

# An initial comparison of the thermal anomaly detection products of MODIS and VIIRS in their observation of Indonesian volcanic activity

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Author post-print (accepted) deposited by Coventry University's Repository

**Original citation & hyperlink:**

Blackett, M. (2015) An initial comparison of the thermal anomaly detection products of MODIS and VIIRS in their observation of Indonesian volcanic activity. *Remote Sensing of Environment*, volume 171 : 75-82

<http://dx.doi.org/10.1016/j.rse.2015.10.002>

DOI 10.1016/j.rse.2015.10.002

ISSN 0034-4257

ESSN 1879-0704

Publisher: Elsevier

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1 **An initial comparison of the thermal anomaly detection products of MODIS and VIIRS in their**  
2 **observation of Indonesian volcanic activity**

3

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6

7 **Abstract**

8 The Suomi National Polar-orbiting Partnership satellite was launched in 2011. On-board this satellite  
9 is the Visible Infrared Imaging Radiometer Suite (VIIRS) with thermal infrared detection capabilities  
10 similar those of the earlier Moderate-Resolution Imaging Spectroradiometer (MODIS) sensors of the  
11 National Aeronautics and Space Administration Earth Observation System. Fire detection products  
12 have been developed using the thermal infrared data for both VIIRS and MODIS and, although having  
13 the observation of fire as their main objective, such products are also sensitive to the radiant  
14 emissions of active volcanic surfaces, but a comparison of their capabilities in this regard remains  
15 outstanding. Here, this comparison is conducted, with a focus on the volcanoes of Indonesia, and  
16 findings are initially promising, suggesting that the VIIRS fire detection capability is an improvement  
17 over that of its predecessor. For example, between 3 April 2012 and 14 July 2014, volcanic activity  
18 was detected on 519 days by the VIIRS product, as compared with 308 days for the MODIS-Aqua  
19 product (MYD14). Causes of this apparent enhanced sensitivity are explored and, with the  
20 examination of additional data from the MODIS-Terra product and the MODVOLC system, are shown  
21 to be the combined influence of spatial resolution, data processing steps, imaging scan width and the  
22 fire product algorithm used. As greater quantities of data become available, a more comprehensive  
23 comparison of these observations will be possible and will be undertaken at a global scale.

24

25 **Introduction**

26 In October 2011 the Suomi National Polar-orbiting Partnership (S-NPP) satellite was launched. It was  
27 to be an introductory, data collecting satellite for the National Aeronautics and Space Administration  
28 (NASA) and the National Oceanic and Atmospheric Administration (NOAA), as part of their Joint Polar  
29 Satellite System (JPSS) Mission. With five sensing instruments, including the Visible Infrared Imaging

30 Radiometer Suite (VIIRS), S-NPP was to provide a continuation in the environmental satellite data  
31 record. This record commenced in the late 1970s with NOAA's Advanced Very High Resolution  
32 Radiometer (AVHRR) satellites and was most recently added to in 1999 and 2001 by NASA's  
33 Moderate-Resolution Imaging Spectroradiometer (MODIS) on-board the Terra and Aqua spacecraft  
34 (Schroeder et al. 2014). These sensors each possess infrared detection capabilities which have been  
35 harnessed to identify terrestrial thermal anomalies. Although commonly used in observing the  
36 characteristic thermal signatures of active fires, such data also have utility in the observation of active  
37 volcanic surfaces, and this has been utilised in various applications (e.g. Harris et al. 1998, Wright and  
38 Flynn, 2003; Webley et al. 2008, Blackett, 2014). For MODIS, a fire detection algorithm has been  
39 developed which utilises its infrared data to produce the Thermal Anomaly/Fire products: MOD14 (for  
40 MODIS Terra) and MYD14 (for MODIS Aqua) (Justice et al. 2002, 2006; Giglio et al. 2003). An Active  
41 Fire Product (AFP) has also been developed for infrared VIIRS data and using this, and the  
42 MOD14/MYD14 algorithm, it also identifies active fires and, as such, any terrestrial thermal  
43 anomalies, including those of volcanic origin (Justice et al. 2013; Csiszar et al. 2014).

44

#### 45 **Volcanic context**

46 Given the huge utility of fire detection products for hazard management agencies on the ground, both  
47 MODIS and VIIRS have been compared in terms of their observation of active fires, and initial  
48 comparisons have shown consistency in near coincident data, even at varying view angles (e.g. Justice  
49 et al. 2013; Csiszar et al., 2014; Schroeder et al. 2014). However, given the higher nominal spatial  
50 resolution of the VIIRS, and its enhanced scanning and sampling techniques, a higher sensitivity to  
51 thermal anomalies would be expected and indeed, has been confirmed for fires (Csiszar et al. 2014;  
52 Schroeder et al. 2014). What is absent in the literature however, is a comparison of the volcanic  
53 observational capabilities of the MODIS and VIIRS thermal anomaly products, and that is what this  
54 paper seeks to undertake. The chief differences between observing active volcanic surfaces, as  
55 compared with fires, are that: 1) the temperature ranges are likely to be higher (with both fresh and  
56 cold, or cooling, lava present), 2) the heat sources are likely to be more pervasive and, 3) there is  
57 likely to be a greater temperature contrast between hot surfaces and surrounding non-volcanic, high-  
58 altitude surfaces.

59

60 The comparison conducted here focuses on observations of the volcanoes of Indonesia. This  
61 archipelago consists of 78 historically active volcanoes which formed as a result of subduction along  
62 the Sunda Arch (Smithsonian Institution 2013). Since the launch of the S-NPP satellite in October  
63 2011, many Indonesia's volcanoes have been particularly active (see Figure 1). In 2012, Mount  
64 Semeru erupted and generated multiple pyroclastic flows that warranted a ban on visitors, and  
65 Mount Soputan emitted an ash plume that extended 9000 m into the atmosphere (CVGHM, 2012;  
66 Darwen VAAC, 2012). Mount Paluweh commenced a period of prolonged activity in early 2013, killing  
67 six and forcing evacuations throughout the year and later, in the same year, the eruption of Mount  
68 Sinabung forced flight cancellations and the evacuation of 17,000 people (Jakarta Post, 2013;  
69 International Business Times, 2013). In 2014, Mounts Kelud and Sinabung erupted, killing tens of  
70 people and forcing the rerouting and cancellation of flights (National Geographic 2014; Jakarta Post,  
71 2014); Mount Sangeang Api also erupted, displacing thousands and forcing flight diversions (The  
72 Guardian, 2014). The extreme vulnerability of Indonesia to the volcanic hazard is reflected by the fact  
73 that two-thirds of the global population exposed to the volcanic hazard are concentrated in Indonesia  
74 (UNISDR, 2015).

75

## 76 **Sensors and algorithms**

77 The MODIS instruments possess mid- and thermal-infrared bands with a spatial resolution of 1 km at  
78 nadir, a swath width of 2330 km and a twice-daily repeat period (Table 1 shows the bands of MODIS).  
79 The MODIS Thermal Anomaly/Fire products (MOD14 and MYD14) extract pixels that display the  
80 characteristics of thermal anomalies at the surface. These characteristics are based on data from  
81 bands 21 or 22 (3.929–3.989  $\mu\text{m}$ ), band 31 (10.780–11.280  $\mu\text{m}$ ) and the application of a fire detection  
82 algorithm initially developed by Justice et al. (2002) and enhanced by Giglio et al. (2003). The  
83 algorithm applies background and contextual threshold tests to identify those pixels representing  
84 potential thermal anomalies, although the precise algorithm differs marginally between day and  
85 night-time applications. The rationale for this difference is that all objects of ambient temperature  
86 (including the Earth's surface) emit detectable levels of infrared radiation, even in the absence of  
87 solar heating and sunlight. Planck's Law however, determines that emissions from ambient objects

88 will be greater in the thermal infrared (i.e. band 31) than in the mid-infrared (i.e. bands 21 and 22);  
89 the reverse will be true for hotter surfaces. These facts mean that the contrast between hot and  
90 ambient surfaces is lower in the daytime, thereby requiring stricter steps to differentiate them from  
91 the background. As such, an initial screen is applied in the algorithm whereby thermally anomalous  
92 pixels in daytime imagery are identified where the MIR brightness temperature exceeds 360 K, as  
93 compared with just 320 K in night-time imagery (Giglio et al. 2003; Justice et al. 2002; Schroeder et al.  
94 2014).

95

96 The MODIS fire products are made available in the Hierarchical Data Format (HDF), with its Scientific  
97 Data Sets (SDS) listing, amongst other characteristics, the longitude and latitude of anomalous pixels,  
98 and the associated fire radiative power (FRP) (Giglio, 2010). The performance of the MODIS algorithm  
99 for observing thermal anomalies has regularly been validated by comparison with corresponding  
100 Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) fire observations both in  
101 terms of anomaly detection (Giglio et al. 2003; Morisette et al. 2005; Csiszar et al. 2006) and emission  
102 quantification (Giglio et al. 2008).

103

104 The VIIRS was developed for cloud and Earth surface observations and initial calibration and  
105 validation steps have shown it as performing very well, producing high-quality data comparable with  
106 that of MODIS (Cao et al. 2013; Cao et al. 2014). It consists of a panchromatic day-night band and two  
107 collections of other bands: five high resolution imagery (I) bands (of 375 m at nadir) and sixteen  
108 moderate (M) resolution bands (of 750 m at nadir); the VIIRS bands are compared with each other,  
109 and with those of MODIS, in Table 1. Each collection of bands has a 3040 km swath width, providing  
110 twice daily global coverage. The I-bands cover the visible spectrum and also include medium and  
111 longwave infrared bands. The M-bands cover approximately the same portion of the spectrum (with  
112 some shorter wavelength bands) but also possess higher spectral resolution i.e. narrower bandwidths  
113 and, with a better signal to noise ratio, are more appropriate for quantitative applications.

114

115 Table 1. The bands of MODIS and VIIRS, compared in terms of their spectral characteristics (\*dual gain  
116 band; † low gain band). The bands outlined are those of relevance to this research.

MODIS			VIIRS							
Band	Spectral range (μm)	Spatial resolution (m)	Spatial resolution: 750 m		Spatial resolution: 375 m		Spatial resolution: 750 m			
			Band	Spectral range (μm)	Band	Spectral range (μm)	Band	Spectral range (μm)		
8	0.405–0.420	1000	M1	0.402 - 0.422	<table border="1"> <tr> <td rowspan="2">DNB</td> <td rowspan="2">0.500 - 0.900</td> </tr> <tr> </tr> </table>				DNB	0.500 - 0.900
DNB	0.500 - 0.900									
9	0.438 - 0.448	1000	M2	0.436 - 0.454						
3	0.459 - 0.479	500								
10	0.483 - 0.493	1000	M3	0.478 - 0.488						
11	0.526 - 0.536	1000								
12	0.546 - 0.556	1000	M4	0.545 - 0.565						
4	0.545 - 0.565	500								
1	0.620 - 0.670	250							I1	0.600 - 0.680
13	0.662 - 0.672	1000	M5	0.662 - 0.682						
14	0.673 - 0.683	1000								
15	0.743 - 0.753	1000	M6	0.739 - 0.754						
2	0.841 - 0.876	250	M7	0.846 - 0.885					I2	0.850 - 0.880
16	0.862 - 0.877	1000								
17	0.890 - 0.920	1000								
19	0.915 - 0.965	1000								
18	0.931 - 0.941	1000								
5	1230 - 1250	500	M8	1.230 - 1.250						
26	1.360 - 1.390	1000	M9	1.371 - 1.386						
6	1628 - 1652	500	M10	1.580 - 1.640	I3	1.580 - 1.640				
7	2105 - 2155	500								
			M11	2.230 - 2.280						
20	3.660 - 3.840	1000	M12	3.610 - 3.790	I4	3.550 - 3.930				
21*	3.929 - 3.989	1000	M13*	3.970 - 4.130						
22	3.929 - 3.989	1000								
23	4.020 - 4.080	1000								
24	4.433 - 4.498	1000								
25	4.482 - 4.549	1000								
27	6.535 - 6.895	1000								
28	7.175 - 7.475	1000								
29	8.400 - 8.700	1000	M14	8.400 - 8.700						
30	9.580 - 9.880	1000								
31	10.780 - 11.280	1000	M15	10.26 - 11.260	I5	10.500 - 12.400				
32	11.770 - 12.270	1000	M16	11.540 - 12.490						
33	13.185 - 13.485	1000								
34	13.485 - 13.785	1000								
35	13.785 - 14.085	1000								
36	14.085 - 14.385	1000								

118

119 The AFP, which has been developed for the VIIRS, is categorised as an Application Related Product  
120 (ARP). An ARP is produced by the S-NPP Ground System's Interface Data Processing Segment (IDPS)  
121 which converts the Raw Data Records into geolocated calibrated measurements, or Sensor Data  
122 Records (SDRs), and then into Environmental Data Records (EDRs) of geophysical parameters, of  
123 which ARPs are a subcategory (Csiszar et al. 2014; Justice et al. 2013). Using the same algorithm as its  
124 MODIS forerunner (although Collection 4, as opposed to the Collection 5 currently used in MODIS  
125 data), it utilises the suite's mid-infrared and thermal infrared bands (M13: 3.970–4.130  $\mu\text{m}$  and M15:  
126 10.260–11.260  $\mu\text{m}$ ), to identify pixels representing thermal anomalies on the surface. Details of the  
127 full algorithm, and its similarities and differences to the equivalent MODIS algorithm, are summarised  
128 in the product's Operational Algorithm Description (JPSS, 2013). Data from M13 are particularly useful  
129 for such studies given its high saturation temperature (634 K) when set in low-gain mode, whereas  
130 those of M15 are suitable for characterising the background thermal conditions (although these have  
131 the potential to saturate for moderate/large thermal anomalies). Similarly to the MODIS fire  
132 algorithm, and with the aim of reducing false alarms, the precise algorithm applied in the daytime is  
133 more stringent than the corresponding night-time product. At the current time, only the longitude  
134 and latitude of those pixels identified as potential fires are listed within the associated HDF file of the  
135 VIIRS AFP, thereby preventing complete comparison with the MODIS data products. However, by the  
136 time the first JPSS satellite is launched in 2017, the product will be upgraded to a full Environmental  
137 Data Record, with the requirement of a fire mask and FRP data; plans are also in place for updating  
138 the algorithm used to the most up to date MODIS Collection 6 version (Csiszar et al. 2014; Schroeder  
139 et al. 2014). To date, only one attempt at quantifying thermal emission data retrieved from VIIRS has  
140 been made: the Nightfire algorithm (Elvidge et al. 2013). This examines VIIRS Sensor Data Records for  
141 anomalies and quantifies the associated thermal emissions, in terms of megawatts, for comparison  
142 with MODIS-derived FRP and, using it, a high correlation between MODIS derived FRP data, and VIIRS  
143 thermal emissions, has been shown (Elvidge et al. 2013).

144

145 Despite the similarity in bands, one important difference in the processing steps between MODIS and  
146 VIIRS data is that, prior to being incorporated into a data product, different approaches are taken to

147 handle the 'bow-tie' effect. This effect is the pixel footprint enlargement and distortion that occurs  
148 towards the ends of an image obtained by scanning radiometers such as MODIS and VIIRS. Not only  
149 does the 'bow-tie' effect reduce the reliability of pixel comparisons (both within and between scenes)  
150 but, by resulting in pixel enlargement towards the end of scan widths, the sensitivity of pixels, for  
151 example to fires and thermal anomalies, also degrades towards the scan edge (Wolfe et al. 1998; Cao  
152 et al. 2013). To reduce this effect in VIIRS data, a novel approach has been taken which incorporates  
153 both the deletion of overlapping pixels, and aggregation of those remaining, based on their distance  
154 from the nadir. This approach results in spatial resolutions that are more comparable (to within a  
155 factor of two, as opposed nearly five for MODIS), and pixels that approximate a square, across the  
156 whole scan (Wolfe et al. 2013; Cao et al. 2014).

157

## 158 **Methods**

159 Using the Smithsonian Institution's Global Volcanism Program (GVP) database (available at:  
160 <http://www.volcano.si.edu/>), all Indonesian volcanoes reported to have displayed activity since the  
161 availability of the VIIRS AFP (3 April 2012) were identified. These volcanoes, 21 in total, are shown in  
162 Figure 1 and all data encompassing elements of this region, for the period 3 April 2012 – 14 July 2014  
163 (835 days and 6754 files), were downloaded from NOAA's Comprehensive Large Array-data  
164 Stewardship System (CLASS, [www.class.noaa.gov/](http://www.class.noaa.gov/)). For comparison, MYD14 data for the same region  
165 and period (6885 files) were downloaded from NASA's Earth Observing System Data and Information  
166 System (Reverb, [reverb.echo.nasa.gov/](http://reverb.echo.nasa.gov/)). Only MODIS Aqua data were used as its local overpass times  
167 (~1.30am and ~1.30pm) are similar to those of S-NPP, thereby facilitating comparison (Csiszar et al.  
168 2014). However, to assist in comparing the performance of the MODIS and VIIRS products, two other  
169 datasets were also obtained: 1. MODIS Terra Thermal Anomaly/Fire Product data (MOD14) for the  
170 same period and 2. Data from the MODVOLC volcanic detection system (Wright et al., 2004). With  
171 regard to MOD14, the differing acquisition times (~10.30am and ~10.30pm), and the rapidly varying  
172 nature of volcanic activity and atmospheric conditions, mean its data cannot be directly compared  
173 with MYD14 or VIIRS data, but it is included to assist in identifying the causes of any MODIS-VIIRS  
174 discrepancies. Data from the MODVOLC system, which uses both Aqua and Terra data, are similarly  
175 included to assist in identifying the causes of any such discrepancies.





177

178 Figure 1. All Indonesian volcanoes recorded as displaying activity according to the GVP database, in  
 179 the period: April 2012 – 14 July 2014. Asterisks refer to volcanoes which displayed thermal anomalies  
 180 that were detected in either, or both, the MYD14 and VIIRS fire product files.

181

182 The geolocation accuracy of MODIS has been confirmed as around 50 m (Wolfe et al. 2002), and for  
 183 VIIRS it is comparable, at around 70 m nadir (Wolfe et al. 2013; Cao et al. 2014). Given these small  
 184 values, extracting data from the respective thermal anomaly product using the longitude and latitude  
 185 of each volcano will provide the corresponding pixel-level data. However, as thermally anomalous  
 186 volcanic phenomena may extend far from the crater of a specific volcano (e.g. via lava flow or  
 187 pyroclastic density current), all thermal anomalies recorded within  $\pm 0.02^\circ$  longitude and latitude of  
 188 each volcano were identified and extracted to ensure no loss of volcanic signal, while also minimising  
 189 the possibility of including nearby non-volcanic thermal sources. The signals were organised into daily  
 190 observations and where there was more than one scene observing the surface on the same day, only  
 191 data from the scene with the highest summed per-pixel thermal anomaly emission (in the case of  
 192 MODIS data) or the greatest number of identified anomalous pixels (in the case of the VIIRS AFP and  
 193 MODVOLC) were considered, so as to avoid compounding the instantaneous daily sum value. To

194 determine the type of volcanic activity potentially responsible for the thermal signals noted, the GVP  
195 database was queried for each detected anomaly.

196

## 197 **Results**

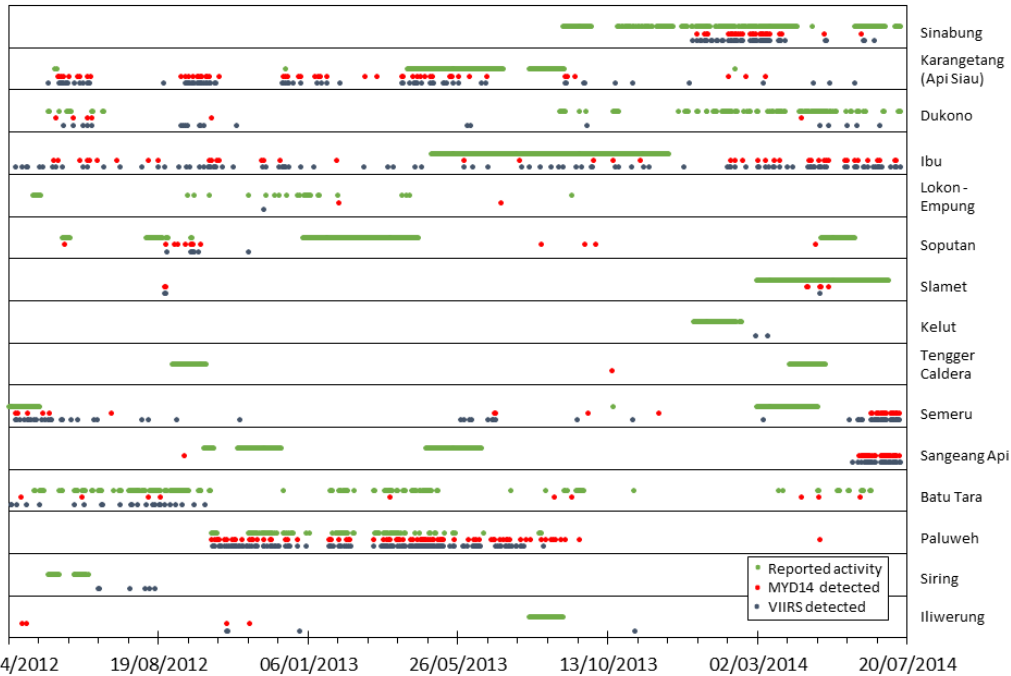
### 198 *Thermal anomaly detection*

199 An initial comparison of the volcanic-observational capabilities of both the MODIS and VIIRS fire  
200 detection algorithms must consist of an examination of their thermal anomaly detection capabilities.  
201 Of the 21 volcanoes reported within the GVP database as displaying volcanic activity during the period  
202 in question, 15 exhibited thermal anomalies that were detected by either, or both, the MYD14 and  
203 VIIRS fire product files (see Figure 1). In many cases, detected anomalies related directly to activity  
204 reported in the GVP database, whereas in others, no activity was reported (see Figure 2 for this  
205 comparison). Where thermal activity was detected but with no corresponding activity reports, it is  
206 likely that either the activity had gone unobserved on the ground or that the thermal activity had a  
207 source other than volcanism; conversely, where no thermal anomaly detections were made during  
208 periods of reported activity, it is likely that cloud, or volcanic emissions, obscured the surface from  
209 view. These discrepancies between observations and recorded activity highlight the relative  
210 sparseness of reported volcanic observations in the region which is largely a function of the  
211 remoteness and inaccessibility of many of Indonesia's volcanoes.

212

213 In the absence of other truly quantitative data from the VIIRS product, comparison between the  
214 MYD14 and VIIRS algorithms can only be extended by examining the presence or absence of  
215 anomalies, and by counting the numbers of anomalous pixels identified. Throughout the period, the  
216 VIIRS AFP detected 923 anomalous pixels, 62% more than MYD14, which detected 569. The VIIRS AFP  
217 also detected anomalies on more days than MYD14 (519 versus 308) and of these days, 26% were  
218 also identified as displaying anomalies by MYD14 while in reverse, of the daily MYD14 detections, 45%  
219 were also identified by the VIIRS AFP. These data (displayed in Figure 2) suggest a superior detection  
220 capability i.e. higher sensitivity to thermal anomalies, for the VIIRS AFP. The discrepancy in detections  
221 between these products could be attributed to a number of factors discussed in due course, ranging

222 from activity type and time of day of observation, to the characteristics of the sensors themselves and  
 223 how their shared algorithm functions.  
 224



225  
 226 Figure 2. Temporal comparison of GVP reported activity at the volcanoes detailed in Figure 1, with  
 227 thermal anomalies at them, as detected by MYD14 and the VIIRS AFP, for a period of 835 days (1 April  
 228 2012 – 14 July 2014). The interval between minor tick marks on the x-axis is 28 days.

229  
 230 The detection capability of both sensors appears, to some extent, to be dependent on the volcano  
 231 being observed. At Sengeang for example, of 29 days of VIIRS AFP detections, 86% had corresponding  
 232 MYD14 detections and, of 30 days of MYD14 detections, 83% had corresponding VIIRS AFP  
 233 detections; at Paluweh, of 130 days of VIIRS AFP detections, 43% had corresponding MYD14  
 234 detections and of 81 days of MYD14 detections, 69% had corresponding VIIRS AFP detections. In  
 235 other cases however, the VIIRS AFP was shown as much more sensitive for example, at Sirung volcano  
 236 over the entire period, no MYD14 detections were made, as compared with 6 days of anomaly  
 237 detection for the VIIRS AFP. Extending this analysis to examine volcanic activity type, Table 2  
 238 compares the number of days on which GVP reports of specific types of volcanic activity were made,  
 239 with the number of days on which thermal anomalies were detected, by product. Confirming a

240 common theme, the VIIRS AFP more regularly detected thermal anomalies than MYD14, for all  
 241 activity types. Overall, those types of activity associated with intense heat (i.e. pyroclastic flows, lava  
 242 flows or explosions) are more comprehensively detected than other activity types, although  
 243 detections remain low, with only 10.3-16.9% of GVP reports detected by the VIIRS AFP, as compared  
 244 with 0.0-11.9% for MYD14.

245

246 Table 2. The number of days that the VIIRS and MYD14 fire products detected thermal anomalies at  
 247 Indonesia's volcanoes, as compared with volcanic activity type derived from the GVP database.

	Plume	Seismicity	Incandescence	Lava dome	PF	Fumarole	Lava	Explosion	Ashfall
Days of recorded activity	1276	418	350	297	118	35	29	19	13
VIIRS AFP detected days	135	22	36	37	20	1	3	2	0
<b>Proportion detected (%)</b>	<b>10.6</b>	<b>5.3</b>	<b>10.3</b>	<b>12.5</b>	<b>16.9</b>	<b>2.9</b>	<b>10.3</b>	<b>10.5</b>	<b>0.0</b>
MYD14 detected days	69	19	17	14	14	1	1	0	0
<b>Proportion detected (%)</b>	<b>5.4</b>	<b>4.5</b>	<b>4.9</b>	<b>4.7</b>	<b>11.9</b>	<b>2.9</b>	<b>3.4</b>	<b>0.0</b>	<b>0.0</b>

248

249 The difference in VIIRS and MODIS thermal detections between day and night (between which the  
 250 algorithm used changes) can also be examined. It was found that 64% (n = 364) of all pixels identified  
 251 by MYD14 as anomalous and 65% (n=601) of all pixels identified as anomalous by the VIIRS AFP, were  
 252 detected in imagery obtained at night. The significance of this is that there is a comparable, reduced  
 253 sensitivity of both algorithms during the day-time. This is a function of the higher (and identical) MIR  
 254 temperature threshold applied within the daytime algorithm.

255

### 256 *Thermal anomaly quantification*

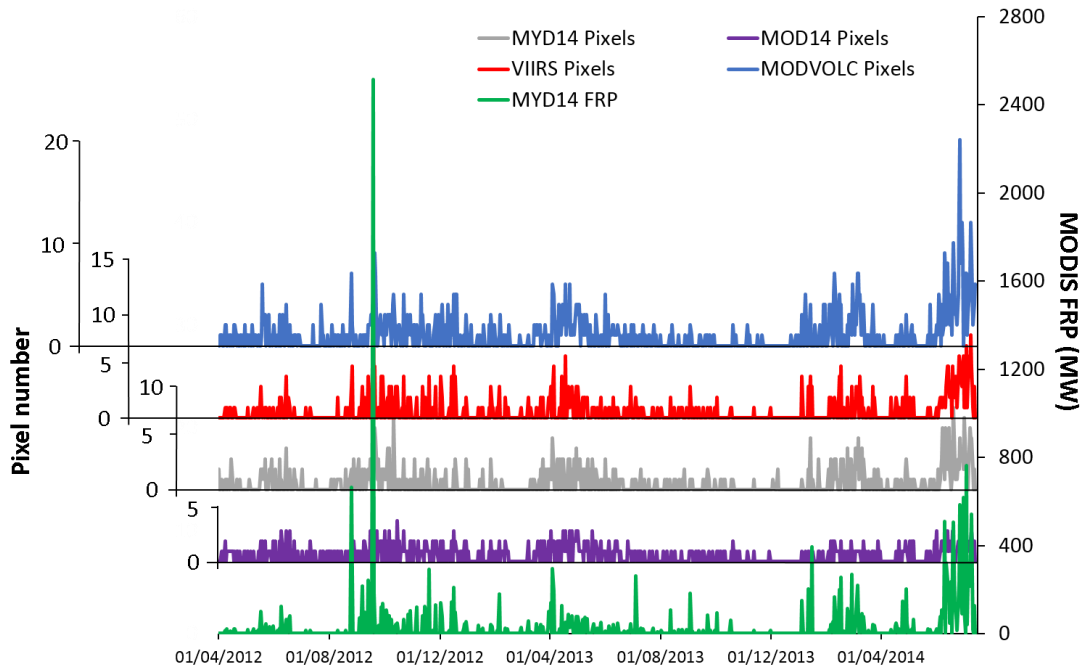
257 The detection of volcanic activity, as is possible with both the MODIS and VIIRS fire detection  
 258 algorithms, is important. Of often greater utility however, is the quantification of such activity so as to  
 259 provide an indication of the activity type and intensity. For both MODIS and VIIRS products, such  
 260 quantification is possible by virtue of the number of anomalous pixels identified, as this effectively  
 261 quantifies the spatial extent of an anomaly; in the case of MYD14 however, quantification is more  
 262 usefully also is additionally provided by the associated total FRP data. For MYD14, the relationship  
 263 here between the number of anomalous pixels and total FRP per scene however, is not particularly

264 strong ( $r^2 = 0.57$ ). This is because there is a range of FRP values that a pixel identified as anomalous  
265 might display. For example, the smallest pixel FRP identified within the dataset was 7.5 MW (for Ibu,  
266 14 June 2012, with no GVP-reported activity) and the largest was 992.3 MW (for Soputan, 18  
267 September 2012, with eruptive activity, including volcanic plumes, reported). The daily sum FRP for all  
268 volcanic activity detected is plotted in Figure 3, along with the corresponding daily numbers of  
269 anomalous pixels as identified by both MYD14 and the VIIRS AFP. Although in many cases peaks and  
270 troughs do coincide, there is only a small positive relationship between both the numbers of pixels  
271 identified as anomalous by both sensors ( $r^2 = 0.28$ ) and between the number of pixels identified as  
272 anomalous by the VIIRS AFP and the corresponding MYD14 FRP retrievals ( $r^2 = 0.15$ ). It is unfortunate  
273 therefore, that until upgraded to an EDR, accurately quantifying the emissions detected from the  
274 more sensitive VIIRS sensor will remain troublesome.

275

276 To assist in determining the cause of the discrepancy in detections between the VIIRS and MODIS fire  
277 products, corresponding daily numbers of anomalous pixels, as identified by the MODIS Terra product  
278 (MOD14), are also displayed in Figure 3. Although there are similar trends, given the difference in  
279 image acquisition time, little relationship exists between either of the variables derived from the Aqua  
280 and Terra products (anomalous pixels:  $r^2 = 0.06$ , FRP retrievals:  $r^2 = 0.03$ ) or between the Terra-  
281 derived anomalous pixel numbers and those from VIIRS ( $r^2 = 0.26$ ). MODVOLC detections for the same  
282 volcanoes and time period are fewer than those from the MODIS fire products (these data are also in  
283 Figure 3). Summed, the number of days that both the MYD14 (308) and MOD14 (386) products made  
284 detections is 694 as compared with 520 for MODVOLC (which utilises both MODIS sensors). This  
285 difference reflects an acknowledged reduced sensitivity of the MODVOLC algorithm (e.g. Vaughan and  
286 Hook, 2006; Blackett, 2013). However for one volcano, Batu Tara, the reverse was found to be true,  
287 with MODVOLC making thermal anomaly detections on 145 days, as compared with just 10 for  
288 MYD14, 16 for MOD14 and 24 for VIIRS.

289



290  
 291 Figure 3. MODIS-derived FRP, and corresponding numbers of pixels identified as anomalous by the  
 292 MODIS (both MYD14 and MOD14) and VIIRS fire detection products, and also the MODVOLC system.

293

294 **Discussion**

295 A number of comparable MYD14 and VIIRS fire product detections of volcanic activity have been  
 296 highlighted however, equally, a number of occasions have been shown with little similarity. Overall,  
 297 the data suggest an enhanced sensitivity of the VIIRS AFP to smaller and/or more subtle thermal  
 298 anomalies, as compared with the MYD14 Product. Given that the algorithm used for both products is  
 299 the same, differences in thermal anomaly detection capabilities must be, primarily, due to variations  
 300 in pixel size – both physically (i.e. 1000 m compared with 750 m) and by virtue of the data processing  
 301 (i.e. VIIRS pixel aggregation and sampling scheme). This suggestion is confirmed by the fact that both  
 302 MODIS Fire Products (MYD14 and [MOD14]), which use the same algorithm and share the same  
 303 spatial resolution, show a significant anomalous pixel under-detection (i.e. 569 [570]) as compared  
 304 with the VIIRS AFP (923). Csiszar et al. (2014) showed how the observed differences between the  
 305 MODIS and VIIRS fire products, in relation to counts of fire pixels, are consistent with those expected  
 306 due to the differences in spatial sampling *i.e.* given that any terrestrial thermal anomaly will  
 307 constitute a greater proportion of the footprint of a smaller pixel, the smaller VIIRS pixels would be

308 expected to detect more, and smaller, thermal anomalies than MODIS, when using a comparable  
309 detection algorithm. In relation to the pixel aggregation and sampling scheme that is used in the VIIRS  
310 data, it also results in smaller pixel footprints towards the scan edge, further improving spatial  
311 resolution here as compared with MODIS (Cao et al. 2013; Justice et al. 2013; Schroeder et al. 2014).

312

313 To represent the influence of spatial resolution, Figure 4 shows a range of possible volcanic surface  
314 configuration simulations and, based on the infrared emissions that each would produce, the  
315 corresponding limits of unsaturated detection (both maxima and minima) for the MODIS and VIIRS  
316 sensors (detection will be possible above the maxima but saturation will mean the associated data  
317 cannot be reliably quantified). The range of volcanic scenarios that the VIIRS can detect is greater in  
318 all respects (up to its pixel size) than for MODIS. The implications of this are that: for a given  
319 temperature, the thermal anomaly must be larger to be detected by MODIS; VIIRS can detect cooler  
320 anomalies of the same size; and, for anomalies smaller than the pixel size, VIIRS will be able to  
321 quantify them up to a greater temperature before saturation (634 K as compared with 500 K for  
322 MODIS). Csiszar et al. (2014) confirms that work is on-going to customise the algorithm used in the  
323 VIIRS AFP for the specific characteristics of this sensor. An enhanced VIIRS fire detection algorithm  
324 has, in fact, already been developed which uses the sensor's 375 m I-bands (bands I4 and I5). This  
325 new product shows improved detection performance over the 750 m product (with, for example, a  
326 25× factor increase in absolute numbers of night-time fire pixels detected) (Schroeder et al. 2014).  
327 The challenge posed by these smaller pixels however, is that saturation will be more regular  
328 (occurring at only 367 K), meaning that it will be quantitatively useful only for smaller and/or cooler  
329 thermal anomalies (Schroeder et al. 2014).

330

331 The requirement of a VIIRS-specific thermal detection algorithm is confirmed when the MODIS Fire  
332 Product data are compared with MODVOLC data. For all volcanoes except Batu Tara, the MODVOLC  
333 algorithm predictably underestimated the number of anomalous pixels. For Batu Tara however, the  
334 MODVOLC algorithm identified thermal anomalies on 135, 129 and 121 more days than MYD14,  
335 MOD14 and VIIRS, respectively. Throughout this period, Batu Tara was persistently active, regularly  
336 erupting ash plumes into the atmosphere and displaying Strombolian and effusive activity (BGVN,

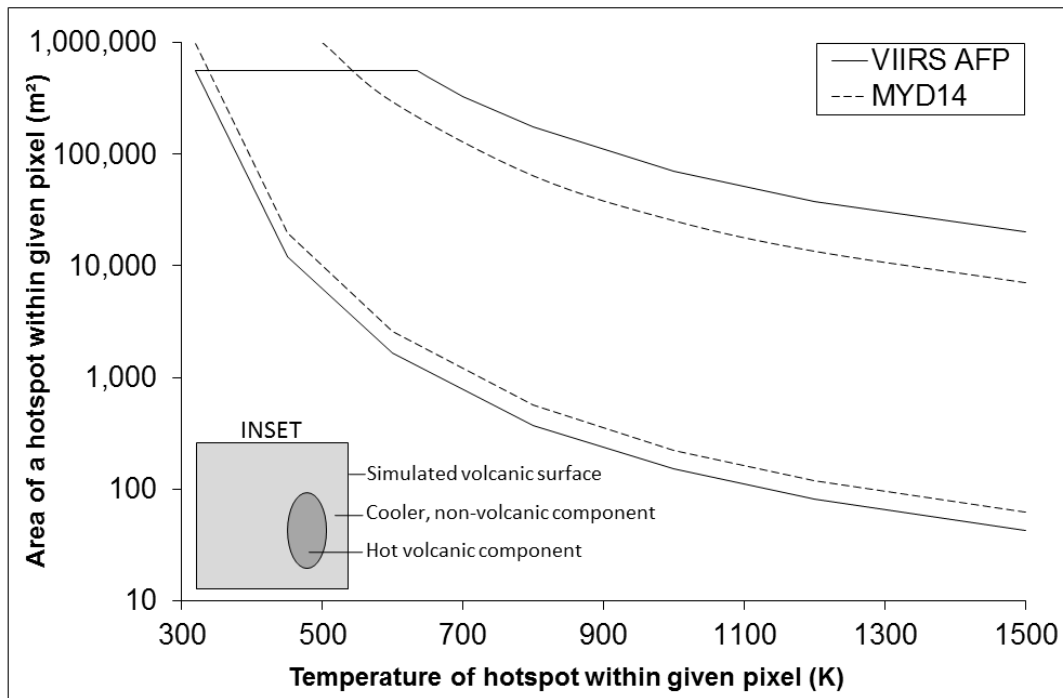
337 2014). The reason for this large difference relates to the water-masking procedure used, and how it is  
338 applied in the thermal detection algorithm of the MODIS and VIIRS products. The algorithm requires,  
339 in most cases, at least six-valid pixels neighbouring a candidate thermal anomaly; pixels masked as  
340 water are invalid (Justice et al. 2006). Given that Batu Tara forms an island (Pulau Komba) of only 4.7  
341 km<sup>2</sup>, even when particularly radiant, the MODIS Fire Product algorithm rarely detects a thermal  
342 anomaly there as only rarely are there adequate valid pixels; those detected by VIIRS number slightly  
343 more as the smaller pixel size means a smaller area of land is required to fulfil the valid pixel  
344 requirement. The MODVOLC algorithm in contrast, does not apply this requirement, hence retrieving  
345 a larger number of detections. There is clearly therefore, room for improvement in the application of  
346 the MODIS and VIIRS fire detection algorithms.

347

348 Added to the spatial resolution explanation, one other factor needs to be considered to more fully  
349 understand the differing sensitivities of the MODIS and VIIRS fire products: the view scan angle. For  
350 the VIIRS sensor, this provides for a swath width of 3040 km, as compared with 2330 km for MODIS.  
351 The significance of this difference is two-fold. Firstly, being 30% larger than the MODIS swath, it  
352 would be expected that 30% more detections would be made by the VIIRS sensor, thereby explaining  
353 a good deal of the 62% increase in VIIRS AFP detections, as compared with MYD14. Secondly, the  
354 larger swath means there are no gaps between orbits (i.e. complete global coverage twice daily), as  
355 compared with MODIS which experiences gaps in coverage around the equator (Cao et al. 2014).  
356 Given that the Indonesian islands are within 10° of the equator, such gaps will have reduced the  
357 capability of the MODIS products to view and detect all Indonesian volcanic activity and, as such, will  
358 also be partly responsible for the smaller numbers of anomalous pixels detected.

359





360  
 361 Figure 4. Here, a range of two-component volcanic surfaces are modelled: a hot volcanic component  
 362 and a cooler, non-volcanic component (this simulated surface is depicted in the inset). The hot  
 363 component is simulated with a range of temperatures (up to 1500 K, x-axis) and sizes (up to the pixel  
 364 footprint size, y-axis). Based on the minimum thresholds as prescribed by the fixed threshold fire-  
 365 detection algorithms, and the maximum unsaturated detection limits of the sensors, points within the  
 366 envelopes delineated relate to scenarios that, based on the corresponding thermal emissions, the  
 367 respective sensors and algorithms would be capable of detecting. Above the upper limits represented  
 368 by these envelopes, thermal activity will still be detected, but saturation will prevent accurate  
 369 emission quantification. The temperature maxima used here relate to the maximum FRP levels of  
 370 detection for VIIRS (5100 MW), as compared with MODIS (3500 MW).

371

### 372 **Conclusion and the future**

373 It has been shown that comparing the volcanic observational capabilities of two remote sensors is no  
 374 simple task. The characteristics of the sensors themselves render precise comparison as impossible,  
 375 and as volcanic activity is sporadic, it is easily missed if the short period of activity is not captured, or  
 376 if observing conditions are sub-optimal (Csiszar et al. 2014). Equally, the sparseness of reported  
 377 volcanic observations in Indonesia against which, remote observations might be compared, is

378 unfortunate and a function of the remoteness and inaccessibility of many of the country's volcanoes.  
379 Fortunately, the fact that remote detections have, in some cases, confirmed recorded activity and,  
380 indeed in others, have isolated activity not recorded elsewhere, evidences the utility of remotely  
381 sensed data, either from VIIRS or MODIS, in filling in the gaps in our knowledge of volcanic behaviour  
382 globally and, given its optimal performance, the VIIRS AFP appears most capable in this task.

383

384 The data presented have shown that the VIIRS AFP constitutes an improvement over the comparable  
385 MODIS product(s) in terms of its sensitivity to, and detection frequency of, volcanic thermal  
386 anomalies. This corroborates the findings of a number of other fire-observation studies and should be  
387 seen by the thermal remote sensing community as confirming VIIRS as a satisfactory follow-on to the  
388 MODIS-era dataset. We are, in fact, lucky to have an extended period of MODIS and VIIRS  
389 observations which coincide and against which such comparisons can be made, and from which the  
390 influences of the different characteristics of both can be analysed. Users need only wait until 2017 for  
391 quantitative VIIRS AFP data to be available against which more thorough comparisons may be made  
392 with MODIS. And the future does indeed look promising based on the findings presented here, with  
393 VIIRS appearing more sensitive than MODIS and, with a much higher saturation temperature, able to  
394 detect and observe a greater range of volcanic scenarios. Researchers additionally have the prospect  
395 of an increasingly rich set of new thermally-sensitive satellite sensors to look forward to, with two Sea  
396 and Land Surface Temperature Radiometers (on board the European Space Agency's Sentinel-3  
397 satellites) also planned to be operational by 2017. As such, 2017 is likely to be a significant year for  
398 the thermal remote sensing community who should, in turn, be optimistic about what it is set to bring  
399 in terms of terrestrial thermal anomaly observation.

400

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498 49.

499

500 **List of figure captions**

501 Figure 1. All Indonesian volcanoes recorded as displaying activity according to the GVP database, in  
502 the period: April 2012 – 14 July 2014. Asterisks refer to volcanoes which displayed thermal anomalies  
503 that were detected in either, or both, the MYD14 and VIIRS fire product files.

504

505 Figure 2. Temporal comparison of GVP reported activity at the volcanoes detailed in Figure 1, with  
506 thermal anomalies at them, as detected by MYD14 and the VIIRS AFP, for a period of 835 days (1 April  
507 2012 – 14 July 2014). The interval between minor tick marks on the x-axis is 28 days.

508

509 Figure 3. MODIS-derived FRP, and corresponding numbers of pixels identified as anomalous by the  
510 MODIS (both MYD14 and MOD14) and VIIRS fire detection products, and also the MODVOLC system.

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512 Figure 4. Here, a range of two-component volcanic surfaces are modelled: a hot volcanic component  
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514 component is simulated with a range of temperatures (up to 1500 K, x-axis) and sizes (up to the pixel  
515 footprint size, y-axis). Based on the minimum thresholds as prescribed by the fixed threshold fire-  
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517 envelopes delineated relate to scenarios that, based on the corresponding thermal emissions, the  
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519 by these envelopes, thermal activity will still be detected, but saturation will prevent accurate  
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521 detection for VIIRS (5100 MW), as compared with MODIS (3500 MW).

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