SATELLITE OBSERVATIONS OF THERMAL EMISSION BEFORE, DURING, AND AFTER, THE JANUARY 2002 ERUPTION OF NYIRAGONGO

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Abstract

This paper presents a two-year archive of thermal observations made before, during, and after the January 2002 eruption of Nyiragongo volcano, Democratic Republic of Congo. Infrared satellite data acquired by the Moderate Resolution Imaging Spectro-radiometer (MODIS), a multi-spectral scanner carried onboard the National Aeronautical and Space Administration's (NASA) Terra and Aqua satellites, indicate an absence of significant thermal activity prior to the start of the eruption on January 17, 2002. Thermal radiance data acquired during the eruption record both the approximate size and spatial distribution of the two main flow units that encroached on the city of Goma, and the subsequent cooling of these flows. In June 2002, four months after the end of the initial effusive episode, magmatic activity resumed in the summit crater of the volcano. MODIS has recorded thermal emission from the summit crater lava lake on a further 114 days, as of February 29, 2004. Trends in the amount of radiance detected from the active lava-lake indicate a gradual increase in the level of activity, and constitute a variable for monitoring the level of magmatic activity in the crater remotely. The data we present were, and continue to be, made available to the Goma Volcano Observatory via the Internet, within 24 hours of MODIS overpass (http://modis.higp.hawaii.edu).

Keywords: MODIS, remote sensing, thermal monitoring, Nyiragongo

Introduction

Satellite remote sensing offers a convenient method for monitoring thermal unrest at erupting volcanoes that are otherwise poorly instrumented or difficult to observe adequately from the ground. The volcanological potential of Earth-orbiting satellites had been demonstrated in the 1970s (e.g. Williams and Friedman, 1970) although it was not until the 1980s, and the launch of the Landsat Thematic Mapper (TM), that concerted efforts were made to develop tools and methodologies for extracting useful volcanological information from the data (e.g. Francis and Rothery, 1987, Rothery et al., 1988, Oppenheimer 1991). Subsequently, space-based measurements of spectral radiance, and parameters derived from them, have been shown to provide useful information regarding a variety of important volcanic processes relating to, amongst other things, the emplacement of lava domes (e.g. Oppenheimer *et al.* 1993, Wright *et al.* 2002a), lava lakes (e.g. Oppenheimer and Francis 1997, Harris *et al.*, 1999), and lava flows (e.g. Flynn *et al.* 1994, Wright *et al.* 2001a).

The adoption of remote sensing technology as a volcano monitoring tool was initially hampered by the low temporal resolution, relative inaccessibility and high cost of the TM data that were being used at the time. Meteorological satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and the Along Track Scanning Radiometer (ATSR), on the other hand, provide data which are both cheap, or free, and acquired at a temporal frequency high enough (~12-72 hours) to study dynamic volcanic phenomena. Several studies showed how these types of data could be used to perform detailed time-series analyses of volcanic eruptions, although in terms of eruption monitoring they were largely proof-of-concept. While the data themselves were acquired at high temporal resolution they were not analysed until months or even years later (e.g. Harris *et al.* 1997, Wooster and Rothery 1997). The work of the Alaska Volcano Observatory, which has incorporated near-real-time analysis of AVHRR data into its monitoring campaign since the early 1990s, is a notable exception, (see Schneider *et al.* 2000, for a summary).

In recent years the insights gained from these and other studies have been incorporated into near-real-time thermal volcano monitoring systems of increasing geographic scope, largely as a result of the opportunities for rapid data transfer that have been facilitated by both advances in desk-top computing power and the arrival of the Internet. The raw data themselves are often telemetered from the satellite to the ground within minutes of acquisition, and with broad-band internet capabilities can be obtained for volcanological analysis within the same time-frame. The Internet provides a medium via which the results of this analysis can be communicated just as quickly. The system described by Harris *et al.* (2001), which uses GEOS data (Geostationary Operational Environmental Satellite) to monitor thermal emission from volcanoes on and within the Pacific 'Ring of Fire', constitutes a type example of such an approach.

The MODVOLC algorithm, developed at the Hawaii Institute of Geophysics and Planetology (Wright *et al.* 2002b, Flynn *et al.* 2002, Wright *et al.* 2004), uses infrared radiance data acquired by NASA's Moderate Resolution Imaging Spectro-radiometer (MODIS) to monitor thermal unrest at all of the Earth's sub-aerially active volcanoes and makes the results available for inspection via the Internet within 24 hours of satellite overpass. This paper describes the results obtained from this system before, during, and after the January 2002 eruption of Nyiragongo. We focus on the results obtained using this

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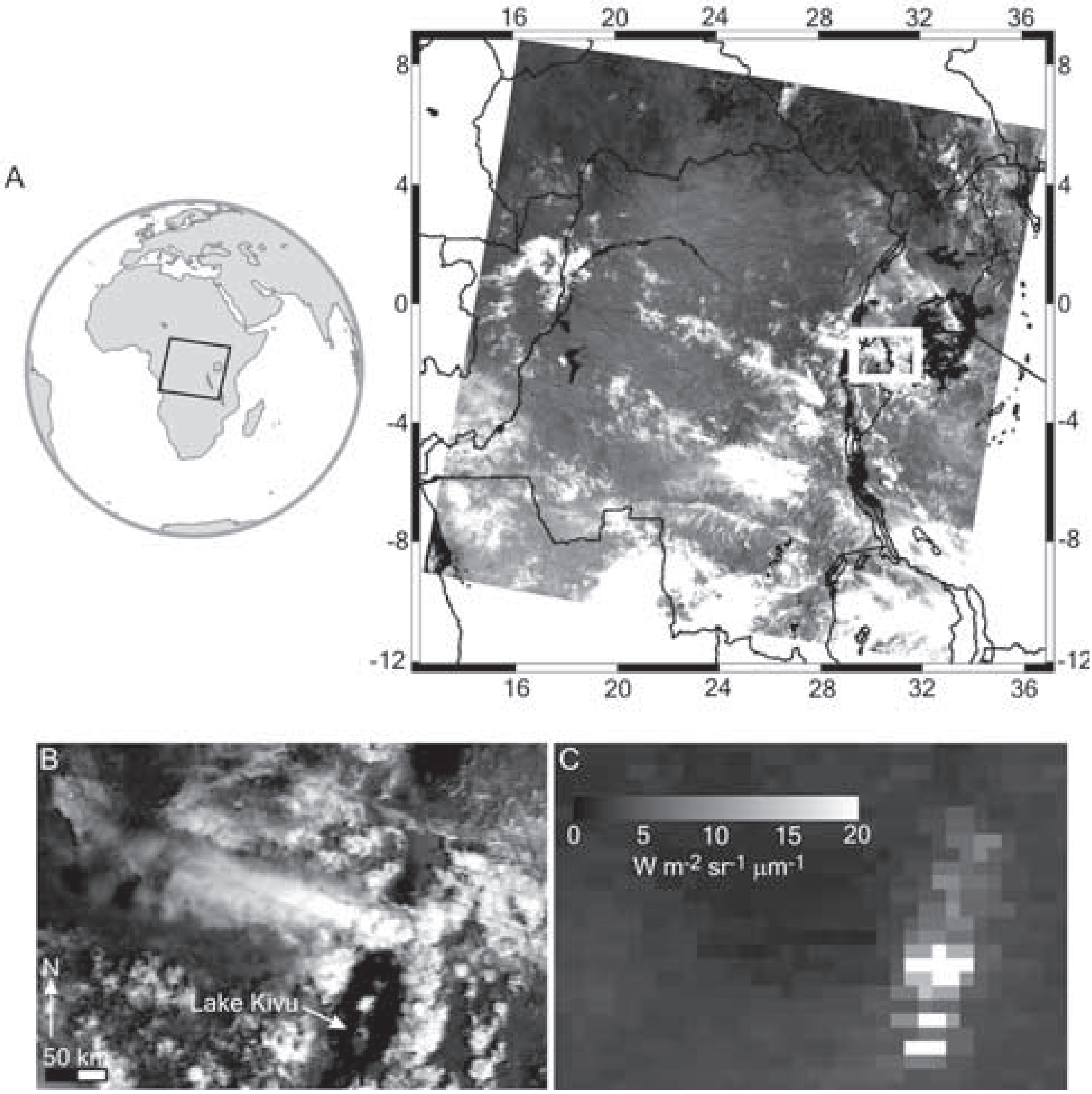

FIG. 1. a) MODIS image of Nyiragongo acquired at 10:50 (local time) on January 17, 2002, less than an hour after the beginning of the eruption. b) Subset of this image; a large west-trending plume obscures the summit of Nyiragongo. c) Subset of a MODIS band 21 (3.959 mm) image acquired at 22:15 on January 18. Bright pixels that contain active lava are easily distinguished from adjacent image pixels that do not, on the basis of the 3.959 μ m spectral radiance. Each pixel measures 1 km on a side.

system because of their pertinence to future monitoring of volcanic activity at Nyiragongo, and its neighbour, Nyamuragira. All of the results we present were produced using data available on-line at http://modis.higp.hawaii.edu. Downloading the data does not require a broad-band internet connection, as the results of the MODVOLC algorithm are stored in small (*i.e.* ~10 kb) space-delimited text files. By illustrating how volcanologically useful information regarding the recent and ongoing activity at Nyiragongo can be gleaned from this data source we will show how the system could be used in the future as a near-real-time monitoring tool by volcano observatories, such as the Goma Volcano Observatory that, currently, have to rely on low band-width, dial-up internet connections.

WEB-BASED MONITORING OF NYIRAGONGO USING MODIS

There are currently two MODIS sensors operating in near-circular, sun-synchronous, low-Earth orbit. The first was launched on NASA's Terra spacecraft in December 1999, the second in June 2002 onboard Terra's sister-ship, Aqua. The MODIS imaging swath is ~1354 km wide

which, given the period of the orbit, results in gaps between adjacent image swaths at the equator and overlap at higher latitudes during any 24 hour period. As a result, each satellite achieves complete global coverage once every 48 hours. Terra and Aqua have local solar equatorial crossing times of 10:30 and 13:30, respectively, corresponding to the descending (Terra) and ascending (Aqua) nodes of their orbits. The same points on the Earth's surface are observed again, in the absence of sunlight, approximately 12 hours later. As a result, ground targets occupying equatorial latitudes, such as Nyiragongo, are imaged up to four times in each 48 hour period, twice by day and twice by night, although the viewing geometry varies.

FIGURE 1 (a) and (b) show a MODIS image of Nyiragongo acquired at 10:50 (all subsequent times given in this paper are local, unless otherwise indicated) on January 17, 2002, two hours after the eruption began. FIGURE 1c shows a subset of a MODIS image acquired at 22:15 on January 18. This image, which was acquired at night, depicts variations in 3.959 μ m spectral radiance caused by differences in surface temperature. A lava flow is conspicuous as an elongate cluster of tonally 'bright' pixels. At 3.959 μ m the amount of spectral radiance emitted by a surface increases approximately with the fourth power of temperature, explaining why those pixels that contain active lava flows emit orders of magnitude more energy than adjacent image pixels that do not, making them relatively easy to distinguish. This principle, which also applies to the detection of active lava features significantly smaller than the 1-km pixel size of the instrument, forms the basis of several automated volcano monitoring systems (e.g. Dehn *et al.* 2000, Harris *et al.* 2001, Kaneko *et al.* 2002).

The MODVOLC system (see Wright *et al.* 2002b, 2004, for details) also exploits this relationship. The algorithm scans each MODIS image acquired and computes a Normalised Thermal Index (*NTI*) from the amount of radiance emitted by each pixel at 3.959 (MODIS bands 21 and 22) and 12.02 μ m (band 32) using,

$$NTI = \frac{L_{22} - L_{22}}{L_{22} + L_{32}}$$

[1]

or, when band 22 is saturated,

$$NTI = \frac{L_{21} - L_{32}}{L_{21} + L_{32}}$$

[2]

Here, L_{21}, L_{22}, and L_{32} refer to the amount of spectral radiance (W m^{-2} sr^{-1} μ m^{-1}) emitted by the pixel in MODIS bands 21, 22, and 32, respectively. Band 22 is used as the primary detection band as it has a higher radiometric precision than band 21 (0.07 K; *cf.* 2.0 K for band 21). However, when band 22 saturates (*i.e.* the emitted radiance exceeds the maximum measurable signal of the band 22 detectors) band 21 is used to calculate the *NTI*, due to its extended measurement range (~500 K; *cf.* ~340 K for band 22).

Those pixels for which the *NTI* exceeds empirically derived threshold values of -0.80 at night and -0.60 during the day are classified as hot-spots, and their details are displayed at the following web-site (http://modis.higp.hawaii.edu).

THE JANUARY 2002 ERUPTION

No thermal anomalies were detected by MODVOLC prior to the beginning of the January 2002 eruption. Enhanced ripening of bananas has been advanced as possible evidence for localised increases in ground temperature prior to the start of the eruption (Smithsonian Institution 2003a). However, such low temperature anomalies, of the order of several degrees above ambient, are below the detection threshold for MODVOLC (see Wright *et al.* 2002b for details) and indeed the other satellite monitoring systems referenced earlier, which are optimised to detect the presence of active lava at the Earth's surface. Rothery *et al.* (1995) provide a discussion of the principles and difficulties of detecting such low temperature thermal anomalies in low spatial resolution satellite data.

The eruption began at 08:35 local time on January 17, 2002, when a series of fissures opened 300-400 m north of the Shaheru crater draining the summit lava-lake, which had been present since 1994 (Smithsonian Institution 2002a). Reports indicate that the eruption ended sometime the following morning, although they also point to continued flow of lava at the surface for several more days (Smithsonian Institution 2002b). Lava flows are not apparent on a MODIS image acquired at 10:50 (local time) on January 17, the summit of the volcano being obscured by cloud and a large west trending plume (FIG. 1b). Later that day, at 23:10, the time of the next MODIS overpass, the Nyiragongo region was totally obscured by clouds. The first cloud-free images of the eruption on which lava flows were visible were acquired at 09:55 and 22:15 on January 18. Cloud cover prevented further observations on overpasses at 10:40 and 23:00 on January 19, 22:05 on January 20, and 10:25 on January 21, before the next cloud-free observation at 22:45 on January 21.

Figures 2 and 3 show the geographic distribution and relative intensity of hot-spot pixels detected by the MODVOLC during the eruption. The geographic location of the centre points of MODIS pixels is known to an accuracy of approximately ± 50 m at satellite nadir (Wolfe *et al.* 2002) with respect to the WGS-84 (World Geodetic System) ellipsoid. This allows the location of the hot-spots to be fairly well constrained with respect to the geography of Nyiragongo and the surrounding area.

At 09:55 on January 18 MODVOLC resolved two distinct lava flows that entered Goma and extended to the shore of Lake Kivu (FIG. 2b). The reported positions of these two flow branches, which are separated by a distance of ~3 km and straddle Mount Goma, are consistent with the results of preliminary field mapping (Smithsonian Institution 2001; FIG. 2a). The absence of hot-spots west of Mount Goma at 22:15 shows that the flows in this area had cooled below the detection limit

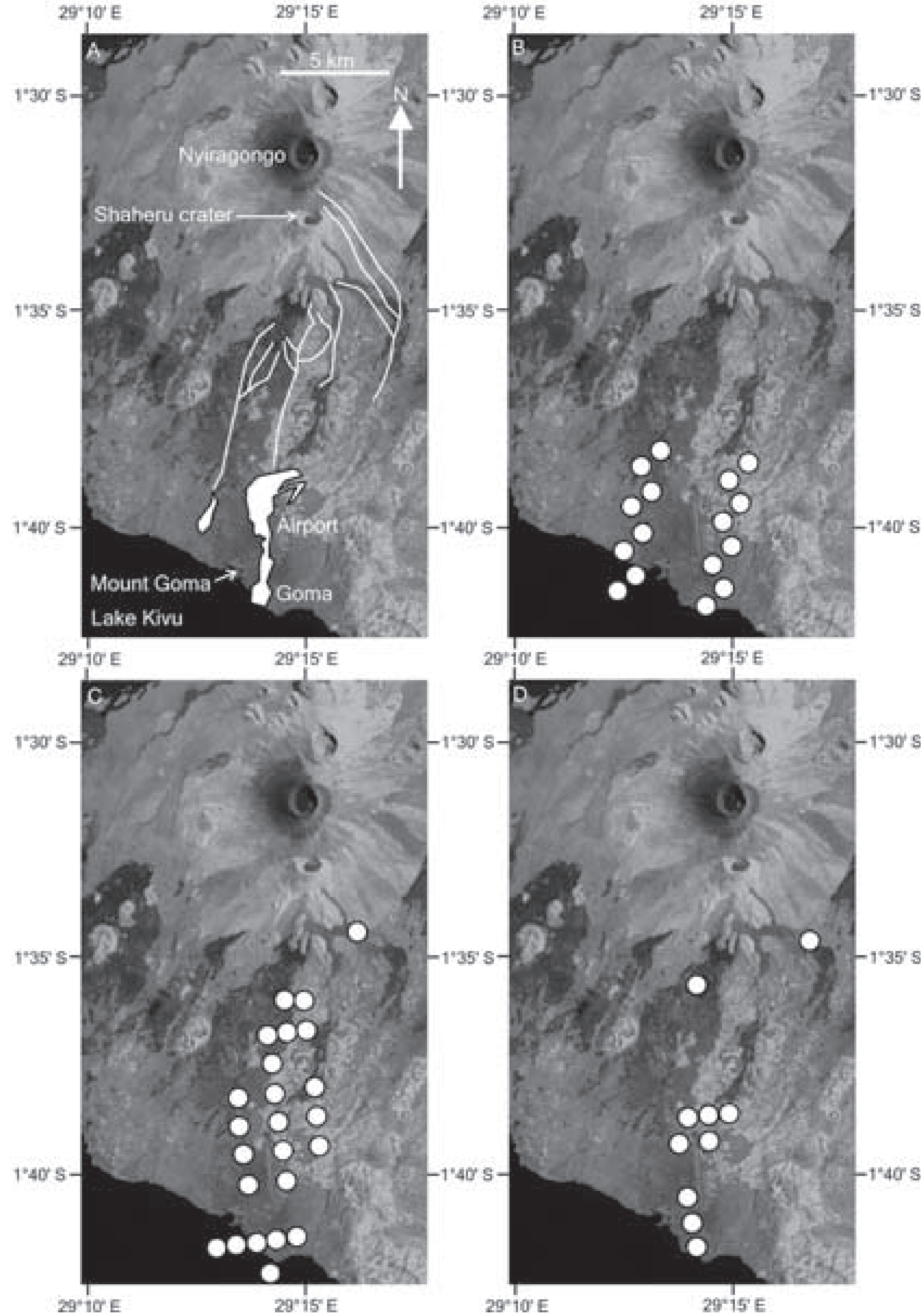

FIG. 2. The location of MODIS hot-spot pixels as detected by MODVOLC during the January 2002 Nyiragongo eruption. a) Landsat Thematic Mapper image, acquired on August 7, 1987, showing the geography of Nyiragongo and Goma. White lines and white polygons denote reported lava flows paths and mapped lava flows, respectively, and are derived from a preliminary field map published by the Global Volcanism Network (Smithsonian Institution 2002b; FIG. 15 therein). b) Hot-spots (white filled circles) detected at 09:55 on January 18, c) Hot-spots detected at 22:15 on January 18. c) Hot-spots detected at 22:45 on January 21. The diameter of the circles is ~1 km, equivalent to the nominal resolution of the MODIS emissive bands used by the MODVOLC algorithm, and each one is centred on a MODVOLC-reported hot-spot location. All images and hot-spots are referenced to the WGS-84 ellipsoid.

of the MODVOLC algorithm, activity being concentrated in the vicinity of Goma's airport (FIG. 2c). On January 21 MODVOLC reported a reduced number of hot-spots, again concentrated around the airport, the size, shape, location and orientation of which mirror exactly the morphology of the main lava flow-field that impacted Goma (FIG. 2a and d).

Although the hot-spot locations reported by MODVOLC are broadly consistent with field mapping, discrepancies, such as the presence of hot-spots actually in Lake Kivu, are apparent. These can be attributed to the fact that the MODIS images acquired on January 18 place Nyiragongo at angles of 39° and 61° from the sub-satellite point. Such extreme off-nadir look angles reduce the accuracy of the MODIS geolocation due to a combination of increased pixel size and overlap of adjacent scan lines (the so-called 'bow-tie' effect; see Wolfe *et al.* 2002). It should also be noted that the MODVOLC algorithm does not distinguish between high-temperature radiators. As a result, vegetation fires started by the passage of the lava flows will undoubtedly make a contribution to the thermal signal detected from one or more of the MODIS image pixels.

The total amount of spectral radiance emitted at 3.959 μ m by the lava flows decreased exponentially across the three observation periods depicted in Figure 3, being 170, 43, and 9 W m^{-2} sr^{-1} μ m^{-1}, respectively. The amount of short-wave infrared energy emitted by a lava flow can be considered an index of flow motion. Lava close to the eruption temperature is continually exposed at the surface of a lava flow while it is moving, as the stresses fracture the chilled crust. When a flow stops moving, the lava exposed in these cracks cools rapidly, as new cracks are not produced to replace them. This reduction in the thermal renewal of the flow surface upon stagnation causes the amount of short-wave infrared radiance emitted by the flow to decrease dramatically (Wright *et al.* 2001b). Based on this observation, and the data presented in FIG. 3, we suggest that lava flows were still active at 09:55 on January 18. Within 12 hours, however, the amount of short-wave infrared spectral radiance from the flow surfaces had fallen by almost an order of magnitude (FIG. 3b) indicating widespread stagnation of the flows. The high radiances measured in the region just north of the airport indicate however, that lava may still have been flowing in this area at 22:15 on January 18 and to a much lesser degree at 22:45 on January 21 (FIG. 3c). Field reports indicate that the eruption ended sometime on the morning of January 18, although surface flows were observed after this time, and lava tubes within the flow-field continued to transmit lava to Lake Kivu for several more days (Smithsonian Institution, 2002b). It is likely, therefore, that the active flows observed by MODIS represent the eruption of lava stored within the flow-field from ephemeral vents, and that these vents became concentrated in the region north of the airport between January 18 and January 21 while flows in other areas cooled and stagnated.

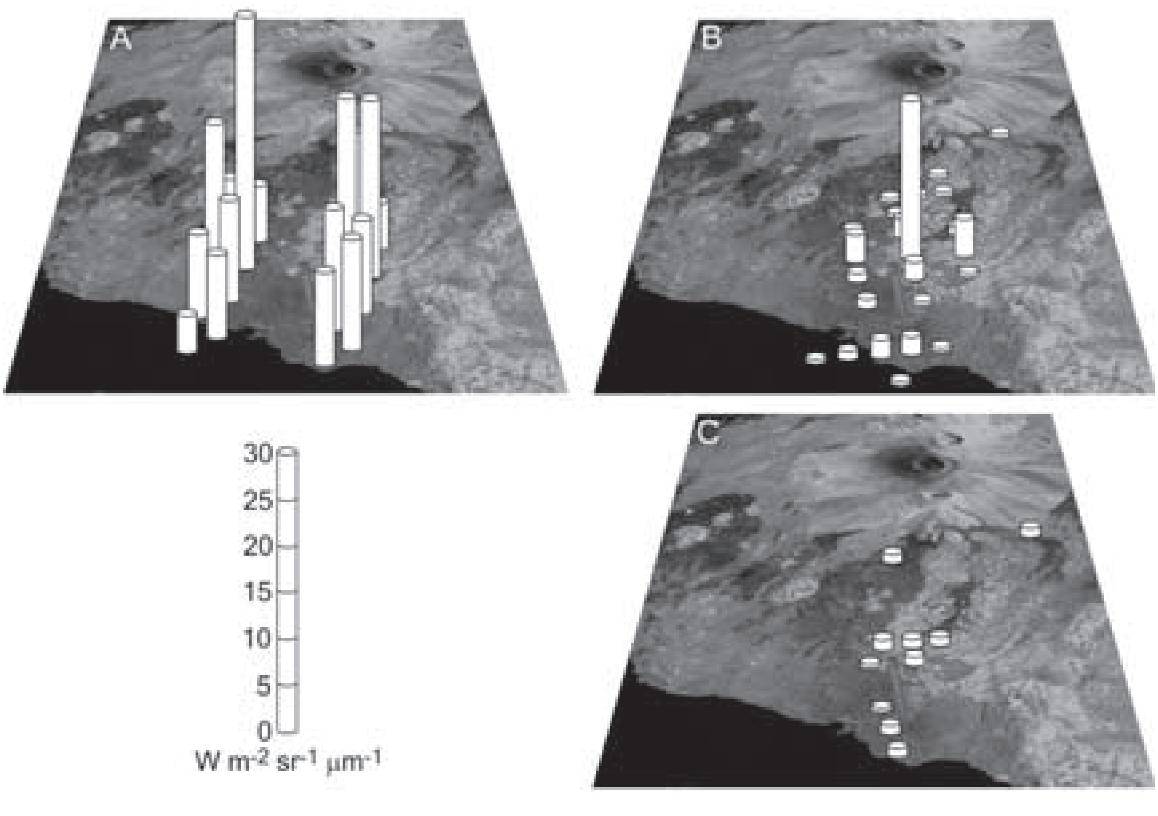

FIG. 3. Relative spectral radiance (3.959 μ m) from each of the hot-spot pixels shown in Figure 2. a) hot-spots detected at 09:55 on January 18, c) hot-spots detected at 22:15 on January 18. c) hot-spots detected at 22:45 on January 21.

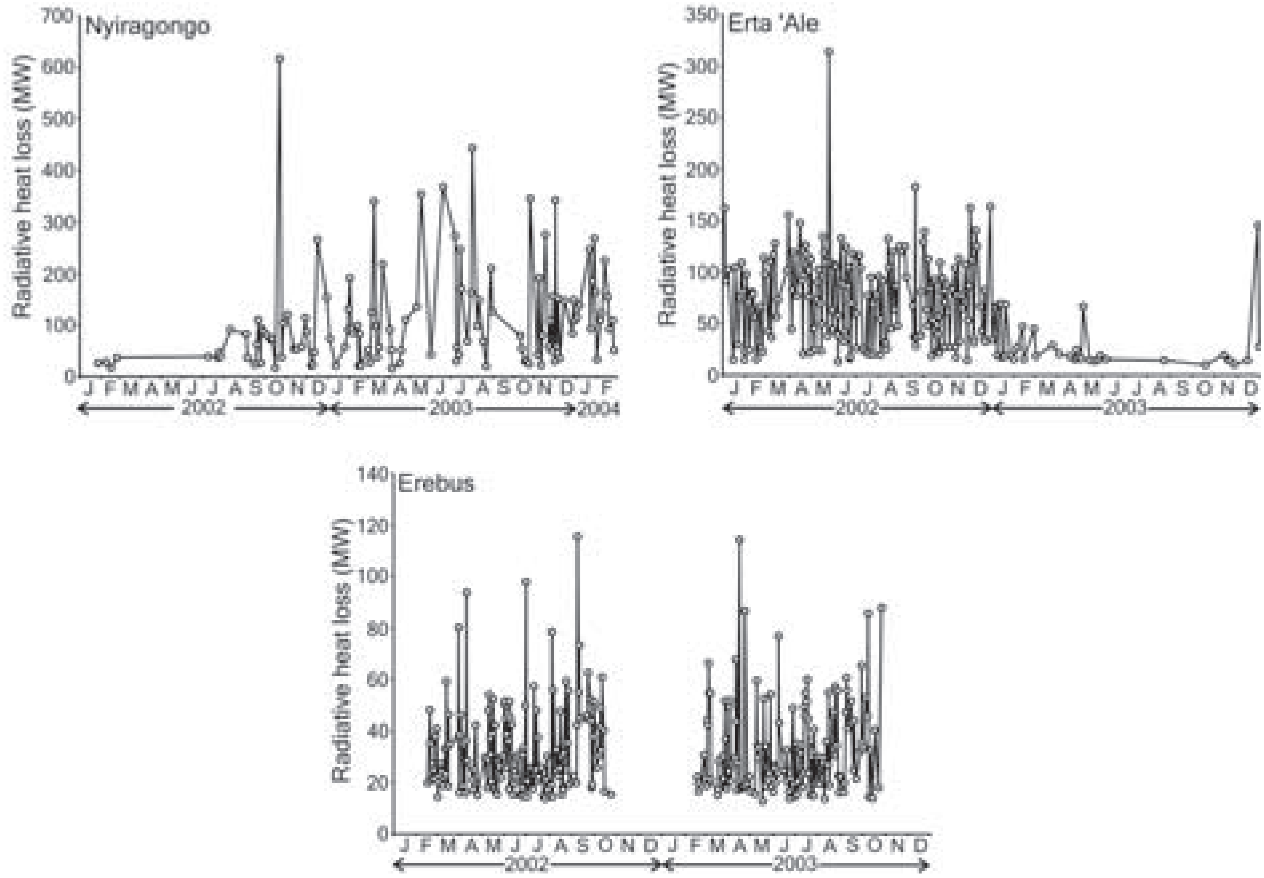

FIG. 4. Radiative heat output (in MW) calculated from MODIS data for lava lakes at Nyiragongo, Erta 'Ale (Ethiopia) and Mount Erebus (Antarctica). Data for Nyiragongo are presented for the period January 1, 2002 to February 29, 2004. Data for Erta 'Ale and Erebus are presented for the period January 1, 2002 to December 31, 2003. Each plot symbol denotes a date when MODVOLC detected a summit crater thermal anomaly; the line merely connects discrete data points, and does not signify continuous observations. Note the different scales of the ordinates. Only results obtained via analysis of the nighttime MODIS data stream are presented, as these measurements are uncontaminated by the effects of solar reflection and solar heating. As we only use nighttime data in our analysis, data gaps exist between late October and mid-February at Erebus, during the Antarctic summer.

POST JANUARY 2002: THE RESUMPTION OF SUMMIT CRATER LAVA-LAKE ACTIVITY

Figure 4 shows how the total amount of heat radiated from Nyiragongo's summit crater varied between February 2002 and October 2003, calculated from the MODVOLC data stream (see Wright and Flynn 2004, for an explanation of the method used). Although the geographic location of the centre point of these pixels is well constrained, it is impossible to determine where within the 1 km MODIS pixels the volcanic hot-spot is located. This accuracy, which is similar to the dimensions of Nyiragongo's summit crater, means that while we can be confident that the hot-spots were within the summit crater we cannot say anything regarding their intra-crater position.

The first summit crater hot-spot was detected by MODIS on January 27, 2002, with a further three observed in February 2002. This initial period of summit crater unrest was followed by a four-month hiatus before the next summit crater hot-spot was observed on July 9, 2002. Since this time MODVOLC has detected hot-spots on a further 114 days, as of February 29, 2004.

The first effusive activity in the summit crater, a small fire fountain approximately 12 m high, was observed on May 18, 2002 (Smithsonian Institution 2002c). However, MODVOLC only began detecting hot-spots at the summit crater on a regular basis after July 9, 2002. This onset of satellite detection correlates with a noted increase in the level of activity in the crater. Observations made on July 17 revealed an extremely active summit crater, with lava fountains 100 m high, suggesting the probable existence of a lava-lake that was not present during the May 2002 visit (Smithsonian Institution 2002d).

The presence of an active lava lake, ~45 m in diameter with an «agitated surface», was confirmed by field observations made in December 2002 (Smithsonian Institution 2003b). The maximum height of lava fountains increased from 100-m in February 2003 to 300-m in late March 2003, and the diameter of the lava lake surface was observed to have increased between late April and early May 2003 (Smithsonian Institution 2003a). By May 22, 2003, the lava-lake had expanded to cover the entire crater floor (Smithsonian Institution 2003c; FIG. 31 therein).

We do not attempt a detailed comparison between these field observations and the MODIS radiance observations, as the day-to-day variations in radiative heat loss presented in Figure 4 are not necessarily indicative of short-term variations in eruptive intensity. A decrease in at-satellite radiance from one observation to the next could be caused by partial obscuration of the lava-lake by intra-crater plumes or scattered meteorological clouds. However, field reports do point to an increase in both the size and activity of the lava lake between July 2002 and June 2003, and we draw attention to the fact that although the amount of heat detected by MODIS from the summit crater has fluctuated during this period, these fluctuations have been superimposed on a general trend of increasing thermal emission (FIG. 4).

Thermal emission from Nyiragongo's summit crater lava-lake has continued to follow a general upward trend. This trend must correspond to further increases in the vigour and/or dimensions of the lake, as described in the previous paragraphs. Although we caution against interpreting each peak and trough in terms the eruptive activity, many studies have shown how extended satellite time-series provide statistically representative thermal emission data sets from which real trends in surface magmatic activity can be discerned, and the long-term eruptive behaviour of the volcano characterised (e.g. Oppenheimer *et al.* 1993, Wooster and Rothery 1997, Harris *et al.* 2001, Dehn *et al.* 2000, Wright *et al.* 2002a). Extending the data set presented in Figure 4 will provide a useful surrogate for field observations of summit crater activity, when such observations cannot be made.

The total amount of heat radiated by Nyiragongo's lava-lake, obtained by integrating the heat flux shown in Figure 4, was 1.4×10^{15} J and 3.8×10^{15} J, in 2002 and 2003, respectively. Clearly, a significant volume of magma must have cooled to yield this amount of thermal energy. Following Francis *et al.* (1993), we assume that the magma that cools to produce the measured surface heat flux becomes thermally isolated from the remaining melt and is emplaced either as dykes (model 1) or cumulates (model 2). The mass of magma needed to balance thermal losses is given by $Q/(H\Delta f + c\Delta T)$, where Q is heat loss (J), H is latent heat of crystallisation (4.2×10^5 J kg^{-1}), and c is specific heat capacity (1.0×10^3 J kg^{-1} K^{-1}). ΔT (cooling interval) and Δf (mass fraction of crystallisation) vary by model and have respective values of 50 °C and 0.25 (model 1; dykes) and 400 °C and 1.0 (model 2; cumulates). By using this model, our data indicate that, during 2002 and 2003, the amount of magma needed to balance the estimated heat loss of $\sim 9.1 \times 10^{15}$ J from the lava lake at Nyiragongo (including convective cooling at a maximum of 75% of radiative cooling; see Wright and Flynn, 2004 for a justification, based on previous work by Head and Wilson 1986, Oppenheimer 1991, Wooster *et al.* 1997; and Neri 1998) was 5.9×10^{10} kg, if emplaced within the edifice as dykes, or 1.1×10^{10} kg, if cooled and crystallized to a greater degree and emplaced as cumulates, at an average rate of between 350 and 1900 kg s^{-1}. Assuming a magma density of 2650 kg m^{-3} for Nyiragongo nephelinite, this implies that a volume of between 0.004 and 0.2 km^3 of magma must have cooled to sustain thermal losses since the resumption of summit crater activity in May 2002. Given that Nyiragongo is situated in an extensional environment likely to promote rifting, we suggest that the upper limit of this volume range, which assumes that the cooled lava is emplaced as dykes, is more realistic.

To place the recent thermal emission from Nyiragongo's lava lake in context, we can compare the thermal emission estimates we present here with those determined previously at Nyiragongo, as well as those determined for lava lakes at other volcanoes. Le Guern (1987) reports radiative heat flux estimates obtained during two expeditions to Nyiragongo, in 1959 and 1972 of 5×10^8 W and 122×10^8 W, respectively. It is difficult to judge how representative these estimates are of longer-term heat fluxes from the lava lakes during these two periods. Certainly, the radiative flux we calculate has varied by two orders of magnitude during 2002 and 2003, being in the range 0.01 to 7×10^8 W, with a mean value of 1×10^8 W. However, it is interesting to note that the radiative heat flux reported by Le Guern for the 1972 expedition is two orders of magnitude greater than the maximum value measured thus far during the current cycle of lava lake activity by MODIS.

Figure 4 also shows radiative heat loss calculated for active lava lakes at Erta 'Ale, in Ethiopia, and Mount Erebus, in Antarctica, during 2002 and 2003. Both volcanoes have probably hosted persistently active lava lakes throughout historic times. In the period January 1, 2002 to December 31, 2003, the lava lake at Nyiragongo radiated more energy, 5.2×10^{15} J, than the lakes at either Erta Ale or Mount Erebus, which radiated approximately 3.0 and 1.4×10^{15} J, respectively, which given the analysis presented previously, points to a significantly higher magma flux.

CONCLUSIONS

The data we present were, and will continue to be, freely available for use by the Goma Volcano Observatory within 24 hours of MODIS overpass. This paper has shown how simple-to-compile MODIS time-series can be used to provide useful information regarding short-lived, but spatially extensive, lava flows and small, but long-lived, lake lakes. Although the January 2002 eruption lasted only two days, and the first cloud-free observation was not made until just after the initial lava effusion ended, MODIS was still able to provide information regarding where lava was still flowing on the surface. During a future, longer-lasting eruption, MODIS will prove useful for mapping both the spatial and temporal distribution of active flows.

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