STROMBOLI MODIS THERMAL ANOMALIES DURING STROMBOLIAN ACTIVITY

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INTRODUCTION

Satellite remote sensing has seen very broad spectrum of applications, deepening and expanding our understanding in environmental monitoring for the last four decades. This technique is now being increasingly used to obtain basic geological information and above all for reducing natural hazards. In particular, the observations recorded by remote sensing satellites now offer additional means of early warning of volcanic hazards and a new way to measure the thermal energy of volcanoes. For this reason, satellite remote sensing has been used to study and monitor volcanic activity for decades, thanks to many orbiting satellite platforms that provide a global coverage of active volcanoes with a high repetition frequency. Sensors on satellite platforms are used routinely for this type of monitoring, with infrared channels offering the potential to detect and measure temperatures of features such as lava bodies and fumarole fields.

Sensors like MODIS-NASA (*Moderate Resolution Imaging Spectroradiometer*) aboard EOS (*Earth Observing System*) satellites, have largely been used to detect, study and monitor thermal volcanic activity (*e.g.,* Harris *et al.*, 1995, 1999, 1999b, 2001, 2002; Harris & Thornber, 1999; Wright *et al.*, 2002, 2005; Wright & Flynn, 2004; Kaneko *et al.*, 2002; Pergola *et al.*, 2004; Patrick *et al.*, 2005) thanks to their features. Several algorithms, generally based on the use of two different spectral bands, have been proposed to detect the hot spot (of volcanic nature or fire) by MODIS sensor. For example, the MODVOLC algorithm (Flynn *et al.*, 2002; Wright *et al.*, 2002; Wright & Flynn, 2004) uses an index named Normalised Thermal Index (*NTI*) based on the investigation of spectral radiance in BAND 21 (3.929-3.989 μm) and BAND 32 (11.77-12.27 μm) channels of the MODIS sensor at the MWIR (Mid Wave Infrared) and LWIR (Long Wave Infrared), respectively. The index is calculated by applying the following equation:

$$NTI = (L22 - L32) / (L22 + L32)$$

where $L22$ and $L32$ are the spectral radiances in $W \cdot m^{-2} \cdot \mu m^{-1} \cdot sr^{-1}$ recorded in the band 22 and 32, respectively. Wright *et al.* (2004) provided a full description of how the MODVOLC algorithm was developed, tested and implemented. In particular, for data collected at night-time and free from the effects of solar reflection, MODVOLC algorithm reports an alert whenever the *NTI* is greater than –0.8 whereas the more appropriate empirical value found by MODVOLC Team to detect a hot spot during day-time is –0.6. By analysing MODVOLC thermal alerts, Patrick *et al.* (2005) and Rothery *et al.* (2005) have shown the efficiency of this approach in detecting and analyzing volcanic activity in remote regions of the planet.

However, it should be considered that some problems still remain for thermal volcanic surveillance by satellite, requiring specific improvements especially in terms of exportability in different geographic areas and under critical observational conditions. In particular, the nominal size at nadir of a MODIS pixel (1 km^2) does not actually allow a continuous monitoring of any volcanoes because of their small size are hardly detectable such as Stromboli which is a dynamic open system with a persistent activity. For this volcano MODIS sensor could provide daily data capable of giving information about the thermal flux and the thermal state of its terrace through a wide *Instantaneous Field of View* (IFOV) (Fig. 1).

For this purpose, our study was been to evaluate the potential for using multi-temporal digital data from the MODIS to estimate the thermal radiation released by Stromboli toward the space. By utilizing the spectral radiance contained in MODIS images (day and night exposures), we investigated the thermal energy emitted between 2006 and 2008, time lapse characterized by low, middle and high Strombolian activity and the 2007 effusive eruption (27 February - 2 April).

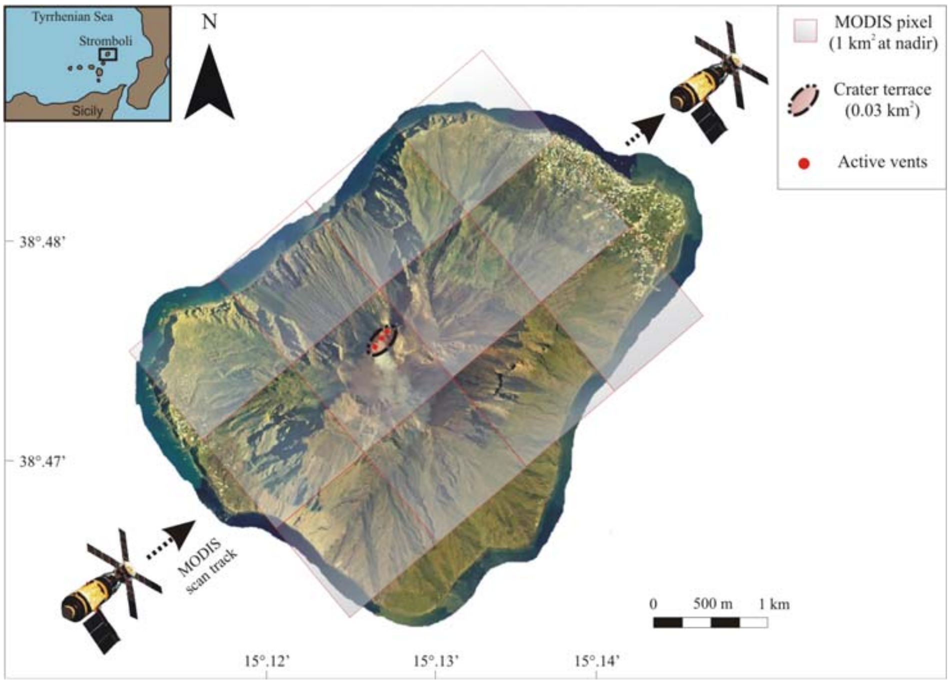

Fig. 1 - Relationship between the size of a MODIS pixel (at nadir) and the thermal anomalies produced during the Strombolian activity (modified after Baldi *et al.*, 2005; orthophoto taken by a survey of May 2001).

METHODOLOGY AND RESULTS

We analysed through an *automatic main routine* (AMR) both night and day-times MODIS level 1b granules (http://ladsweb.nascom.nasa.gov; Xiong & Barnes, 2006), acquired over Southern Tyrrhenian during the period ranging from 1 January 2006 to 15 October 2008 (about 5000 granules). AMR allowed us to analyse each MODIS image and to extract the data contained on a spatial mask centered on Stromboli (spatial mask of 15 × 15 km). In particular, AMR has saved a cubic matrix for each MODIS image composed by the spectral radiance of Stromboli land registered by BAND 21 and 32 as well as the spatial coordinates, the time of acquisition and the viewing geometry of satellite (*satzen*).

A first analysis on all the 5000 cubic matrices allowed us to concentrate our investigation on the 2007 eruption by refining *NTI* threshold in the light of the geography and the seasonal changes at Stromboli (Fig. 2). For this purpose, we applied a *NTI* threshold of –0.88 (obtained by applying a fluctuating threshold; Fig. 2a) and –0.7 (fixed threshold; Fig. 2b) for night-time and day-time, respectively. This approach has alerted more pixels than the original MODVOLC algorithm and gave us the capability to better quantify the thermal energy emitted during this eruptive crises.

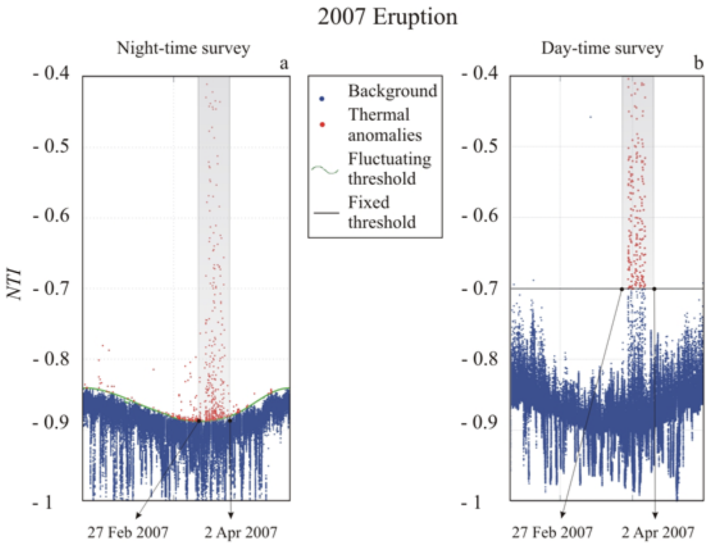

Fig. 2 - *NTI* index adapted for night-time and day-time survey for Stromboli area: the red points show thermal anomalies produced during the 2007 Eruption occurred between 27 February and 2 April 2007. a: night-time survey obtained by considering a *NTI* of -0.88 (fluctuating threshold). b: day-time survey obtained by considering a *NTI* of -0.7 (fixed threshold).

In particular, the net spectral radiance emitted by lava flow, and shared between more than one MODIS pixels, is calculated by summing the $L22$ spectral radiance of each pixel contaminated by the flow during single satellite overpass (Wright and Flynn, 2004) for night and day-time images. Therefore, the sum of $L22$ for the alerted pixels ($L22_{HOT}$) time-series can be used as an indicator of the intensity of volcanic activity; the background is represented by the mean of $L22$ ($L22_{BK}$) of the pixels not contaminated by lava flow (Wright and Flynn 2004; Rothery *et al.*, 2005). However, clouds, atmospheric attenuation and *satzen* effects introduce noise into the time series. Thus, we applied the following two steps before calculating $L22_{HOT}$ and $L22_{BK}$:

- we analysed all the single MODIS overpasses to distinguish between clear and cloudy conditions by applying the algorithm proposed by Giglio and co-authors (2003) based on brightness temperature and reflectance in the LWIR and VNIR (visible and near infrared), respectively.

- the quality of viewing geometry effect has been considered through the *satzen* value: we accepted all spectral radiances when Stromboli has been captured by MODIS sensor with *satzen* < 45°.

Note that, during the analysed period (35 days), from a total of 194 MODIS overpasses, 30 images (≈ 18%) have been acquired under clear sky and *satzen* < 45°. Finally, we obtained Radiative Heat Flux (Q_{RAD}) time series expressed in MW following the method proposed by Wooster *et al.* (2003) (Fig. 3):

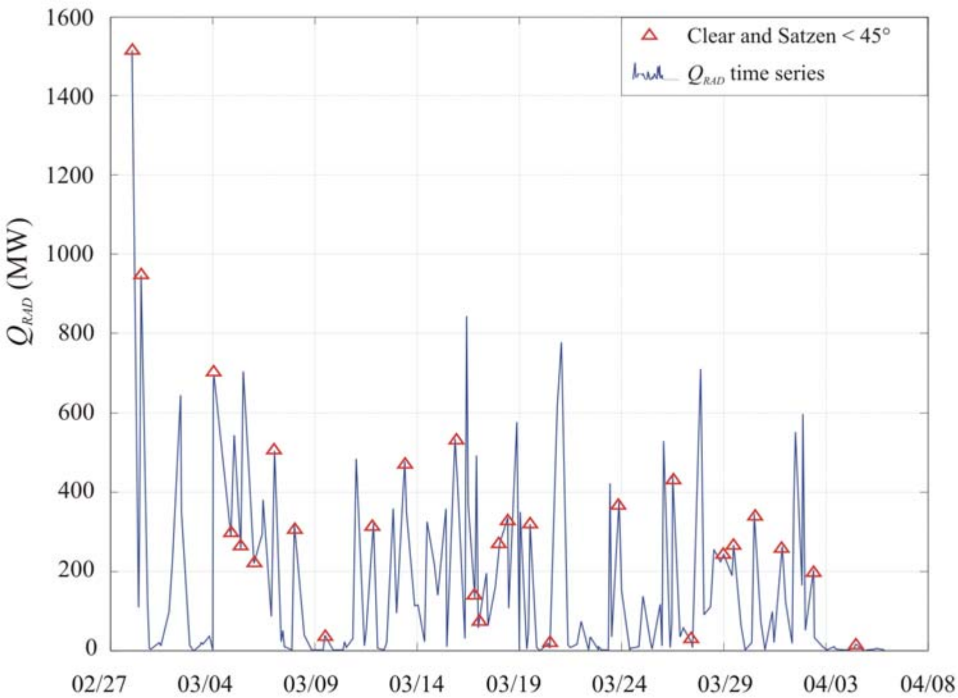

Fig. 3 - Q_{RAD} time series calculated for the 2007 eruption (blue line). Optimal conditions for MODIS overpasses are indicated with triangles.

$$Q_{RAD} = 1.89 \cdot 10^7 \, (L22_{HOT} - L22_{BK})$$

Otherwise, Strombolian activity has been detected by applying two main considerations:

- an in depth investigation for each cubic matrix in order to analyse Stromboli land pixels, and compute the variables used in literature for detecting the hot spot, background spectral radiances and the cloud index.

- for filtering the data from background effect, they have been used synchronous images centered on Salina island were thermal anomalies are absent. The choice related to Salina is justified by four main reasons: the absence of thermal anomalies on Fossa delle Felci; the proximity of the two islands which allows the spectral radiances to be measured at the same time (within the same MODIS image); the topographic resemblance between Fossa delle Felci (961 m a.s.l.) and the summit of Stromboli (Pizzo sopra la Fossa; 918 m a.s.l.); finally, the climatic similarity between the two islands. For the spatial mask centred on Salina have been applied the same considerations above mentioned for Stromboli.

The equation applied for 2007 eruption (Wooster *et al.*, 2003) allowed us to calculate the Radiative Heat Flux (± 30%) when the *Te* (effective temperature of the sub pixel emitter that would provide the observed MWIR signal) of the lava flow ranges between 600 and 1500 K. Since Te related to Strombolian activity can be highly variable (due to the impulsive nature of Strombolian explosions), the *Radiance Flux* ($L22_{HOT} - L22_{BK}$) may only be regarded as an index of the radiative heat flux produced by Stromboli.

Therefore, we estimated the spectral power emitted both by Stromboli and Salina Island ($\Phi L22_{STR}$ and $\Phi L22_{SAL}$) by considering exclusively the anomaly in the MWIR signal ($\Phi L22$) which is expressed as:

$$\Phi L22 = L22_{HOT} - L22_{BK}$$

where $L22_{HOT}$ is the MWIR spectral radiance of the hot spot contaminated pixel and $L22_{BK}$ is the MWIR spectral radiance of the background in absence of thermal anomalies.

We may assume that $\Phi L22_{STR}$ signal is composed by two components: the first related to thermal anomalies of Strombolian activity ($\Phi L22_{STR\ ACT}$), the second likely due to residual seasonal background. Therefore assuming this factor as the $\Phi L22_{SAL}$, we subtracted the two spectral powers of the two islands to compute $\Phi L22_{STR\ ACT}$. This procedure has been improved through several logic equations that discriminate clear sky conditions on both islands. In doing so, we may assume that $\Phi L22_{STR\ ACT}$ time series is calculated by the best MODIS data acquired daily (Fig. 4).

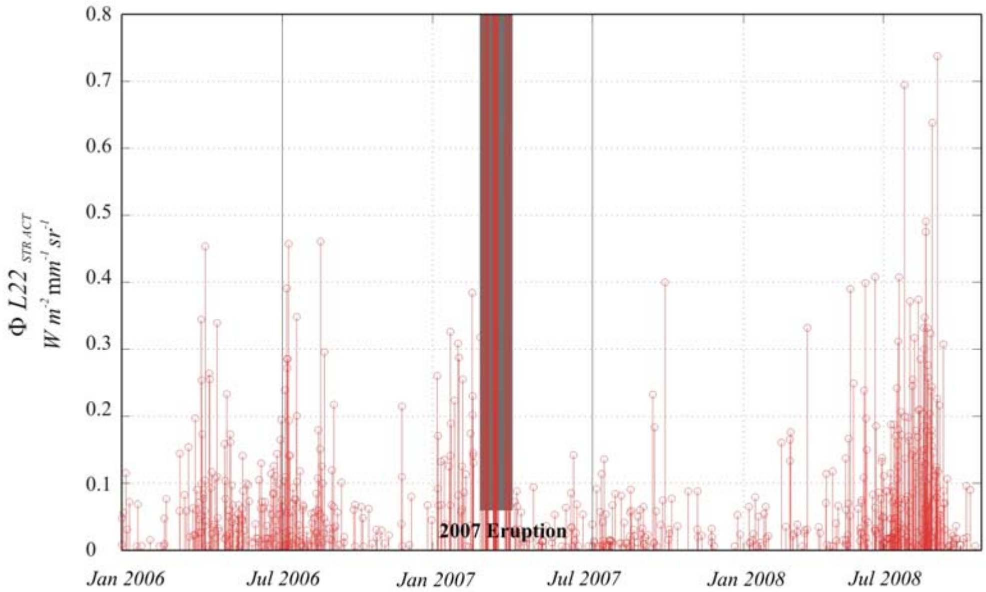

Fig. 4 - $\Phi L22_{\ STR\ ACT}$ time series (night-time and day-time series).

DISCUSSION

However, the frequency of Strombolian activity (which may range between 96 and 290 explosions per day; Delle Donne *et al.*, 2006; Patrick *et al.*, 2007) is supposed to have a great influence on the probability that during the acquisition of an image, the MODIS detects an explosion. Therefore, we assumed that the daily average of $\Phi L22_{STR\ ACT}$ (averaged on 15 days) is the improved approximation of the mean thermal radiation emitted in a single day by the Strombolian activity ($\Phi D_{STR\ ACT}$) (Fig. 5a). This approximation allowed us to compare this parameter with several others data acquired *in situ* by University of Firenze (*Laboratorio di Geofisica Sperimentale - DST*), such as thermal (thermal camera-FLIR™) and seismic signals (VLP and volcanic tremor). $\Phi D_{STR\ ACT}$ is well correlated with the cited parameters confirming that the obtained trend is appropriate and not attenuated by cloud coverage. Noticeably, the good correlation with the daily explosions (*exp/days*) recorded by the thermal camera (≈ 0.6 - Fig. 5b) allowed us to estimate a time lapse of ≈ 28 minutes as the time threshold between two consecutive explosions (*time/ex*) to produce a significant MODIS signal. In particular, we introduced an additional index (ψ) that relates the signals of $\Phi D_{STR\ ACT}$ to those of *exp/days* recorded by FLIR™ (Fig. 5c). The index ψ is not significant during the periods characterized by *exp/days* < 50 (*time/ex* > 28 minutes).

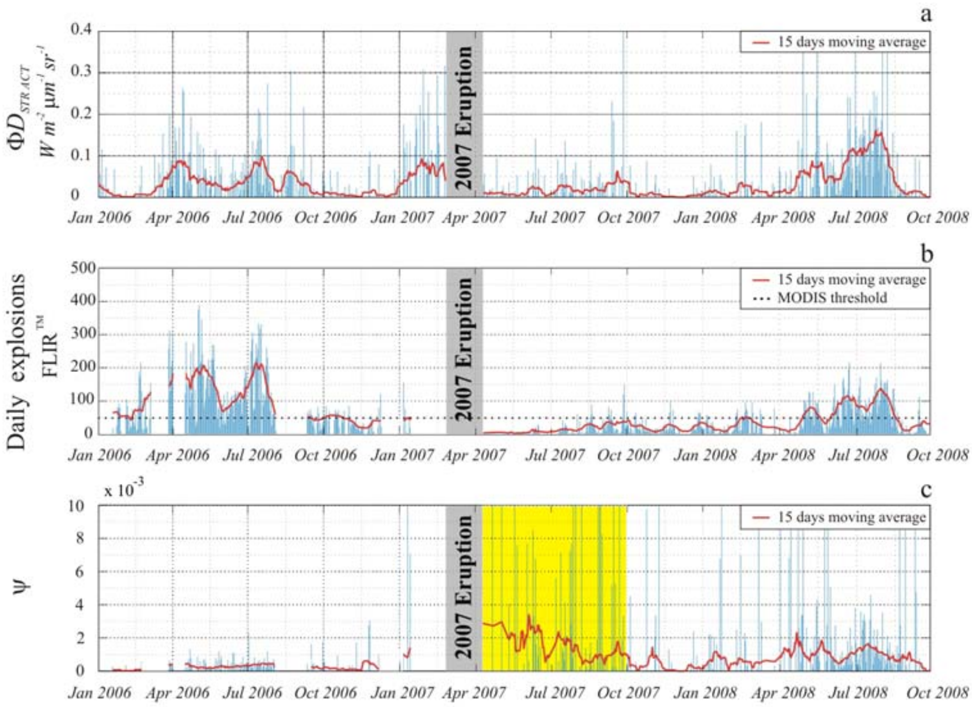

Fig. 5 - Comparison between daily explosions measured by thermal camera and $\Phi D_{STR\ ACT}$. a: $\Phi D_{STR\ ACT}$ and 15 days moving average. b: Daily explosions of the FLIR™ (University of Firenze). c: ψ describes the heat flux density during a day characterized by Strombolian activity. Yellow box shows the *time/ex* > 28 minutes.

This relationships led us to infer that the integrated area temperature of terrace and/or the integrated temperature of the explosions associated with Strombolian activity suffered a drastic increase before the 2007 eruption (as well as since January 2008 to the end of period investigated), thus suggesting a general increase in the activity of the volcano. We can conclude that $\Phi D_{STR\ ACT}$ is a valuable approach to identify the periods of Medium to High Strombolian activity by MODIS.

Finally, by utilizing the Q_{RAD} released during the latter eruptive cycle, we converted it into *Time Averaged Discharge Rates* (TADR) by calibrating our final estimates on the data sets independently obtained by other authors (Spinetti *et al.*, 2007; Marsella *et al.*, 2009) (Fig. 6). The general trend of 2007 eruption exhibits a fast decline of TADR from the initial 17.3 ± 5.19 $m^3\ s^{-1}$ to ≈ 10.8 ± 3.24 $m^3\ s^{-1}$. The following days were characterized by the steady effusion of lava estimated between 1.5 - 3 $m^3\ s^{-1}$. These were occasionally interrupted by peaks in flow rates ranging from 5 ± 0.45 to 8 ± 2.4 $m^3\ s^{-1}$. According to Marsella *et al.* (2009), the 2007 eruption "can be interpreted as a two-phased event". The lava were emitted in 35 days with a mean of *eruption rate* (ER) of ≈ 4.27 ± 1.28 $m^3\ s^{-1}$.

We can conclude that the methods developed in this research can be extended to other remote volcanoes hard to monitor and that show similar activity and size.

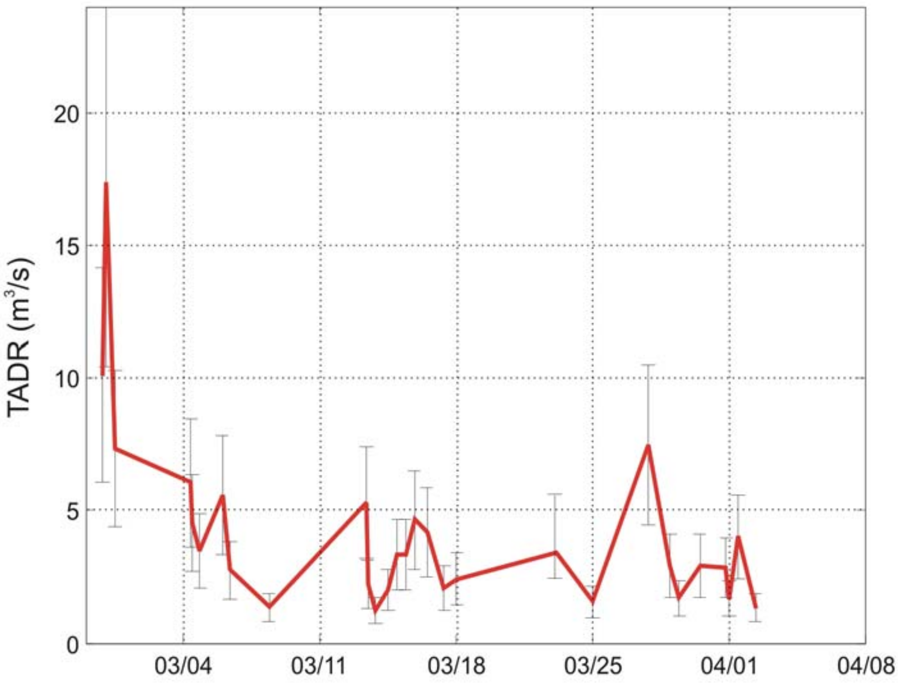

Fig. 6 - MODIS TADR time series.

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REFERENCES

Baldi, P., Fabris, M., Marsella, M., Monticelli, R. (2005): Monitoring the morphological evolution of the Sciara del Fuoco during the 2002-2003 Stromboli eruption using multi-temporal photogrammetry. *J. Photogram. Rem. Sens.*, **59**, 199-211.

Delle Donne, D., Lacanna, G., Marchetti, E., Ripepe, M., Ulivieri, G. (2006): Monitoring explosive volcanic activity using thermal images, Stromboli Volcano, Italy. *Eos Trans. AGU*, **87**, Fall Meet. Suppl., Abstr., V43B-1795.

Flynn, L.P., Wright, R., Garbeil, H., Harris, A.J.L., Pilger, E. (2002): A global thermal alert using MODIS: initial results from 2000–2001. *Adv. Environ. Monitoring Modeling*, **1**, 37–69.

Giglio, L., Descloitres, J., Justice, C.O., Kaufman, Y. J. (2003): An Enhanced Contextual Fire Detection Algorithm for MODIS. *Remote Sensing Environ.*, **87**, 273-282.

Harris, A.J.L. & Thornber, C.R. (1999): Complex effusive events at Kilauea as documented by the GOES satellite and remote video cameras. *Bull. Volcanol.*, **61**, 382-395.

Harris, A.J.L., Swabey, S.E.J., Higgins, J. (1995): Automated threshold of active lava using AVHRR data. *Int. J. Remote Sensing*, **16**, 3681-3686.

Harris, A.J.L., Wright R., Flynn, L.P. (1999): Remote monitoring of Mount Erebus volcano, Antarctica, using polar orbites: progress and prospect. *Inter. J. Remote sensing*, **20**, 15 and 16, 3051-3071.

Harris, A.J.L., Pilger, E. Flynn, L.P., Garbeil, H., Mouginis-Mark, P.J. Kauahikaua, J., Thornber, C. (2001): Automated high temporal resolution thermal analysis of Kilauea volcano, Hawai'i, Using GOES satellite data. *Int. J. Remote Sensing*, **22**, 945-967.

Harris, A.J.L., Pilger, E., Flynn, L.P. (2002): Web-Based Hot Spot Monitoring using GOES: What it is and How it Works. *Adv. Environ. Monitoring Modelling*, **1**, 5-36.

Kaneko, T., Yasuda, A., Ishimaru, T., Takagi, M., Wooster, M.J., Kagiyama, T. (2002): Satellite hot spot monitoring of Japanese volcanoes: a prototype AVHRR based. *Adv. Environ. Monitoring Modelling*, **1**, 125-133.

Marsella, M., Sonnessa, A., Proietti, C., Bernardo, E., Coltelli, M., Tommasi, P. (2009): The Sciara del Fuoco subaerial slope evolution during the 2007 eruption of Stromboli volcano: relation between lava effusion activity and deformation processes. *J. Volcanol. Geotherm. Res.*, **182**, 201-213.

Patrick, M. (2005): Strombolian eruption dynamics from thermal (FLIR) video imagery, PhD dissertation. Department of Geology & Geophysics, University of Hawaii, 281 p.

Patrick, M.R., Harris, A.J.L., Ripepe, M., Dehn, J., Rothery, D.A., Calvari, S. (2007): Strombolian explosive styles and source conditions: insights from thermal (FLIR) video. *Bull. Volcanol.*, **69**, 769-784.

Pergola, N., Tramutoli, V., Marchese, F. (2004): Automated detection of thermal features of active volcanoes by means of Infrared AVHRR records. *Remote Sensing Environ.*, **93**, 311-327.

Rothery, D.A., Coppola, D., Saunders, C. (2005): Analysis of volcanic activity patterns using MODIS thermal alerts. *Bull. Volcanol.*, **67**, 539-556.

Spinetti, C., Buongiorno, M.F., Doumaz, F., Musacchio, M., Lombardo, V., Harris, A.J.L., Steffke, A., Amici, S. (2007): Rapporto eruzione Stromboli 9-16 Marzo 2007, 16-21 Marzo 2007, 21-29 Marzo 2007, 29 Marzo-30 Aprile 2007. INGV, sezione CNT-LABTEL e Università delle Hawaii, HIGP/SOEST.

Wooster, M.J., Zhukov, B., Oertel, D. (2003): Fire radiative energy for quantitative study of biomass burning: derivation from the bird experimental satellite and comparison to MODIS fire products. *Remote Sensing Environ*., **86**, 83-107.

Wright, R. & Flynn, L.P. (2004): Space-based estimate of the volcanic heat flux into the atmosphere during 2001 and 2002. *Geology*, **32**, 189-192.

Wright, R., Flynn, L. Garbeil, H., Harris, A.J.L., Pilger, E. (2002): Automated volcanic eruption detection using MODIS. *Remote Sensing Environ.*, **82**, 135-155.

Wright, R., Carn, S.A., Flynn, L.P. (2005): A satellite chronology of the May-June 2003 eruption of Anatahan volcano. *J. Volcanol. Geotherm. Res.*, **146**, 102-116.

Xiong, X.X. & Barnes, W. (2006): An overview of MODIS radiometric calibration and characterization. *Adv. Atmos. Sci.*, **23**, 69-79.