^{-23}\,\mathrm{J\,k^{-1}}$), L is spectral radiance ($\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}}$) and c is the velocity of light in a vacuum ($3 \times 10^8\,\mathrm{m\,s^{-1}}$).

By including instruments sensitive to infrared radiation on Earth-orbiting satellites, the repetitive nature of satellite observations can be harnessed for the thermal monitoring of volcanoes. This potentially allows the collection of large time-series datasets that may be useful for detecting changing trends in volcanic thermal anomalies and for documenting the appearance of thermal activity that might otherwise remain unobserved.

1.2 *Remote sensing satellite-based instruments and volcano monitoring*

Systems that can be used for operational and post-event satellite monitoring include US National Aeronautics and Space Administration (NASA) Landsat, the NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the US National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellites (GOES), the NASA Moderate Resolution Imaging Spectroradiometer (MODIS), the European Space Agency (ESA) Along Track Scanning Radiometer (ATSR) and the NOAA Advanced Very High Resolution Radiometer (AVHRR).

Review articles describing the use of satellite remote sensing in this paper and monitoring of active volcanoes, with detailed sections on thermal methods, include Oppenheimer (1998), Francis and Rothery (2000) and Mouginis-Mark *et al.* (2000). Satellite remote sensing data can vary in spatial resolution from tens of metres (ASTER) to several kilometres (GOES), and provide temporal resolutions of minutes (geostationary systems) to weeks (high spatial resolution polar-orbiting systems). For monitoring of active volcanoes, a compromise must be reached between spatial resolution and measurement frequency, especially considering that during many overpasses the volcano may be obscured by cloud. The use of GOES, MODIS, Landsat and ATSR for this purpose is illustrated in the example papers of Harris *et al.* (2002*a*), Wright *et al.* (2004), Flynn *et al.* (2001) and Wooster and Kaneko (1998), respectively.

The 1.1-km nadir spatial resolution and 3–4-h repeat cycle of AVHRR in Central America (available due to the multiple operational AVHRR instruments flying on different platforms, each of which provides a near 12-h imaging frequency) make it a potentially good compromise instrument, offering moderate spatial resolution and relatively frequent coverage along with spectral channels capable of detecting both surface thermal anomalies and airborne volcanic ash. As relatively affordable PC-based local receiving stations (under £50 000 or less than ~US$100 000) are now available for directly capturing AVHRR data from the host NOAA satellites, there is the possibility to obtain the data in a very timely manner in areas where data from other sensors may be difficult to access (due to, for example, slow or unreliable network connections).

The Alaska Volcano Observatory (AVO) was instrumental in demonstrating the efficacy of the approach of using a single receiving station to monitor ~100 volcanoes across Alaska and Kamchatka, including Bezymianny (Ramsey and Dehn 2004), Shishaldin (Dehn *et al.* 2002), Mount Cleveland (Dean *et al.* 2004) and Okmok (Patrick *et al.* 2005). Dean *et al.* (1998, 2002) provide a detailed description of AVO's remote sensing techniques for volcano monitoring. Dehn *et al.* (2000) stated that five of the last seven recent eruptions monitored by AVO had been preceded by thermal anomalies detected by AVHRR. In addition, AVHRR has been used in the study of thermal features at several volcanoes globally, including Erebus, Antarctica (Wiesnet and D'Aguanno 1982, Rothery and Oppenheimer 1994), Etna, Italy (Bonneville *et al.* 1985, Scorer 1986, Bonneville and Kerr 1987, Harris *et al.* 1997*a*) and Vulcano, Italy (Harris and Stevenson 1997).

Harris *et al.* (1997*b*) were among the first to suggest the possibility of equipping volcano observatories with AVHRR receiving stations to enhance their monitoring programmes. According to Jayaraman *et al.* (1997), such low-cost satellite-based approaches have the potential to similarly enhance hazard management in developing countries if appropriately applied. Here we examine the first use of a low-cost, AVHRR-based local volcano monitoring system in a developing country context, and provide results targeted at the monitoring of Fuego, a particularly active volcano situated in Guatemala, Central America.

1.2.1 The AVHRR system in Central America.

The AVHRR data used in this work were collected by a local PC-based receiving station installed at the Instituto Nicaraguense de Estudios Territoriales (INETER), the Nicaraguan Governmental Institute responsible for the national geophysical monitoring programme. The project was funded by the Engineering Knowledge and Research Programme run by the UK Department for International Development (DfiD), with the primary aim of evaluating the efficacy of this technology for complementing the existing volcano monitoring approaches applied across Central America. From November 2004 to December 2005, four separate periods of heightened activity occurred at Fuego, during which time AVHRR data were collected and examined by those directly responsible for geohazard monitoring. The locally collected AVHRR data were compared to those from other, centralized remote sensing-based volcano monitoring systems operated by the University of Hawaii (Harris *et al.* 2002*a*, Wright *et al.* 2004). Analysis was carried out on past AVHRR data for Cerro Negro to determine the relative signals that should be seen from an active volcano within Central America. As Fuego volcano was the most active volcano within our station's region during this period and was of most interest to the local scientists, it was chosen as the test case. This paper reports results from this comparative study, and evaluates the use of the satellite-derived information in the local context of hazard management at Fuego.

2. Fuego volcano, Guatemala

Fuego volcano (figure 1) forms part of the Central American Volcanic Arc (Carr *et al.* 2003) and is currently one of Earth's most active volcanoes (Martin and Rose 1981, Vallance *et al.* 2001). Fuego threatens large populations, with more than 20 000 people being potentially at risk to pyroclastic flows and heavy ash fall from a Volcanic Explosivity Index (VEI; Newhall and Self 1982) 4–5-type eruption. In historical times, Fuego has erupted 60 times (Vallance *et al.* 2001): for example, in 1717, 1932, 1971 and 1974 explosive eruptions of Fuego produced large pyroclastic flows (Davies *et al.* 1978) and deposited volcanic ash on the cities of Escuintla (population 75 000+; 20 km south), Antigua Guatemala (population 25 000; 15 km southwest) and Guatemala City (population 2.2 million; 40 km southwest) (Vallance *et al.* 2001); see their location in figure 1(*b*). Deger (1932), Feldman (1993) and Rose *et al.* (1978) provide additional information on some of the eruptions at Fuego volcano. Vallance *et al.* (2001) provide a detailed report of the associated hazards with Fuego and the neighbouring Acatenango volcano.

The task of monitoring Fuego and responding to increases in volcanic activity is undertaken by two Guatemalan institutes, the National Institute of Seismology, Volcanology, Meteorology and Hydrology (INSIVUMEH) and the National Institute for Disaster Reduction (CONRED). INSIVUMEH provides the main observation and forecasting capability through seismic monitoring and ground

(*a*)

(*b*)

Figure 1. (*a*) Volcano Fuego as situated within the Guatemalan volcanic chain and (*b*) a three-dimensional view.

observatories at the major volcanoes and issues daily activity bulletins, which during periods of heightened volcanic alert are increased in frequency to up to one bulletin per hour. CONRED deals with disaster reduction strategies and hazard evacuation plans, partly in response to the information received from INSIVUMEH. Together with the Guatemalan national government, CONRED and INSIVUMEH are responsible for the decision making at the institutional level that is carried out during volcanic crises, when they are required to provide information on the volcanic activity and how best to plan disaster reduction strategies.

From January to August 2003, there were several events that caused volcanic crises and alerted both INSIVUMEH and CONRED. In January and February 2003, seismic data showed an increase in activity that plateaued and then decreased. CONRED sent staff to the summit and to local towns where evacuations took place. These were later assessed to have been unnecessary. In April of the same year, there was no eruption but the same sequence was noted in the seismic signal. During June and July, there was the same increase in the sequence but no levelling and a large eruption occurred. CONRED responded with an evacuation of local communities. In August 2003, there was no eruption but the same sequence in the seismic signal. It was a result of these periods of heightened activity that volcano monitoring using the AVHRR data from INETER began.

During January 2004, there was a major volcanic eruption. The local observers were prepared to make evaluations and proceed to safety, without the benefit of an early warning emitted by CONRED. It was the local observers that notified CONRED of the dangerous situation, not the reverse. When notified that the local community was preparing to evacuate, CONRED officials were surprised by the decision given the scientific data they had at their disposal. CONRED personnel state that the events of June 2003 and January 2004 had completely changed their perception of the way the volcano behaves. The crucial issue was the time-span between the first signs of unrest and the generation of a flow, which for the January 2004 case was only a few hours. The difficulty of establishing a base level for abnormal activity and distinguishing between that threshold and a level of activity above normality becomes even more so when the weather or darkness makes it impossible to carry out visual monitoring.

3. Remote sensing data sources

With Central America, there have been numerous studies looking at the use of remote sensing for volcanic thermal monitoring. For example, Harris *et al.* (1997*b*) showed data from AVHRR for Cerro Nergo volcano in Nicaragua, Harris *et al.* (2002*b*) reported GOES data for Fuego in January 2000, Galindo and Dominguez (2002) describe AVHRR data for Colima volcano in Mexico and Wright *et al.* (2004) published MODVOLC data for Colima and Popocatepetl in Mexico. Galindo and Dominguez (2002) show comparisons between AVHRR data and ground-based seismic observations and how locally collected AVHRR data can be very useful for thermal monitoring and ash cloud detection. Locally collected data have the potential to be used more widely by the local scientists as they have more control of the products produced and the application of the data for hazard mitigation.

The PC-based satellite data reception station based at INETER captures AVHRR data transmitted directly from the NOAA Polar Orbiting Environmental Satellite (POES). Full details of the AVHRR system are provided by Kidwell (1998). Each AVHRR image is recorded in five spectral channels (table 1), and at the nadir point each pixel covers an area of approximately 1.21 km^2. The ground receiving station, whose characteristics are discussed in detail in Wooster *et al.* (2005), captures all AVHRR data transmitted while the satellite is in range, in this case resulting in imagery covering all of Central America. Once captured, the data are geolocated and calibrated into measurements of spectral radiance in each channel.

Of particular interest to volcano monitoring is the AVHRR mid-infrared (MIR) channel (table 1) because, as the temperature increases, the thermal emittance

Table 1. The spectral channels of the AVHRR sensor carried onboard the NOAA Polar Orbiting Environmental Satellites. On the most recent NOAA satellites, AVHRR Channel 3 operates in two modes, denoted as 3a (1.6 μm observations during the daytime) and 3b (3.7 μm observations at night), whilst on the older satellites the 3.7 μm mode operates continuously.

Channel	Central wavelength (μm)	Spectral region
1	0.6	Visible (VIS)
2	0.8	Near Infrared (NIR)
3a*	1.6	Shortwave Infrared (SWIR)
3b*	3.7	Middle Infrared (MIR)
4	11	Thermal Infrared (TIR)
5*	12	Thermal Infrared (TIR)

increases much more rapidly in this wavelength region than it does at the longer thermal infrared (TIR) wavelengths of AVHRR channels 4 or 5 (see figure 2). This has the effect of making the AVHRR MIR channel very sensitive to the presence of even strongly sub-pixel resolution but high-temperature surfaces, whereas the same features may be completely undetectable in AVHRR channels 4 or 5. Discrimination techniques generally work by comparing signals in the various AVHRR thermal channels (Harris *et al.* 1997*b*), and by checking for changes in these signals at each overpass, the volcano monitoring system can provide multiple observations per day. Dozier (1981) was the first to indicate the possibility of identifying these kinds of subpixel-sized heat sources using AVHRR and studies such those of as Wiesnet and D'Aguanno (1982) and Harris *et al.* (1997*a*) have indicated the relevance of the technique for volcanological studies.

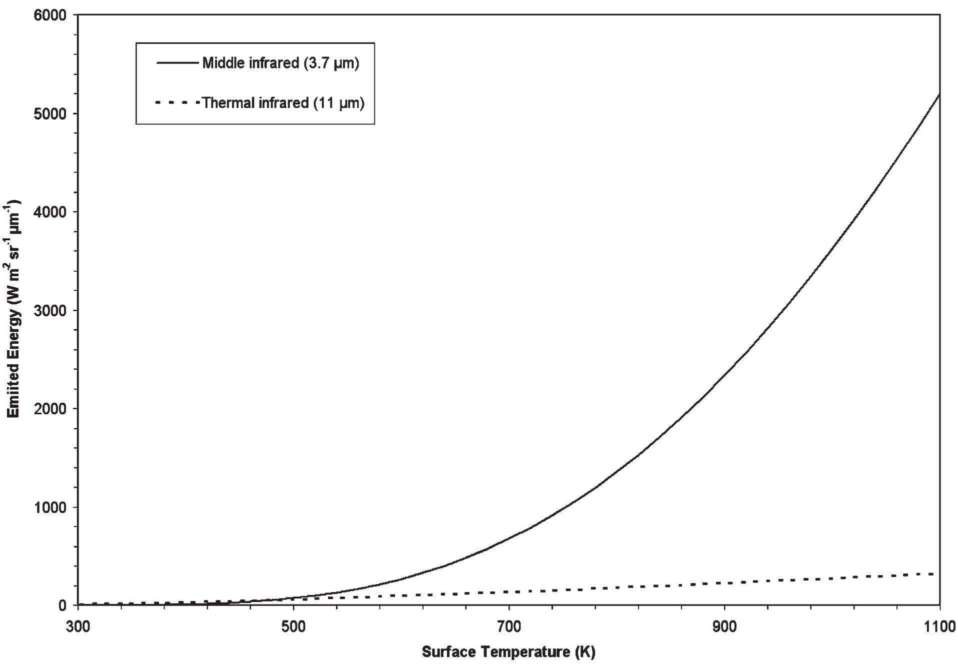


Figure 2. Thermal output from surfaces at MIR and TIR wavelengths modeled according to Planck's Radiation Law.

Analysis of the AVHRR data captured at INETER is conducted immediately after each overpass by software routines operated automatically on the captured imagery. The latitude and longitude location of the volcano of interest is determined in the geolocated imagery, and a 15×15 pixel grid surrounding this location is subset from the data. Pixels determined to be cloudy were not used in any of the thermal activity analysis and if the region surrounding the volcano was >60% cloudy then the radiance calculations were not used. With the cloud analysis, we have used tests based on those from Saunders and Kriebel (1988), Stowe *et al.* (1999), Kriebel *et al.* (2003) and Heidinger (2004). We have added in a noisy data test to the cloud analysis. This was found to be very useful and removes any problems that exist from poor quality data across the volcanic region.

Detailed descriptions of the cloud-detecting algorithms and sensitivity analysis of their accuracy can be found in the Wooster *et al.* (2005) report of the DfiD project. In addition, as we only use night-time data, sunglint from undetected clouds close to the summit is eliminated and at night it is harder to mistake cloud signals for any volcanic thermal signals. Any missed cloudy regions would just lower the measured signal compared to the actual thermal radiance. The mean and standard deviation of the brightness temperature (BT) difference recorded over the grid between the AVHRR MIR and TIR wavebands were calculated. A threshold derived from these values was used to confirm whether or not each pixel within the grid can be classed as 'thermally anomalous':

$$T_{3-4} > \overline{T_{3-4}} + (2 \times \sigma_{T_{3-4}}) \quad \rightarrow \quad \text{Thermally anomalous} \tag{2a}$$

$$T_{3-4} \leq \overline{T_{3-4}} + (2 \times \sigma_{T_{3-4}}) \quad \rightarrow \quad \text{Ambient background} \tag{2b}$$

where all units are in Kelvin and $T_{3\text{–}4}$=AVHRR channel 3 BT (MIR) – channel 4 BT (TIR), $\overline{T_{3-4}}$=mean (AVHRR MIR BT – TIR BT) and $\sigma_{T_{3-4}}$=standard deviation of (AVHRR MIR BT – TIR BT).

Further calculations were conducted on the set of identified thermally anomalous pixels only, most notably the derivation of the 'radiance anomaly' parameter discussed in Wooster (2001). For each thermally anomalous pixel this involves calculating the difference between the observed AVHRR MIR spectral radiance and the simulated MIR signal calculated using the observed TIR BT in equation (1). The overall radiance anomaly is then the sum of all the individual radiance anomaly measures for that volcanic scene. This method offers the advantage that the effect of elevation changes is largely accounted for because it affects both the MIR and TIR signals. One disadvantage is, however, that if the volcanic thermal anomaly is large enough to also significantly affect the AVHRR TIR spectral channel then the volcanic anomaly measure will be somewhat underestimated. For this reason, a series of additional anomaly measures were also derived, based, for example, on the signal difference between the 'volcanic' MIR pixels and the surrounding non-volcanic pixels, although in practice the results from each were found to be fairly similar and only the 'radiance anomaly' approach is discussed here.

For each volcano observed, the radiance anomaly time series is updated after each satellite overpass and displayed on a dedicated website operated by INETER (http://sat-server.ineter.gob.ni/); examples are shown in figure 3. An automated alert system that sends emails to the relevant in-country personnel when a potentially significant change in anomaly intensity is noted is linked to the website. In addition to the hotspot time series and email alerts, the 'split window' method of Prata (1989), illustrated in Wen and Rose (1994) and Schneider *et al.* (1995), is used to identify image areas that may contain airborne volcanic ash. There may be problems with this simple approach in conditions of high atmospheric water vapour concentration (Simpson *et al.* 2000, 2001, Prata *et al.* 2001) for opaque clouds or ice-rich clouds (Rose *et al.* 1995, 2000, 2003). More complex methods may be required for accurate volcanic ash detection under humid/cloudy circumstances (Pergola *et al.* 2004).

An alternative to the local remote sensing data reception and processing approach discussed above is the more centralized design adopted by the successful hotspot monitoring systems operated by the Hawaii Institute of Geophysics and Planetology (HIGP) at the University of Hawaii. HIGP uses MODIS (Wright *et al.* 2002, 2004) and GOES data (Harris *et al.* 2001, 2002*b*) to monitor volcanoes across the Americas, and in the former case also across the world, using data from essentially similar spectral bands to those on the AVHRR. For night-time passes, the MODVOLC system is similar to the AVHRR system and website operated by INETER, with the advantage of global coverage but at a reduced temporal resolution compared to the INETER AVHRR-based dataset. The HIGP GOES hotspot system locates and measures the intensity of volcanic hotspots, placing the information on a dedicated website that is updated many times per day (http://goes.higp.hawaii.edu/). The system provides a more frequent observation capability than that provided by the INETER AVHRR receiver, although at a reduced spatial resolution. Here, we present four cases studies for Fuego volcano, Guatemala during 2004 and 2005. We compare the locally collected AVHRR data to those from the GOES and MODIS global systems and ascertain the usefulness for a locally operated thermal remote sensing system in Central America for volcano monitoring.

Figure 3. Real Time thermal remote sensing project website (http://sat-server.ineter.gob.ni/).

4. Case studies at Fuego volcano

4.1 *Event 1: November 2004*

Between 9 and 20 November 2004, Fuego experienced avalanches of incandescent volcanic material such as lava flows and scoria, as observed by CONRED and INSIVUMEH personnel, and mild Strombolian activity that resulted in significant thermal anomalies being detected by the AVHRR (figure 4). On 16 November, the increasing activity levels coupled with the large amount of summit debris gave rise to concerns that large pyroclastic flows might be generated. During the November 2004 event, the AVHRR imagery captured locally at INETER (figure 4) shows a similar spatial pattern to the MODVOLC thermal anomaly image for the Fuego time-series composite over a similar period (8–22 November; figure 5). Figures 6(*b*) and 6(*c*) show the MODIS and GOES MIR thermal anomaly intensities, respectively, which both peak on 17 November, as does that of AVHRR (figure 6(*a*)).

Figure 6(*a*) shows the INETER-AVHRR radiance anomaly time series for November 2004, indicating significant intensity variations, peaking on 17 November, and by 21–22 November it had returned to its pre-crisis level. The spatial extent of the anomaly, indicated in figure 4, grew in accordance with the anomaly magnitude indicated in figure 6(*a*), and at this time there was concern

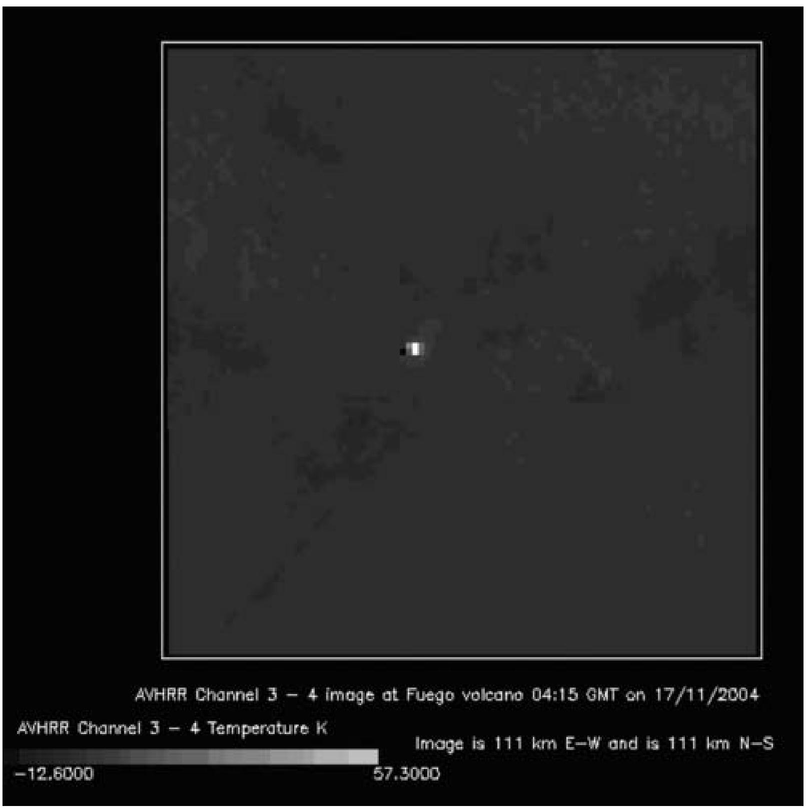


Figure 4. AVHRR Hotspot Evidence. MIR - TIR temperature difference imagery for 17/11/2004 at 04:15 UTC.

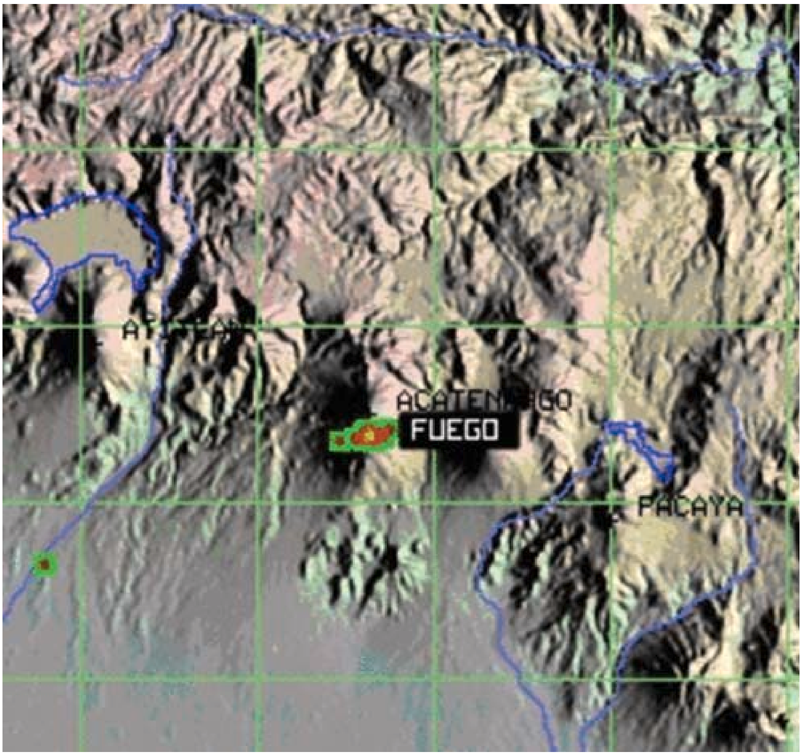


Figure 5. MODIS MODVOLC hotspot image for Fuego from thermal alert website from 08/11/2004 – 22/11/2004.

within INSIVUMEH and CONRED that the increased activity could be a forerunner to a much larger eruption, as had occurred in June 2003. In fact, during the last week of November, avalanches of incandescent volcanic material continued towards ravines on the volcano's southeastern and southwestern flanks. Small and moderate explosions expelled abundant incandescent lava to heights ~150 m above the crater. Some explosions generated rumblings, shock waves, and fine ash that was deposited on the flanks of the volcano. By the end of the month, however, INSIVUMEH had reported that the energy level of the eruption had decreased (GVP 2004). Figures 4–6 shows that, by 21 November 2004, the radiance signal had returned to pre-event levels.

4.2 *Event 2: December 2004*

Fuego's activity developed into another significant eruptive episode on 23–24 December 2004. The pattern of this effusive eruption was similar to that of 8–9 January 2004, with a large lava fountain, not much ash production, no important eruptive column, and no large crater rim or lava flow collapses with associated block and ash flows. However, local scientists noted that there where some small- to medium-scale block and ash flows (3–4 km long), but none of them put the communities at significant risk. During this kind of activity the main concerns of the local scientists and emergency managers were the block and ash flows, which could result by the collapse of unstable material accumulated on the summit area and could be triggered by the eruptive activity.

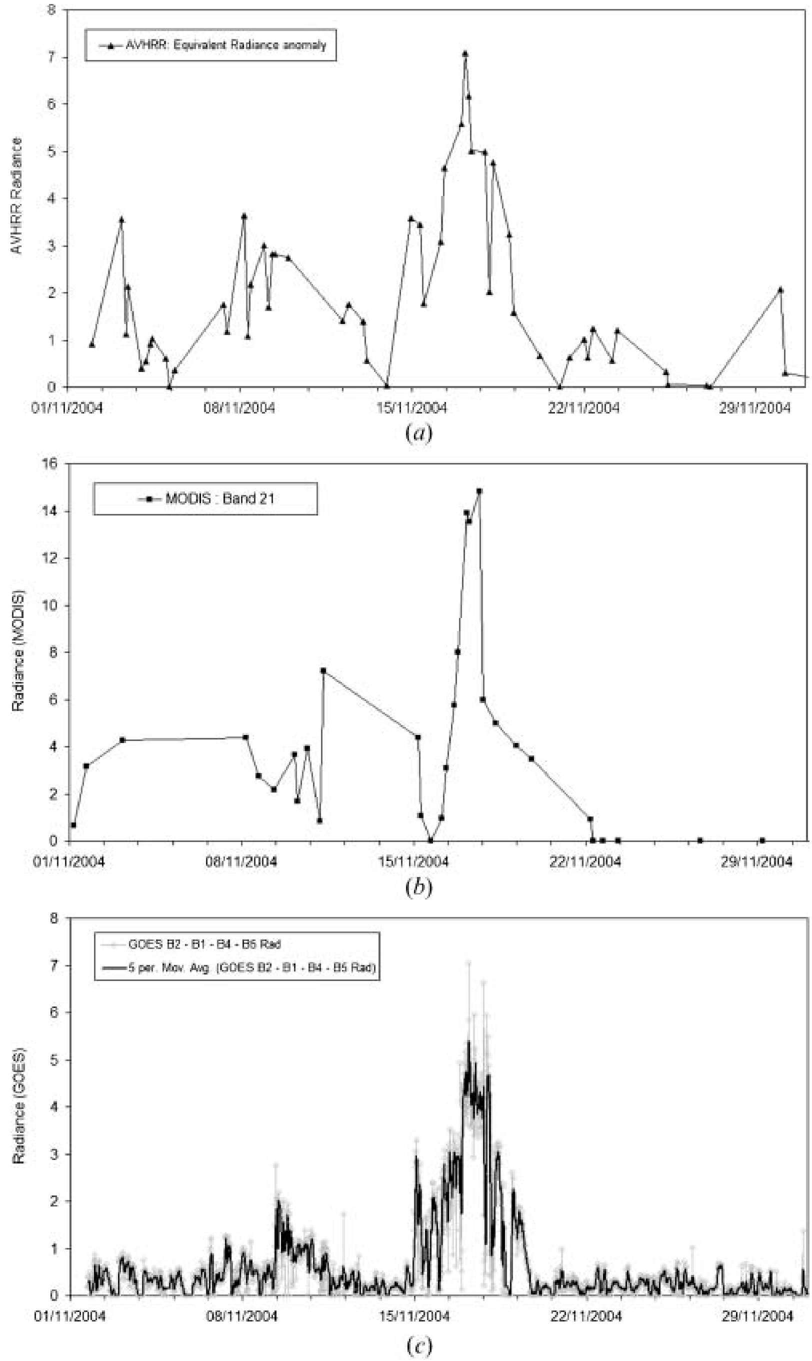


Figure 6. (*a*) AVHRR Equivalent Time series, (*b*) MODIS Band 21 and (*c*) GOES Radiance Time series for Fuego in November 2004.

Figure 7 shows the spatial distribution of the anomaly for 24 December, where a maximum brightness temperature (MIR-TIR) difference of 50 K occurs and between 3 and 5 AVHRR pixels are highlighted as thermally anomalous. This

Figure 7. AVHRR Hotspot Evidence. MIR-TIR temperature imagery for 24/12/2004 at 03:31 UTC.

signal is probably the result of the hot material deposited on the slopes of the volcano during the ongoing eruption. Figure 8 shows the hotspot as determined by the MODVOLC system for the 2 weeks surrounding 23 and 24 December, with evidence of a thermal signal seen away from the volcano's summit. Figure 9(*a*) shows the AVHRR radiance anomaly time series for the period, indicating a significant anomaly increase from 16 December 2004. The maximum radiance anomaly is reached on 26 December 2004, after the signal has been elevated for around 10 days.

Figure 9(*b*) shows the MODIS time series for December 2004, determined by MODVOLC, where a significant thermal signal occurs on 23 and 24 December and where evidence of an increase from 11 December onwards can be seen (prior to this no hotspot pixels were detected by the MODVOLC algorithm). Figure 9(*c*) shows the GOES radiance anomaly, where little or no significant thermal anomaly signal is seen during early December 2004. On 19 December, there is an increase in signal that continues until 22 December, when a rapid signal increase builds to a maximum on 24 December. The pre-eruption signal returns by the end of the month.

4.3 *Event 3: February 2005*

The third volcanic thermal event occurred at Fuego on 11–13 February 2005. This was a much smaller event than the one in November and December 2004, with ash

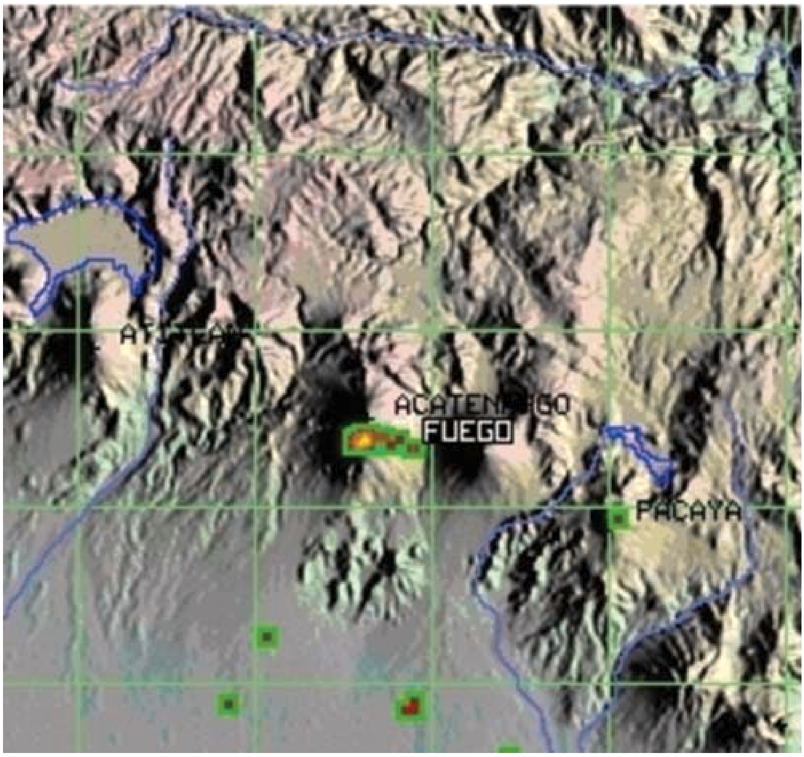


Figure 8. MODIS MODVOLC hotspot image for Fuego from thermal alert website from 16/12/2004 - 30/12/2004.

columns of 1–1.2 km, lava fountains up to 70–100 m in height and lava flows up to a maximum of 2 km in length on 13 February 2005. This event would be expected to result in a smaller thermal signal. Figure 10 shows the spatial arrangement of the hotspot pixels, covering several pixels, with a maximum MIR-TIR brightness temperature difference around 45 °C. This expectation is mirrored in the thermal anomaly time series where an increased thermal signal is apparent from 7 to 16 February 2005 but with a maximum signal of only 3.5 $W m^{-2} sr^{-1} \mu m^{-1}$. For the previous November 2004 event, AVHRR data indicate that the peak thermal signal was 7 $W m^{-2} sr^{-1} \mu m^{-1}$ and for December 2004, it was 6 $W m^{-2} sr^{-1} \mu m^{-1}$.

Figure 11 shows the thermal hotspots detected from the MODVOLC algorithm for the 2-week period bracketing the event. Fewer pixels are termed to be thermally anomalous than was the case for the previous events studied (anomalies away from Fuego are due to other volcanoes or to fires). Figure 12(*b*) shows the MODIS radiance time-series signal, where there is a maximum in the thermal signal for Fuego over 12–17 February 2005. Figure 12(*c*) shows the GOES radiance time series, which shows a similar pattern. The low background thermal signal that is seen in early February 2005 returns for the last 10 days of February. Once again, the AVHRR, GOES and MODIS thermal anomaly time series match fairly well. However, the MODIS time series does show a higher radiance signal than the AVHRR on 14–15 February 2005. The AVHRR data are ‘saturated’ on some satellite passes between 9 and 15 February 2005. As a result, the AVHRR thermal

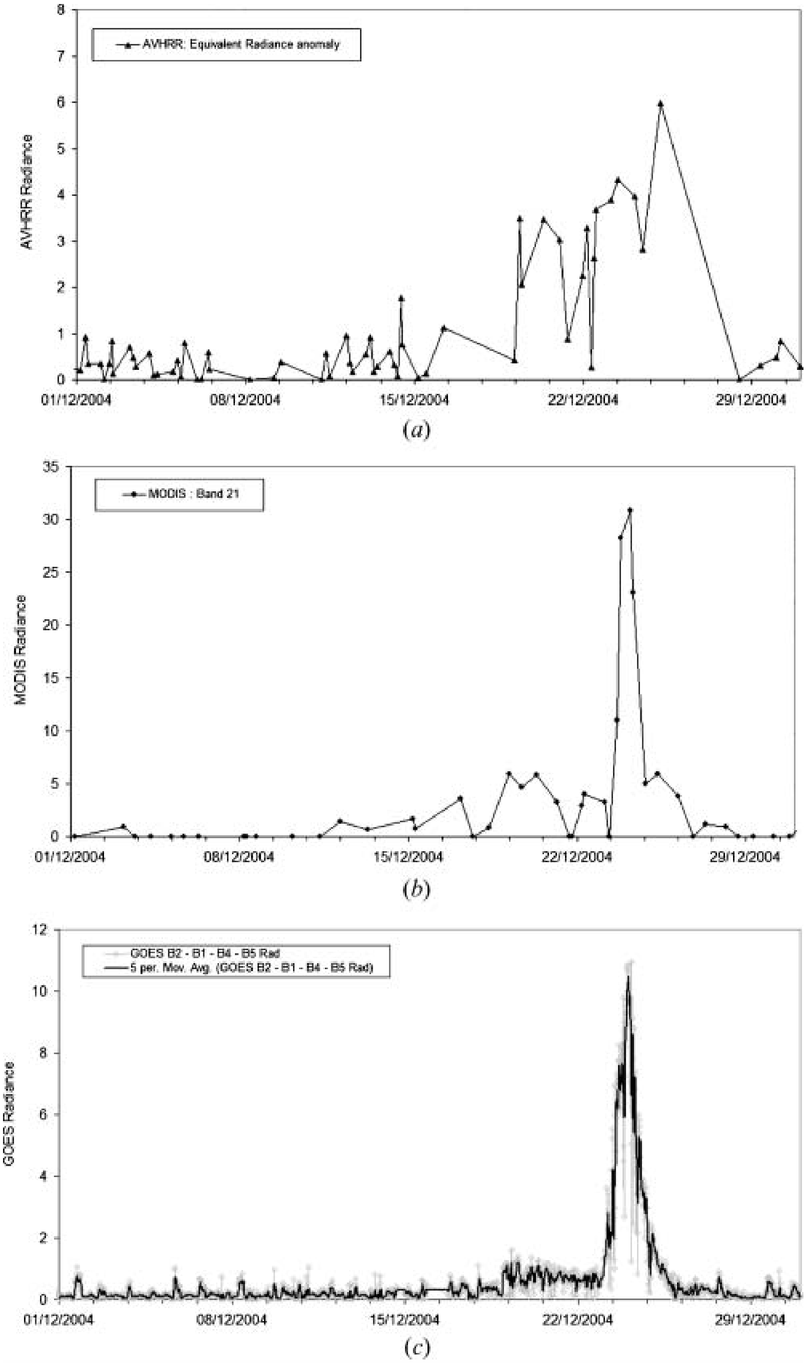


Figure 9. (*a*) AVHRR Equivalent Time series (*b*) MODIS Band 21 Time series and (*c*) GOES Time series for Fuego in December 2004.

radiance calculated will be lower than the true thermal signal. MODIS has a higher temperature, which results in pixel saturation, so would be able to measure a greater thermal radiance for this period.

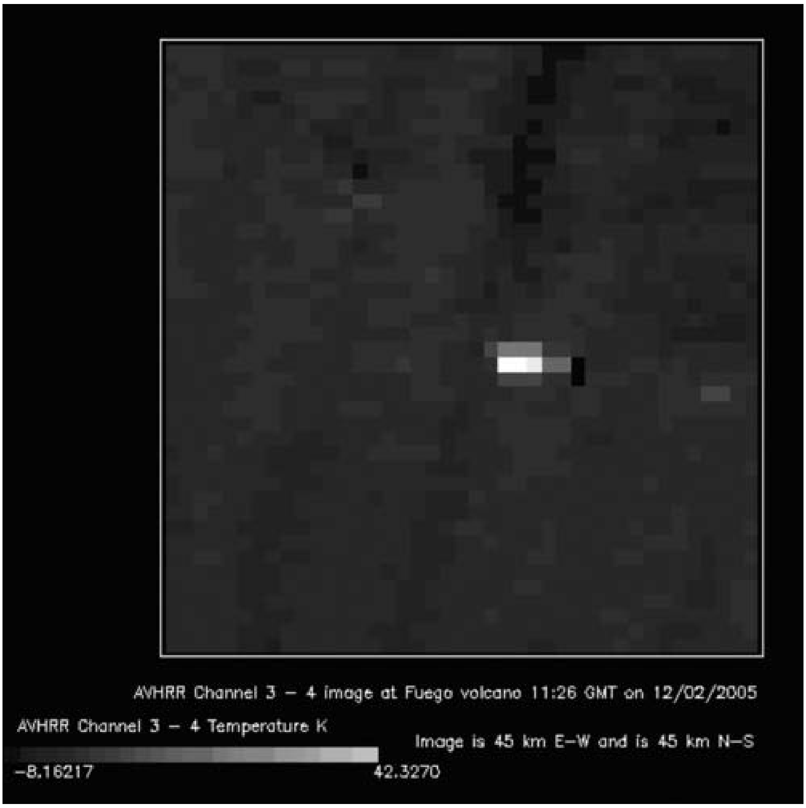


Figure 10. AVHRR Hotspot Evidence. MIR-TIR temperature imagery for 12/02/2005 at 11:26 UTC.

4.4 *Event 4: December 2005*

This event begins on 27 December 2005 at about 11:45 UTC and produced lava flows that travelled down ravines to the south and southwest of Fuego's summit region, initially extending ~800 m and 1200 m, respectively. At 12:02 UTC, a pyroclastic flow descended down a ravine to the south of the summit and produced a drifting column of ash that rose to a height of ~2 km above the volcano. A small amount of ash fell to the west and southwest of the volcano in the villages ~7 km from the volcano. Volcanic activity continued through 28 December 2005, with lava flows travelling down the volcano's flanks, and a dark gas-and-ash plume rising to ~1 km above the volcano. Figure 13 shows the spatial distribution of the anomaly for 27 December 2005. The hotspot is clearly evident, with maximum MIR–TIR brightness temperature differences of approximately 60°C. Figure 14 shows evidence of an ash cloud at 10:44 UTC on 27 December 2005, using the Prata (1989) split-window method. The ash cloud can be seen to emanate in the south-southwest direction away from the volcano. The strongest split window temperature difference is −1.51 K, evidence of a small ash plume.

Figure 15 shows the MODVOLC hotspot detection images for December 2005 and for each day between 26 and 28 December 2005. An anomalous signal occurred from 27 to 28 December only and no MODVOLC hotspot is evidenced on 26 December, contrary to the evidence from the AVHRR imagery (figure 13(*a*)).

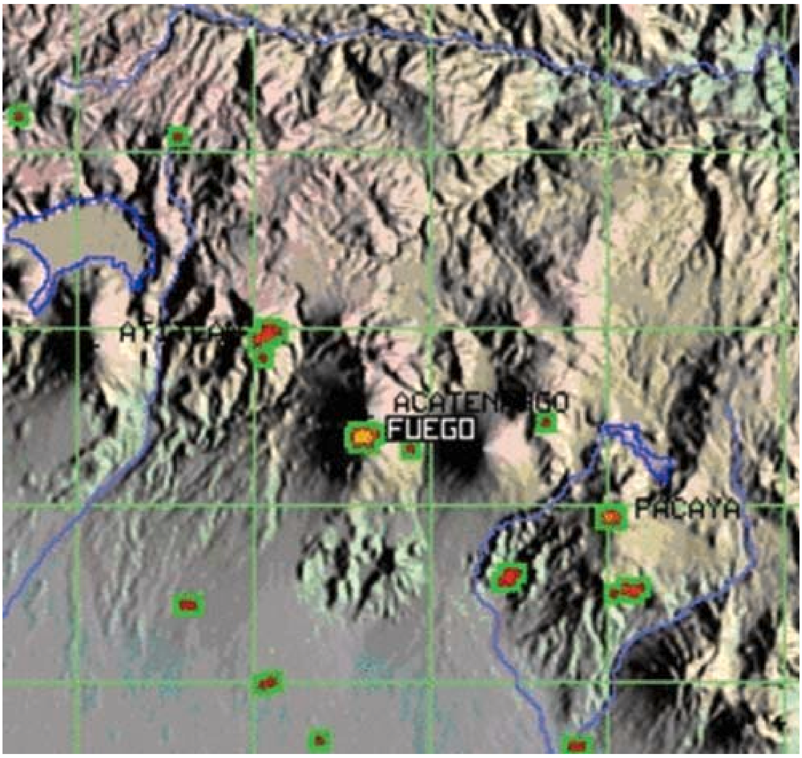


Figure 11. MODIS MODVOLC hotspot image for Fuego from thermal alert website from 02/02/2005 – 16/02/2005.

Figure 16(*a*) shows the AVHRR thermal anomaly time series from December 2005 to January 2006, with evidence of heightened activity during early December and the eruptive event during the end of December 2005. The AVHRR peak anomaly of nearly $8\,W\,m^{-2}\,sr^{-1}\,\mu m^{-1}$ was the largest of the four events discussed in this paper. For the MODIS time-series data (figure 16(*b*)), there is evidence of the activity on 27–29 December 2005, but because of lack of data as accessed from the MODVOLC website, we are unable to detect the post-activity period and it is difficult to make any categorical assumptions of precursor activity given no post-eruption baseline. For the GOES time-series data (figure 16(*c*)), the activity period from 27–31 December 2005 shows no evidence of eruption precursors.

5. Discussion

All three data sets show good temporal agreement across the four cases. However, the MODIS radiance data seem to be greater than those seen in the AVHRR and GOES. A possible reason for this is the higher saturation temperatures in the MODIS sensor bands. MODIS bands 21 and 22 detect thermal radiance at 4 μm, similar to the 3.6 μm of the AVHRR channel 3, but MODIS has higher saturation temperatures in these bands than on the AVHRR sensor and comparable bands on the GOES (Wright *et al.* 2002). As the measured ground temperatures in the satellite are determined from the thermal radiance, then higher radiances are measured at the MODIS sensor before the sensor saturates.

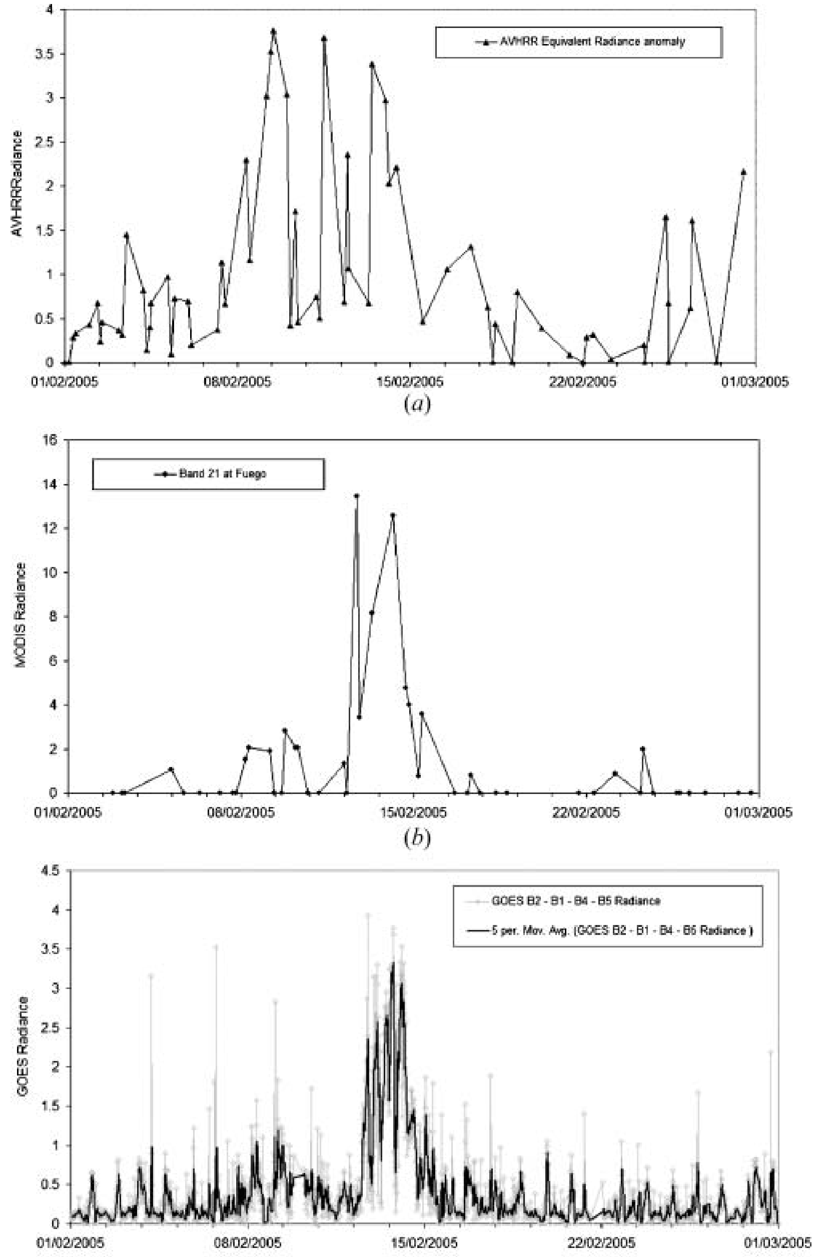


Figure 12. (*a*) AVHRR equivalent time series (*b*) MODIS band 21 time series and (*c*) GOES time series for Fuego in February 2005.

For the November 2004 event, it is clear that GOES, MODIS and AVHRR all show very similar thermal anomaly patterns, indicating that they are likely to be a relatively correct representation of the true situation, even with the possibility of cloud cover and the temporal resolutions affecting the data coverage. AVHRR has an increased number of available data points for detecting the thermal signal when

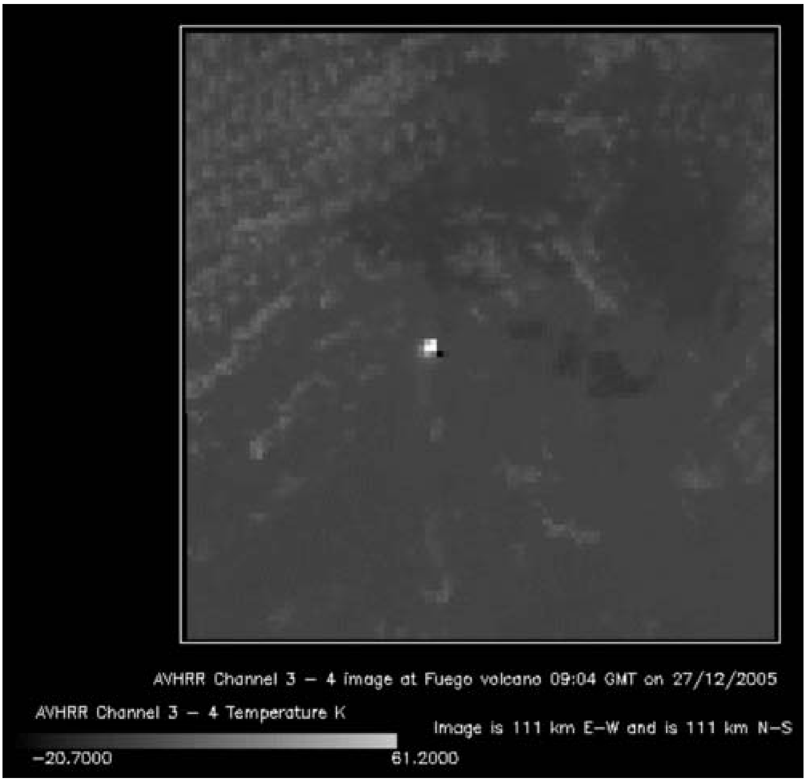


Figure 13. AVHRR Hotspot Evidence. MIR-TIR temperature imagery for 27/12/2005 at 09:04 UTC.

compared to MODIS, although GOES has the most temporally complete dataset but poorer spatial resolution. All three sensors show that by 21 November 2004, thermal anomaly magnitudes have returned to pre-crises values. For the December 2004 event, all three remote sensing datasets are shown to indicate similar thermal anomaly signals, particularly around 23–24 December 2004. The AVHRR- and MODIS-based measures detect more of the pre-eruptive activity signal (16–22 December) because of their higher spatial resolution in the thermal channels. For the volcanic event in February 2005, AVHRR, GOES and MODIS all provide similar data sets and temporal thermal signals. Across the fourth event in December 2005, all three datasets match fairly well, although in the case described the AVHRR data appear to show increased evidence of an eruption precursor compared to the other datasets.

With the INETER-AVHRR system, there are some limits to the full real-time volcano monitoring capability. First, the temporal coverage of the AVHRR satellites means that information on the volcano's thermal activity is available, at best, once every 3 h. Although data are processed for each AVHRR satellite pass, the current system is limited to night-time data for thermal monitoring, and so the temporal resolution is degraded further. During the daytime, the system is used for the monitoring of volcanic ash clouds. A second limiting factor is the cloud coverage within the Central American region during the rainy season. As the AVHRR satellite system was designed for meteorological purposes, cloud cover will limit the thermal monitoring capabilities.

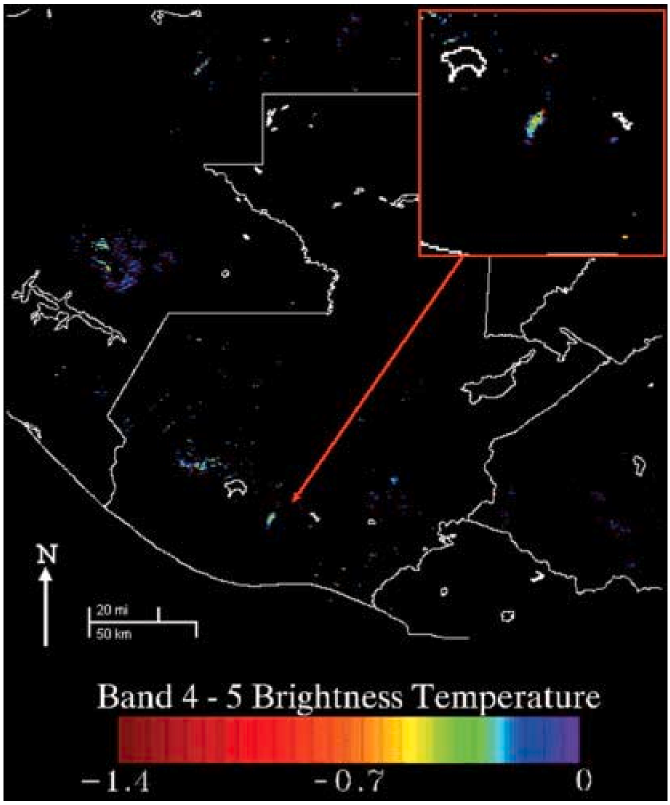


Figure 14. AVHRR Ash cloud evidence for 27/12/2005 at 10:44 UTC using the split window method. Inserts for the Fuego volcano region, with its location highlighted by a red cross.

How could the INETER-AVHRR system be better used in the future? First, there is the opportunity of using the daytime data for thermal monitoring of Central American volcanic activity. As part of the DfiD project, a study analysed daytime data to determine how forest fires would affect the detection of volcanic thermal activity. It found that, especially during the dry season, forest fires within 20 km of the volcanic summit could be detected as 'volcanic' activity using the current monitoring system, and ground-based observations would be required to validate any detection made. Wright *et al.* (2002) state that night-time images provide the best opportunity for resolving subtle temperature anomalies. Although it is potentially possible to use daytime data for large eruption detection, to use the data quantitatively for monitoring thermal signals is difficult because of changes in ambient heating (solar heating) and problems of sunglint (or reflected sunlight) from small, undetected cloud around the volcanic summit contaminating the 'volcanic' thermal signals. Further work would be required to fully test this and find out how best to use daytime data for automated thermal monitoring from these INETER-AVHRR data.

Second, the volcanic ash cloud data available could be compared to ash dispersion models, such as HYSPLIT (Draxler and Hess 1998) and Puff (Searcy *et al.* 1998), to help in detecting and tracking volcanic ash clouds. These ash clouds are a serious risk to aviation traffic in Central America; for example,

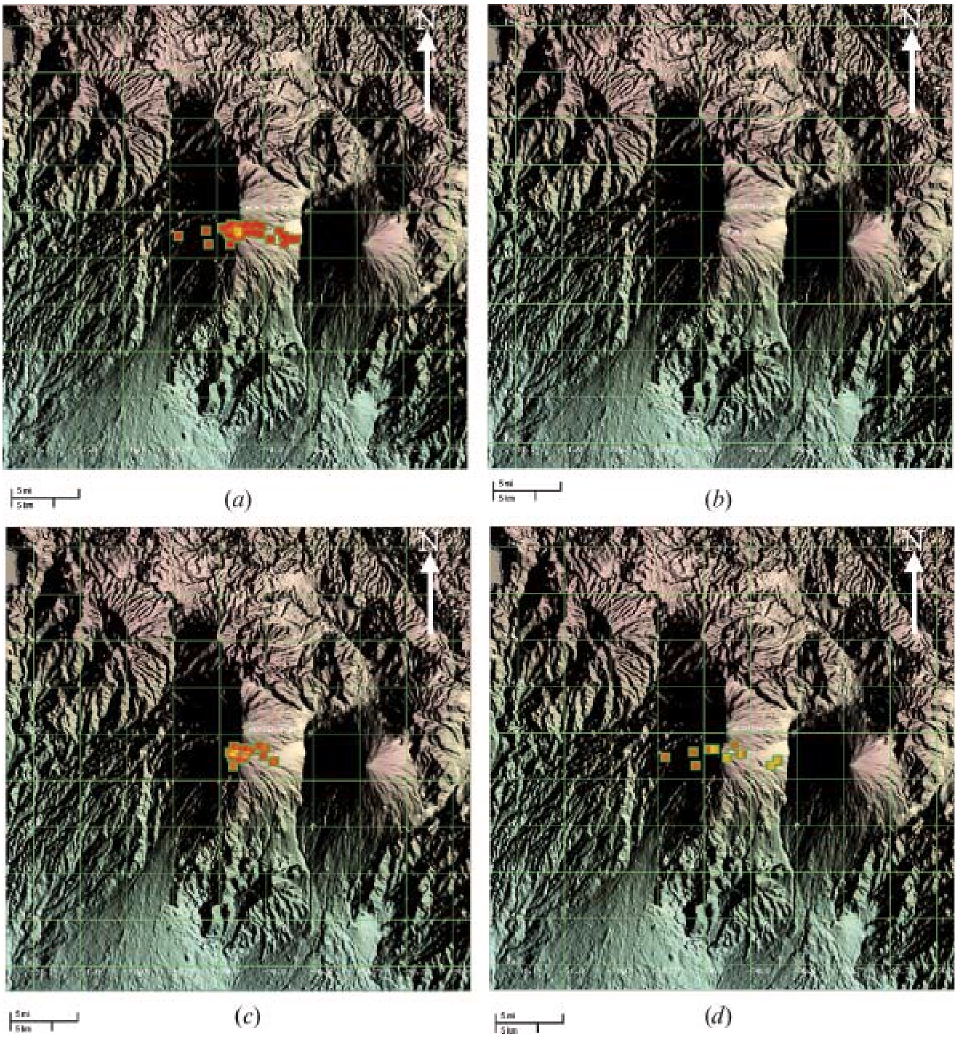
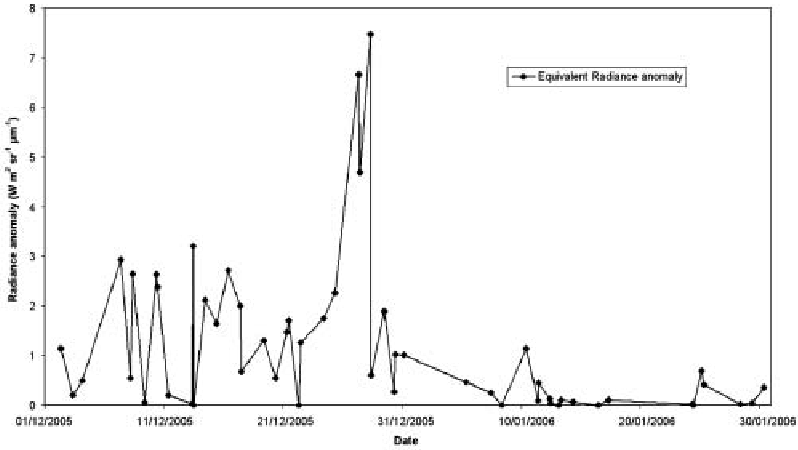
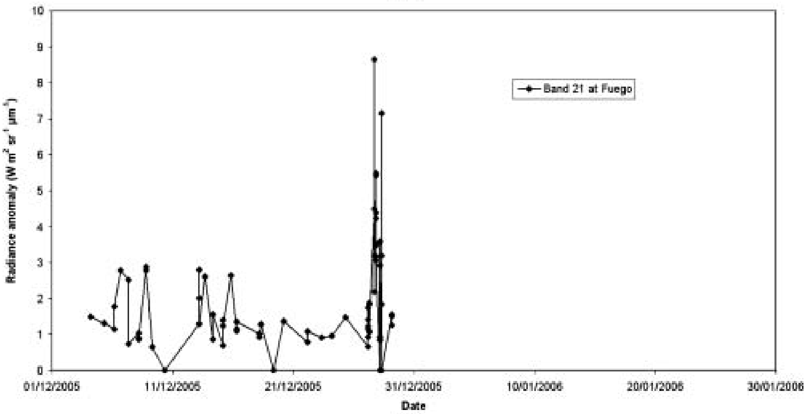


Figure 15. MODIS hotspot image for Fuego from thermal alert website for (*a*) December 2005, (*b*) 26/12/2005 (*c*) 27/12/2005 and (*d*) 28/12/2005.

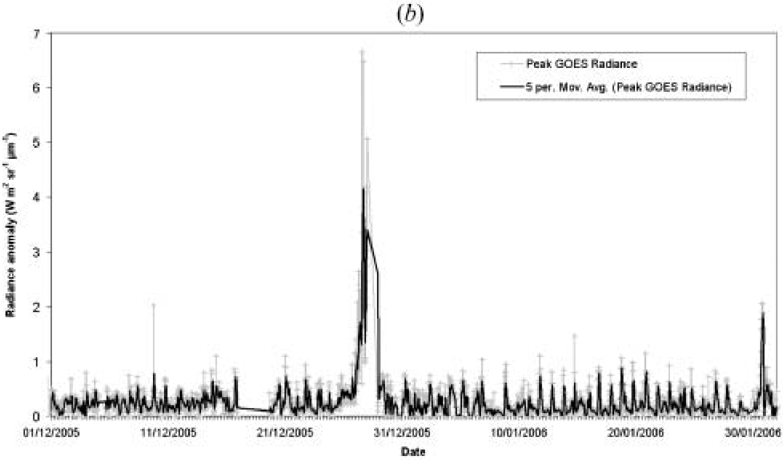
Fuego is only about 40 km from Guatemala City. However, this is currently beyond the scope of the operational system envisaged as it would require some considerable validation studies before operational products could be considered useful. Third, the data acquired from the AVHRR system could be validated with ground-based observations, such as those from forward-looking infrared (FLIR) cameras. Again, this is beyond the scope of the project, although they would provide an invaluable data source for comparison to the remote sensing thermal signals. Here, we have shown that, for Central America, the local AVHRR receiving station data provide more information than is possible from the MODIS or GOES website interfaces for this region. The AVHRR station can detect and monitor a volcanic event even though it does not reach a significant volcanic eruption, providing a means to monitor the background activity of the volcano without needing to visit it.



(*a*)



(*b*)



(*c*)

Figure 16. (*a*) AVHRR equivalent time series, (*b*) MODIS band 21 time series and (*c*) GOES time series for Fuego in December 2005–January 2006.

6. Summary and conclusions

The AVHRR system, based at INETER, is the first of its kind in developing country geoscience organizations and it allows locally collected and processed data to be used for volcano monitoring across Central America. As case studies, four discrete volcanic events at Fuego were detected and monitored by the AVHRR station, and the thermal anomaly signals derived locally in near-real time were compared to those from the GOES- and MODIS-based 'hotspot' systems. The AVHRR has a higher spatial resolution than GOES, and a higher temporal resolution than MODIS (although AVHRR is more prone to sensor saturation). In most cases, the actual information derivable about the trends in the thermal anomaly signals match well between the different sensors. The advantages of the AVHRR data are that Central American geoscientists can be involved directly in the data processing (which, though fully automated, has thermal anomaly thresholds that can be adjusted manually) and that the results are available locally within one hour of data capture by the system from the NOAA satellite. In Guatemala, both the local observers on the volcanoes and governmental staff agree on the usefulness of having a locally based station for Central America as an early warning could be critical for assisting in the decision to evacuate local populations. In addition, CONRED scientists express a desire to work on establishing an activity baseline for Fuego based on visual observations from the ground, seismic records and AVHRR data. Such a baseline on Fuego and other volcanoes may assist in decision-making processes and provide an early verification of the value of remote sensing to volcano monitoring operations in Central America.

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