Lava discharge rate estimates from thermal infrared satellite data for Pacaya volcano, Guatemala: Implications for time-averaged eruption processes and hazards

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ABSTRACT

The Pacaya volcanic complex has been producing lava flows nearly continuously since 1961. Matías (2009) compiled a detailed database including information such as length, surface area, volume, duration, and effusion rates for the 248 lava flows that occurred during this time. This investigation aimed to calculate time-averaged discharge rates for a subset of Pacaya’s flows using a satellite-based method initially applied to infrared satellite data for Etna by Harris et al. (1997). Satellite-based estimates potentially provide a quicker, safer, and less expensive alternative to ground-based measurements and are therefore valuable for hazard mitigation. The unique database of Matías (2009) provides an excellent opportunity to test the applicability of this method at Pacaya, where results can be compared with reliable ground-based measurements. In addition, this study assesses whether measurements from two sensors of differing temporal and spatial resolutions can be used simultaneously: MODIS (one image every 6 hours, 1-km pixels) and GOES (one image every 15 minutes, 4-km pixels). A total of 2403 MODIS and 2642 GOES images were analyzed, and due to the relatively low intensity of Pacaya’s effusive activity, each image was searched manually for “hot spots”. It was found that while MODIS data allowed good estimations of effusion rates, GOES did not. The small, sub-resolution flows typical of Pacaya may have surpassed the limits of GOES data for this particular method. MODIS effusion rates derived in this study were used to describe and parameterize eruptive cycles, as well as to explore conduit models. A pattern was found over the past two decades of short higher-effusion rate periods and longer lower-effusion rate periods. It was suggested that the lower effusion rates experienced during longer “bleeding” of the conduit approximate the magma supply rate to the shallow system. Higher effusion rate eruptions may represent release of volumes collected during phases of non-eruptive degassing.
1. INTRODUCTION

1.1 Geologic Background

The Pacaya volcanic complex (14.381N, 90.601W) is part of the Central American Volcanic Front, which stretches over 1100 km along the Pacific coast from southern Mexico through Costa Rica (Figure 1). Volcanism here results from the NE-trending subduction of the Cocos plate beneath the Caribbean plate (Mann et al. 2007). Pacaya is located 30 km south of Guatemala City, just outside the southern rim of the actively resurging Amatitlan caldera (Wunderman and Rose 1984).

Eggers (1971) described three distinct periods of Pacaya’s eruptive history. Phase I was characterized by the growth of an ancestral andesitic cone. Phase II followed with an increase in explosive activity, voluminous pumice eruptions, and lava dome construction. Phase III (further split into the initial, historical, and modern subphases) produced basaltic lava flows has continued to the present day. Kitamura and Matías (1995) used tephrachronology to date the start of this most recent phase at less than 23k years B.P. Between 2000 and 400 years B.P., the initial cone collapsed, producing an amphitheatre-shaped scarp (Vallance et al. 1995). The scarp currently protrudes along the western side of modern Pacaya, providing a topographic barrier for most lava flows (Matías 2009). Activity throughout Phase III has been highly episodic; eruptive periods featuring emission of scoria and basaltic lava last 100 to 300 years, and are separated by longer repose periods of 300 to 500 years (Conway et al. 1992). Historical activity began in 1565 when the first reliable account of an eruption was recorded; other major eruptions are thought to have occurred in 1756 and 1880 (Eggers 1971). After nearly a century of repose, Pacaya awoke on March
10th, 1961 and has been erupting nearly continuously ever since (Conway et al. 1992). Lavas throughout Phase III are porphyritic olivine basalts exhibiting no significant temporal chemical or petrographic variation (Eggers 1971, Bardinsteff and Deniel 1992, Matías 2009). Eggers (1971) suggested that this consistency might be due to a continuous supply of magma to a small, open magma chamber; a theory that this investigation appears to support.

The modern Pacaya complex consists of the Cerro Chino scoria cone, the Cerro Grande and Cerro Chiquito lava domes, and the main center of current activity, the Mackenney cone (Eggers 1971). Since the onset of activity in 1961, the MacKenney cone has been steadily built up of lava flows and tephra erupted during episodes of Strombolian and Vulcanian activity (Eggers, 1983). The main volcanic hazards posed by Pacaya include tephra fall, lava flow, and debris avalanche (Vallance et al. 1995). During the May 2010 eruption, tephra blanketed an area of over 100 km² and ballistics damaged structures up to 3.5 km north of the vent (Wolf, 2010). Over the past 50 years, lava flows have tended not to extend beyond the immediate vicinity of the flanks of the MacKenney cone and are blocked to the east by the collapse scarp (Matías 2009). However, in 2006 lava flows finally filled the valley between the cone and collapse scarp and breached the scarp for the first time (Matías 2009). During the May 2010 eruption a vent opened to the east of the collapse scarp, a location where no historical flows had been recorded. This flow extended extremely rapidly (at rates of 100 m/hr), eventually reaching a length of ~5 km and destroying 3 houses (Wolf 2010).

The appearance of a new vent outside of the historical area of activity and the breaching of a significant topographic barrier present unique circumstances for lava flow risk assessment. Future work will need to account for the possibility of lava reaching previously untouched areas and posing new threats to the surrounding communities. It is therefore important to expand the current understanding of lava flow activity at Pacaya, especially the effusion rates at which flows are fed, this being one of the primary controls on lava flow length (Walker 1973).
1.2 Lava Effusion Rate

This report adopts the lava effusion rate terminology defined by Harris et al. (2007). An instantaneous effusion rate is the volume flux of erupted lava feeding a flow at any point in time. The term time-averaged discharge rate (TADR) refers to volume flux averaged over a given time period. The effusion rates calculated for this project are most accurately termed TADR (Wright et al. 2001). An eruption rate is defined as the total volume of lava accumulated at a given point during an eruption divided by the time elapsed since the start of the eruption. Mean output rate is the final volume divided by the total duration of an eruption. The “effusion rates” calculated by Matías (2009) are thus actually mean output rates.

Effusion rate is an important parameter that has been shown to be directly related to flow area and length (e.g. Walker 1973, Malin 1980, Wadge 1978, Pieri and Baloga 1986, Kilburn and Lopes 1988, Pinkerton and Wilson 1994, Harris et al. 2007). Effusion rates can be used to assess mass balance, i.e. the balance between erupted and degassed masses (e.g. Francis et al. 1993, Allard et al. 1994, Ripepe et al. 2005). In addition, effusion rate is a primary parameter used in lava flow modeling software (e.g. Wadge 1994, Harris and Rowland 2001, Del Negro et al. 2008). Because of these applications, effusion rate estimates are valuable to hazard mitigation efforts (e.g. forecasting flow paths, predicting lengths, and issuing appropriate warnings) (e.g. Rowland et al. 2005, Del Negro et al. 2008).

Effusion rates can be estimated through a variety of techniques. Direct measurements of channel dimensions and active flow velocity can yield instantaneous effusion rates (e.g. Guest et al. 1987, Barberi et al. 1993). Post-eruption measurements of total flow volume can be used to calculate a mean output rate if the duration of the eruption is also known (e.g. Wadge 1981, Rowland 1996). More recently, both ground-based (e.g. Calvari et al. 2005, Harris et al. 2006) and satellite-based (e.g. Harris et al. 1997a, Wright et al. 2001) thermal infrared (TIR) imagery have been used to estimate effusion rates. Satellite-based estimates are particularly attractive because they allow study of eruptions that otherwise couldn’t be accessed due to geographic, financial, or political restrictions.
1.3 Satellite-based TIR Remote Sensing of Lava Flows

While active lava emits radiation over a range of wavelengths, peaking in the medium wavelength infrared (MIR, 3.5-4.0 µm) region, the Earth at ambient temperature peaks in the long wavelength infrared (LWIR 10-14 µm) region. Figure 2 illustrates this with the Planck function, which defines how emitted radiance varies as a function of temperature and wavelength for a black body following the relation:

\[
L(\lambda, T) = \frac{2\pi h c^2}{\lambda^5} \left[ \exp \frac{hc}{\lambda kT} - 1 \right]^{-1}
\]

where \( h, c, \lambda, k, \) and \( T \) are Planck’s constant (6.6256 x 10^{-34} J s), the speed of light (2.9979 x 10^8 m/s), wavelength (m), Boltzmann gas constant (1.38 x 10^{-23} J/K), and temperature (K), respectively. There are three important points to notice about this graph. First, as an object increases in temperature, the peak of emitted radiance shifts towards shorter wavelengths. For example, freshly erupted lava at 1000°C emits radiation at an order of magnitude higher at 4 µm (MIR) than at 11 µm (LWIR). Second, the radiance

Figure 2: Planck function with GOES and MODIS wavebands (gray and red bars, respectively). Temperature curves are labeled at the peak of emitted radiance. GOES Band 2 and MODIS Bands 21 & 22 record data in the medium wavelength infrared (MIR) region (~3.9 µm) where emitted radiance from lava peaks. GOES Band 4 and MODIS Band 31 record data in long wavelength infrared (LWIR) region (~11 µm) where emitted radiance from Earth peaks. See text for further discussion.
curves for objects at different temperatures converge with increasing wavelength, so that the difference in emitted radiance between a hot and cold object decreases significantly toward longer wavelengths. This means that the difference in radiance between a 400°C and 450°C object is significant at 4 µm, but less so at 11 µm. Third, radiances drop off abruptly towards shorter wavelengths, so a cold object at 25°C emits a vanishingly small amount of radiation at shorter wavelengths, but continues to emit radiation at longer wavelengths.

Several space-borne sensors image the Earth in the thermal infrared region, which is especially useful for detecting and analyzing volcanic heat sources. For the purposes of this investigation, a “hot spot” in a TIR image as a thermally anomalous pixel that results from the presence of a hot (lava temperature) component within the pixel (Figure 3). Such pixels often appear bright in MIR images, and when strong enough, can also brighten LWIR (~11 µm) bands. However, since a relatively large portion (>0.1%) of the LWIR pixel must be occupied by a hot component in order to raise the pixel-integrated radiance above background levels (Harris et al. 1997b), very small flows (like most of those encountered during this project) may not cause observable increases in radiance at LWIR wavelengths. Consider the following example from Wright et al. (2001): a 1-km thermally homogenous MODIS pixel at 300 K emits 0.4 Wm⁻²sr⁻¹µm⁻¹ at 4 and 9.5 Wm⁻²sr⁻¹µm⁻¹ at 11 µm. If a sub-pixel lava flow at 850 K occupies 0.05% (i.e. 500 m²) of that pixel, the radiance increases to 1.3 Wm⁻²sr⁻¹µm⁻¹ at 4 and 9.6 Wm⁻²sr⁻¹µm⁻¹ at 11 µm. That is, emission at 11 µm increases by 1%, but at 4 µm, emission increases by more than 200%. This negligible radiance increase in LWIR bands allows extraction of “anomalous” radiances from MIR bands and “background” radiances from the corresponding pixels in LWIR bands.

Several space-borne sensors provide TIR data, but the Moderate Resolution Imaging Spectrometer (MODIS) and the Geostationary Operational Environmental
Satellites (GOES) imager were chosen for this project. These sensors provide measurements in units of spectral radiance. However, these values are not particularly useful to the volcanological community, so it is desirable to convert them to heat flux or volume flux (i.e. effusion rate) estimates, which then have a variety of possible applications. A method for calculating TADR from heat flux was initially described by Pieri and Baloga (1986) and Crisp and Baloga (1990), and was applied to TIR satellite data by Harris et al. (1997a). Harris et al. (1997a) used a two-component pixel mixture model to estimate the area of active lava surface required to attain a given radiance measurement. This was then used to calculate the heat lost by the flow due to radiation and convection. The heat flux was next converted to volume flux (i.e. effusion rate) via an adapted approach of Pieri and Baloga (1986) and Crisp and Baloga (1990). The resulting effusion rate is best described as a time-averaged discharge rate (TADR) rather than an instantaneous effusion rate (Wright et al. 2001). This approach was chosen to calculate time-averaged discharge rates for this investigation.

1.4 Previous Work and the Matías (2009) Database

Activity during the modern eruptive phase (1961 – present) has occurred under the scrutiny of thorough scientific observation, so that Pacaya’s recent activity has been relatively well documented, monitored, and studied. Matías (2009) compiled an extensive database containing information on 248 lava flows erupted between 1961 and 2009, and produced a corresponding volcanological map. The database includes important measurements such as eruption starting and ending dates, as well as lava flow lengths, surface areas, volumes, and mean output rates. To compile this database, first, surface area was calculated from planimetric area via an algorithm that utilized slope angles from a digital elevation model (DEM) (Matías 2009). Volumes were then calculated by multiplying the derived surface area by estimated flow thickness. Lava flow thicknesses can be difficult to measure accurately, so minimum, intermediate, and maximum thicknesses were individually defined for each flow. Dividing the total volume by the total emplacement time yielded minimum, intermediate, and maximum mean output rates for each respective volume. Values from this database were used to calibrate satellite-derived effusion rates calculated here.
1.5 Objectives

1. Estimate lava discharge rates for a subset of Pacaya’s historical flows from thermal infrared satellite data, and to calibrate the method of Harris et al. (1997a) using the ground-base volumetric values calculated by Matías (2009).

2. Compare results from the MODIS and GOES sensors and explore the possibility of combining measurements into a single dataset to provide more complete coverage of flows, and to make inferences on the feasibility of using low-spatial resolution data (GOES) for the small flows typical of Pacaya.

3. Use the volumetric database to potentially define a relationship between output rate and supply rate over two decades at Pacaya, and to make inferences about the dynamics of, and hazard posed by, this persistently active system.
2. METHODS

2.1 Satellite Data Sources

2.1.1 MODIS (Moderate Resolution Imaging Spectroradiometer)

MODIS was chosen because it provides moderately high spatial-resolution data (1-km in TIR wavelengths), which are downloadable directly from NASA at no cost from http://modis.gsfc.nasa.gov/data. MODIS is flown aboard Aqua and Terra, both sun-synchronous, near-polar orbiting satellites that pass over a point on the equator twice daily (Guenther et al. 2002). This configuration generally provides four to six images containing Pacaya per day. MODIS/Terra science-quality data are available as of February 2000 and MODIS/Aqua data as of July 2002 (Guenther et al. 2002). MODIS collects data in 36 spectral bands at various resolutions. The bands used here are Band 21 (4 µm), Band 22 (also 4 µm), and Band 31 (11 µm), each of which has 1-km resolution (Table 1). Though MODIS provides reasonable spatial resolution for the purposes of this project, its relatively poor temporal resolution warrants supplementation with a second dataset.

2.1.2 GOES (Geostationary Operational Satellites)

GOES data was chosen to provide the high temporal resolution perspective. GOES images the entire Earth disc at ~26 minute intervals, and can image smaller sections at higher temporal resolutions (GOES Databook). Data from the satellite stationed at the GOES East position (75° W longitude) were used for this project. The GOES series of geosynchronous weather satellites carries an imager that collects data in five spectral bands at various resolutions (GOES Databook). The bands used here are Band 2 (3.9 µm) and Band 4 (10.7 µm), each of which has 4-km resolution (Table 1).

<table>
<thead>
<tr>
<th>Temporal Resolution</th>
<th>MODIS</th>
<th>GOES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Resolution</td>
<td>6 hours</td>
<td>~15 minutes</td>
</tr>
<tr>
<td></td>
<td>1000 m</td>
<td>4000 m</td>
</tr>
<tr>
<td>Region</td>
<td>MIR</td>
<td>MIR</td>
</tr>
<tr>
<td>Central Wavelength (µm)</td>
<td>3.96</td>
<td>3.96</td>
</tr>
<tr>
<td>Saturation (K)</td>
<td>~335</td>
<td>~300</td>
</tr>
</tbody>
</table>

Table 1: MODIS & GOES Specifications.
Images were acquired from an archive held by the Hawaii Institute of Geophysics and Planetology (HIGP). GOES data were thus obtained in order to supplement the temporal resolution of MODIS data, and to explore the feasibility of combining measurements from both sensors into a single time series for a given eruption.

### 2.2 Data Acquisition and Image Processing

The temporal breadth of this investigation was limited primarily by the availability of satellite data. From the total of 248 flows listed by Matías (2009), a subset of 10 flows occurred after the launch of MODIS/Terra (November 1999). A total of 2403 MODIS and over 25,000 GOES images were acquired for flows that occurred during this period. Table 2 lists these flows and some selected attributes.

All available MODIS data acquired for the seven short-duration flows (< 35 days). For the two intermediate-duration flows (210 and 239 days), data volume was slightly reduced by utilizing MODVOLC alert files. MODVOLC is a near-real-time hot spot detection system operated by the Hawaii Institute of Geophysics and Planetology (Wright et al. 2002, 2004). All available MODIS data was downloaded for days when at least 1 hot spot alert was registered by MODVOLC (reducing data volume by ~20%). For the longest flow (810 days), only nighttime images (in which hot spot are most easily identified) were acquired, reducing the data volume by about half. All available GOES data were acquired, totaling over 25,000 files. However, due to gaps in the archive at the time of data acquisition, GOES data was not available for every flow, and sometimes only for a portion of the total duration of a given flow.

<table>
<thead>
<tr>
<th>#</th>
<th>Start Date</th>
<th>End Date</th>
<th># Hotspots</th>
<th>Surface Area* (m²)</th>
<th>Length* (m)</th>
<th>Duration* (days)</th>
<th>Volume* (m³)</th>
<th>E.* (m³/s)</th>
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<tr>
<td>1</td>
<td>06/12/04</td>
<td>06/15/04</td>
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<td>5222</td>
<td>142</td>
<td>3</td>
<td>11488</td>
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<td>12/23/04</td>
<td>08/17/05</td>
<td>74</td>
<td>517234</td>
<td>1223</td>
<td>239</td>
<td>879299</td>
<td>0.04258</td>
</tr>
<tr>
<td>3</td>
<td>05/08/05</td>
<td>05/15/05</td>
<td>4</td>
<td>11234</td>
<td>370</td>
<td>7</td>
<td>28085</td>
<td>0.04644</td>
</tr>
<tr>
<td>4</td>
<td>04/01/06</td>
<td>04/04/06</td>
<td>2</td>
<td>1500</td>
<td>72</td>
<td>3</td>
<td>3000</td>
<td>0.01157</td>
</tr>
<tr>
<td>5</td>
<td>04/01/06</td>
<td>04/04/06</td>
<td>2</td>
<td>336</td>
<td>38</td>
<td>3</td>
<td>671</td>
<td>0.00259</td>
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<tr>
<td>6</td>
<td>04/04/06</td>
<td>04/07/06</td>
<td>5</td>
<td>40778</td>
<td>990</td>
<td>3</td>
<td>138646</td>
<td>0.53490</td>
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<td>06/30/08</td>
<td>--</td>
<td>854339</td>
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<td>590368</td>
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<tr>
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<td>02/18/09</td>
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<td>330561</td>
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<td>210</td>
<td>1652803</td>
<td>0.09109</td>
</tr>
<tr>
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<td>01/24/09</td>
<td>01/30/09</td>
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<td>8290</td>
<td>181</td>
<td>6</td>
<td>18239</td>
<td>0.03518</td>
</tr>
<tr>
<td>10</td>
<td>05/27/10</td>
<td>06/30/10</td>
<td>10</td>
<td>1740000</td>
<td>5550</td>
<td>33</td>
<td>3840000</td>
<td>1.22054</td>
</tr>
</tbody>
</table>

* Matías (2009)

Table 2: List of lava flows included in this investigation.
All images were viewed and enhanced using ENVI 4.1 (Environment for Visualizing Images) software. MODIS images were georeferenced using the “Georeference MODIS 1B” function built-in to ENVI. This function corrects for several sources of geometric distortion, but was performed primarily so that Pacaya could be quickly and precisely located (after the correction was applied, calculated latitude/longitude coordinates for each pixel could be viewed in the Cursor Location/Value window). Geographic information also helped to determine whether or not a suspected hot spot was coincident with the location of Pacaya. To further reduce processing time, only Bands 21, 22, and 31 were georeferenced (as opposed to all 32 available bands). Additional image processing was unnecessary for GOES images because they arrived as clipped, 1000 x 1000 pixel sub-images, in which Pacaya was always in the same location.

2.3. Determining Data Quality

Three main factors affected satellite data quality: cloud cover, solar heating, and geometric distortion. Thick clouds frequently covered Pacaya and the surrounding area, especially during the summer (see Appendix A for examples). Since even thin clouds can significantly interfere with the total amount of radiation reaching a sensor, all images in which clouds were observable over Pacaya were discarded. At 1-km (the resolution of MODIS), cloud cover was easily identifiable. Determining the extent of cloud cover for the lower resolution GOES data was somewhat problematic at night (when hot spots are most easily identified) because the accompanying 1-km visible-wavelength images were not usable.

Solar heating hindered the identification of hot spots during the daytime by contaminating pixels with extra radiance from the surrounding heated surface, thereby raising the pixel-integrated radiance and often making hot spots indistinguishable (Harris et al. 1997b). Daytime images were contrast enhanced in order to highlight the most radiant pixels, sometimes revealing a clear hot spot. In other images, solar heating was so intense that anomalous pixels were indistinguishable from background pixels. It was relatively uncommon for a hot spot to be clearly identifiable during the daytime in either MODIS or GOES images. Most daytime images were discarded due to solar heating, but
occasional clearly identifiable hot spots did occur (Appendix). Since very few daytime hotspots were usable, daytime images were not acquired for the long 810-day flow (April 2006 – June 2008) in order to reduce data volume.

Cloud cover and solar heating affected both MODIS and GOES images, but geometric distortion was only a problem with MODIS images. MODIS has 1-km spatial resolution at nadir, but that resolution decreases toward the edge of the image. Because hot spots appeared in different positions in each image, they were distorted to different degrees. This effect is minimal up to a viewing angle of ~30° (Harris et al. 1997a), so hot spots that were beyond this scan angle were not used to calculate effusion rates. A related problem was that many of the MODIS images acquired were unusable because Pacaya was not actually located on the image. Though the MODIS image archive was searched geographically using latitude and longitude parameters centered over Pacaya, the search frequently returned images where Pacaya was just beyond the swath width. Those images had to be opened and searched in order to determine if Pacaya was actually contained in the image.

Thus, in order to be used to calculate an effusion rate, an image had to 1) contain Pacaya, 2) have no observable cloud over Pacaya, 3) not exhibit distortion, 4) not be contaminated by solar heating, and 5) contain a hot spot. Out of 2403 MODIS images, 248 (10%) met these criteria. From the 2642 GOES images that were viewed, 704 (27%) met these criteria.

2.4 Hot Spot Identification

A “hot spot” is a pixel or group of pixels that is thermally anomalous (i.e. it has a higher radiance) compared to the surrounding pixels. In single-band MIR images, hot spots appeared visibly brighter than adjacent ambient pixels. When MODIS pixels were saturated beyond the maximum measurable radiance (see Table 1), they appeared black and registered a value of -999. No GOES pixels viewed during this investigation were saturated. Appendix A provides some examples of hot spots of varying quality and characteristics.

Several hot spot detection algorithms have been developed for fire-detection and volcanological applications (e.g. Higgins and Harris 1997, Tramutoli 1998, Wright et al.
2002, Di Bello et al. 2004). Each algorithm has unique strengths and weaknesses, but none are able to detect 100% of the hot spots that can be identified by the human eye (Steffke and Harris, 2011). The most significant limitations of algorithms are the tendencies to falsely identify hot spots and/or to overlook true hot spots. Most of the flows analyzed for this project were relatively small in area, and therefore caused only small increases in radiance. This change was apparent to a trained human observer, but might have been overlooked by an algorithm. Some flows were very short-lived, so to ensure as complete a dataset as possible, hot spots were identified manually, maximizing the inclusion of true hot spots and minimizing the inclusion of false hot spots. This investigation used images acquired over 6 years and through all seasons and weather conditions. If a hot spot detection algorithm were utilized, it would need to have a high success rate in a variety of conditions, which is unlikely given the limits of current detection algorithms. Therefore, manual identification of hot spots was beneficial because it provided valuable hands-on image interpretation experience and also because it helped to ensure a complete and accurate dataset.

All MODIS images were individually opened, georeferenced, evaluated for quality, and searched manually for hot spots. The relative location of Pacaya was different in each MODIS image, so to ensure that a hot spot was actually over Pacaya the “Cursor/Location Value” window, which displays the latitude and longitude of the georeferenced pixels as the cursor hovers over them, was utilized. This eliminated the inclusion of false hot spots, such as those due to fire or other volcanoes (Figure 4a). Hot spots were generally 1 to 4 pixels large, but for the May 2010 eruption, several hot spots were larger than 10 pixels. Band 22 saturates at a lower temperature than Band 21 (Table 1), so a pixel saturated in Band 22 still appeared bright in Band 21 (unless it was also saturated) (Figure 5). Band 21 was never saturated for images viewed in this project. MODIS Bands 21 and 22 were always opened and viewed simultaneously in adjacent ENVI windows so that saturated pixels would not be mistakenly overlooked. This configuration was especially important in nighttime images, when black saturated pixels often appeared indistinguishable from cool background pixels. After a hot spot was identified in Bands 21 and 22, the corresponding pixel or pixels were next viewed in Band 31. The majority of hot spots did not provide sufficient extra radiance in Band 31 to
raise the radiance above ambient. However, in some cases (e.g. for the larger flows), there was a slight observable increase in Band 31 pixels (Figure 5). Radiances, in units of Watts per square meter per micrometer per steradian (Wm\(^{-2}\)µm\(^{-1}\)sr\(^{-1}\)), were recorded in each of the three bands for each anomalous pixel. The MIR band (21 and 22) measurements represented anomalous radiances (Band 21 was substituted for Band 22 when the latter was saturated), and the LWIR band (31) radiances represented ambient or “background” radiances. On occasions when the Band 31 radiance was above ambient, the background radiance was instead averaged from adjacent Band 31 pixels (Figure 5). “Volcanic” radiances (defined as anomalous radiance minus background radiance) were plotted in a time series for each eruption.

Over 25,000 GOES images were acquired, so it would have been impractical to view every one of them. Instead, images were opened at ~3 hour intervals. When a hot spot was identified, the image in which it first appeared was found, and each successive file was opened until the hot spot disappeared (usually because of cloud). During long periods of heavy cloud cover (sometimes lasting several weeks), only ~4 images per day were opened, in order to monitor cloud conditions. Locating Pacaya in GOES images was simpler than in MODIS images, because Pacaya always appeared in the same location. The location was confirmed by overlaying several GOES images with suspected Pacaya.

![Figure 4](image-url)
hot spots over a Google Earth image of the region (Figure 4b). After those hot pixels were confirmed to match the geographic location of Pacaya, only images that contained hot spots in the designated area were considered. GOES hot spots were usually 1-3 pixels large and generally appeared duller than MODIS hot spots because of the lower spatial resolution (i.e. the radiance emitted by the lava was diluted by the large ambient surface). Band 2 was the only GOES MIR band available, and saturated pixels were never found in any images viewed. When a hot spot was indentified in Band 2, it was then viewed in Band 4 to confirm that no increase in temperature was present. In a few rare cases, the hot pixels in Band 4 were found to be slightly anomalous. GOES pixel values were retrieved as temperatures in Kelvin. Temperatures were recorded in both Bands 2 and 4 for each anomalous pixel. Band 2 temperatures represented the anomalous temperature and Band 4 temperatures represented background. When an anomalous pixel was detectable in Band 4 (very rarely), the background temperature was instead averaged from the adjacent pixels. The hot spot temperatures were converted to radiances and plotted in a time series for each eruption.

If no hot spot was observed in the LWIR image (MODIS Band 31, GOES Band 2), then this was used to provide the background radiance, instead of averaging the surrounding MIR pixels (Wright and Flynn 2005). Using a single band for both anomalous and background radiance would have resulted in errors in many cases. For example: if using just LWIR radiances, the pixel at the center of the Pacaya sub-scene is usually coldest (because of elevation) and if a flow isn’t strong enough to
increase the Band 31 radiance above that of the adjacent pixels, then resulting volcanic radiance would actually be negative.

Additionally, each hot spot was given a qualitative ranking of “Good”, “Fair”, or “Poor”. “Good” hot spots were clearly identifiable (bright), had no clouds near the vicinity of Pacaya, were not distorted, and were not affected by solar heating. “Fair” hot spots may have had a slight chance of cloud contamination, or may have been daytime hot spots. “Poor” data either had a high probability of cloud contamination or contained other interesting anomalies, and were saved for reference purposes. “Poor” hot spots were never used in final data sets.

2.5 Effusion Rate Calculation

All calculations were performed in Microsoft Excel ©. The effusion rate calculation method described by Harris et al. (1997a) is based on the method of Pieri and Baloga (1986) and Crisp and Baloga (1990) and consists of two main steps: estimation of lava flow area from radiance measurements, and subsequent calculation of effusion rate. This conversion was initially based on an assumption that, in cooling from eruption temperature to the temperature at which motion ceases, the heat loss from the flow is balanced by the heat supplied (Harris et al. 1997a). In this model, heat is supplied from advected heat plus the latent heat of crystallization ($Q_{\text{cryst}}$):

$$Q_{\text{adv}} = E_r \rho C_p (T_{\text{erupt}} - T_{\text{stop}})$$

$$Q_{\text{cryst}} = E_r \rho \phi C_L$$

where $E_r$, $\rho$, $C_p$, $T_{\text{erupt}}$, $T_{\text{stop}}$, $\phi$, and $C_L$ are the TADR, lava density, specific heat capacity, eruption temperature, the temperature at which flow motion ceases, average mass fraction of crystals grown in cooling through $(T_{\text{erupt}} - T_{\text{stop}})$, and latent heat of crystallization, respectively. If heat lost through conduction is negligible, the total heat lost by the flow is from radiation plus convection ($Q_{\text{out}}$):

$$Q_{\text{rad}} = A_{\text{tot}} \sigma \varepsilon T^4$$

$$Q_{\text{conv}} = A_{\text{tot}} h_c (T - T_{\text{amb}})$$

where $A_{\text{tot}}$, $\sigma$, $\varepsilon$, $T$, $h_c$, and $T_{\text{amb}}$ are the total area of the lava flow, Stefan Boltzmann constant, lava emissivity, lava surface temperature, convective heat transfer coefficient,
and ambient air temperature, respectively. Because $Q_{in}$ is equal to $Q_{out}$, these equations can be combined and rearranged to solve for eruption rate:

$$Q_{in} = Q_{out},$$

$$E_r \rho C_p (T_{erupt} - T_{stop}) + E_r \rho \phi C_L = A_{tot} \sigma \varepsilon T^4 + A_{tot} h_c (T - T_{amb}),$$

$$E_r = \frac{Q_{tot}}{\rho [C_p \Delta T + \phi C_L]} \quad (6)$$

where $Q_{tot}$ is the total heat loss (from radiation and convection) and $(T_{erupt} - T_{stop})$ has been simplified to $\Delta T$.

Terms in the denominator of Equation 6 were set from literature values (Table 3). This equation requires an estimation of lava flow area in order to calculate $Q_{tot}$. The area of lava for each hot spot was calculated from measured radiances using a thermally mixed-pixel model. But first, the measured pixel values had to be transformed into radiance values, which was achieved via the Planck function:

$$L(\lambda, T) = c_1 \lambda^{-5} \left(\exp^{c_2 \lambda T} - 1\right)^{-1} \quad (7)$$

where the constants from Equation 1 have been simplified to $c_1 (2\pi hc^2)$ and $c_2 (hc/k)$. This equation was then rearranged in order to calculate temperatures from MODIS pixel radiances:

$$T = \frac{c_2}{\lambda \ln \left(\frac{c_1 \lambda^2}{L(\lambda, T) + 1}\right)} \quad (8)$$

Anomalous and background radiance measurements were made at different wavelengths (~3.9 and ~11 µm, respectively), and were transformed into radiances of the same wavelength to complete the calculations. For example, MODIS Band 31 background radiances were converted to Band-22-equivalent radiances. Because radiance varies as a function of wavelength and temperature (Figure 2), if the temperature of an object is known, the radiance it emits at any given wavelength can be calculated. MODIS temperatures were already calculated from radiances via Equation 8 and GOES measurements were already in units of temperature. The background temperatures (MODIS Band 31 and GOES Band 2) were input into Equation 7 to find the radiance that
would be emitted at a wavelength of 3.9 µm (MODIS Band 22 and GOES Band 2 central wavelength).

### Table 3: Parameters used to calculate effusion rates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lava density*</td>
<td>ρ</td>
<td>2678</td>
<td>kg m⁻³</td>
<td>1,2,3</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>C_p</td>
<td>1130</td>
<td>J kg⁻¹ K⁻¹</td>
<td>4,5</td>
</tr>
<tr>
<td>T_edge - T_amb</td>
<td>ΔT</td>
<td>Variable (initially 200)</td>
<td>K</td>
<td>5</td>
</tr>
<tr>
<td>Mass fraction of crystals grown in cooling through ΔT</td>
<td>φ</td>
<td>.50</td>
<td>fraction</td>
<td>4</td>
</tr>
<tr>
<td>Latent heat of crystallization</td>
<td>C_L</td>
<td>350000</td>
<td>J kg⁻¹</td>
<td>5</td>
</tr>
<tr>
<td>Stefan-Boltzmann constant</td>
<td>σ</td>
<td>5.67 x 10⁴</td>
<td>Wm⁻²K⁻¹</td>
<td>4</td>
</tr>
<tr>
<td>Emissivity</td>
<td>ε</td>
<td>.9887</td>
<td>--</td>
<td>4</td>
</tr>
<tr>
<td>Convective heat transfer coefficient</td>
<td>h_c</td>
<td>10</td>
<td>Wm⁻¹K⁻¹</td>
<td>5</td>
</tr>
<tr>
<td>Ambient air temperature</td>
<td>T_amb</td>
<td>25</td>
<td>C</td>
<td>4</td>
</tr>
<tr>
<td>Lava area</td>
<td>A_hot</td>
<td>calculated</td>
<td>m²</td>
<td>calculated</td>
</tr>
<tr>
<td>Lava surface temperature</td>
<td>T</td>
<td>250, 350, and 600</td>
<td>C</td>
<td>4</td>
</tr>
<tr>
<td>Vesicularity</td>
<td>v</td>
<td>.10</td>
<td>fraction</td>
<td>4</td>
</tr>
</tbody>
</table>

* Bulk values are used (i.e. vesicle correct values)


Next, the area of lava contained in a hot spot could then be calculated. A single-band mixed-pixel model was applied (Harris et al. 1997a), which assumes that a pixel contains two thermal components; hot (lava) and ambient (background surface) (Figure 3). This was rearranged to solve for $p$, the portion of the pixel containing the hot component (lava flow):

$$R_\lambda = p L(\lambda,T_h) + (1- p)L(\lambda,T_a),$$  \hspace{1cm} (9a)

so that

$$p = \frac{R_\lambda - L(\lambda,T_a)}{L(\lambda,T_h) - L(\lambda,T_a)}$$  \hspace{1cm} (9b)

where $R_\lambda$, $L(\lambda,T_a)$, and $L(\lambda,T_h)$ are the measured radiance of the hot pixel, the radiance of the cold portion, and the radiance of the hot portion, respectively. In Equation 9, the wavelength $\lambda$ is known, $R_\lambda$ is the measurement (anomalous radiance), and $L(\lambda,T_a)$ is an approximation represented by the background radiance measurement. Two unknowns remain; $p$ and $T_h$, one of which must be assumed. Because lava surface temperature is easier to confine (Harris et al. 1997a), $T_h$ was assumed. Three mixture models were applied for lava surface temperatures of 250°C, 350°C, and 600°C, respectively, in order to span a range of realistic situations.

With the pixel portion $p$ calculated, the area of the hot (lava) portion of the pixel is then given by:

$$A = p A_{pixel}$$  \hspace{1cm} (10)
where \( A_{\text{pixel}} \) is the pixel area (1000 m\(^2\) for MODIS and 4000 m\(^2\) for GOES). To find the total area of lava associated with a given hot spot covering multiple pixels, the lava areas extracted for each pixel across the anomaly were summed:

\[
A_{\text{tot}} = \sum A_1 + A_2 + A_3 + ... A_n
\]

(11)

where \( A_{\text{tot}} \) is the sum of the areas calculated for each pixel in a given hot spot. This area was then used to calculate the heat flux terms given by Equations 4 and 5, yielding all of the terms necessary to calculate effusion rate using the Equation 6 approach. Calculations were carried out for each hot spot at each of the three lava temperature models (250°C, 350°C and 600°C), yielding time-averaged discharge rates (TADR) in cubic meters per second (m\(^3\)/s) for a range of lava surface temperatures.

Note that Equation 6 can be simplified to a linear relationship between area and effusion rate (Wright et al. 2001, Harris and Baloga 2009):

\[
E_r = \frac{Q_{\text{tot}}}{\rho \left[ C_p \Delta T + \phi c_L \right]},
\]

\[
E_r = A_{\text{tot}} \frac{\sigma \varepsilon T^4 + h_c (T - T_{\text{amb}})}{\rho \left[ C_p \Delta T + \phi c_L \right]},
\]

\[
E_r = A_{\text{tot}} M
\]

(12)

where \( M \) is a coefficient that relates effusion rate and area. This was the relationship tested and used here. That is, using the single-band mixed-pixel model of Equation 9, the area of lava could be estimated if its temperature was assumed. This could then be directly converted to effusion rate using the relation of Equation 12.

2.6 Volume Calculation

Volume estimates were made between each effusion rate measurement and were summed to yield cumulative volume. The volume erupted between measurements was found by integrating the area between each measurements using the trapezium rule:

\[
V_i = \int_{a}^{b} f(x) dx \approx (t_i - t_2) \frac{E_{r_1} + E_{r_2}}{2}
\]

(13)

where, \( t_i, \) \( t_2, \) \( E_{r_1}, \) and \( E_{r_2} \) are the total elapsed time in seconds of the first measurement, total elapsed time of the second measurement, effusion rate at time 1, and effusion rate at
time 2, respectively (time = 0 was set to the first measurement of a given dataset). Volume summed over each successively longer period of time can be used to derive a running cumulative volume of each flow:

\[ V_{\text{current}} = \sum_{i=1}^{n} V_i \]  
(14)

where \( V_{\text{current}} \) is the cumulative volume at a given measurement \( n \). The total cumulative volume, \( V_{\text{tot}} \) is then given by:

\[ V_{\text{tot}} = \sum V_1 + V_2 + V_3 + ... V_n \]  
(15)

where \( n \) is the total number of volume estimates during a given eruption. Running cumulative volumes were plotted for each flow.

2.7 Best-Fitting

The initial effusion rate and cumulative volume estimates were made using the assumptions shown in Table 3. As previously stated, Equation 6 can be simplified to a linear relationship wherein effusion rate is related to area by a coefficient \( M \) (Equation 12). Therefore, the key to calculating accurate effusion rates via this method is to define the correct value of \( M \) for a given flow. To define the \( M \) for each dataset, the initial estimates were adjust to best fit the volumes from Matías (2009) using the medium-temperature 350°C model. To produce the desired volume, one or more of the terms constituting \( M \) had to be adjusted. It is important to note that the coefficient \( M \) must account for all factors that may influence the relationship between area and effusion rate such as slope, terrain, or rheology (Harris and Baloga 2009).

For simplicity, only one term was allowed to vary. Since \( M \) is essentially a value representing the true relationship between area and effusion rate, manipulation of a single variable was a reasonable approach. Density (\( \rho \)), specific heat capacity (\( C_p \)), and latent heat of crystallization (\( C_L \)) are not realistically variable, as they were set at literature values (Table 3). Three possible terms then remain; percent vesicles (\( \nu \)), percent crystallization (\( \phi \)), and cooling (\( \Delta T \)). Since \( \nu \) and \( \phi \) are fractions and can only vary between 0 and 1, they were held constant at realistic values of 0.1 and 0.5, respectively, and only \( \Delta T \) was allowed to vary.
Volumes from Matías (2009) were used as target values for the cumulative volume calculations described above. However, it is important to note that missing data at the beginning and/or end of a flow had to be accounted for. That is, if the first measurement occurred 3 days after the start of a flow, then the volume accumulated during that time must be subtracted from the total volume. To reduce the target volume to the proper value, the total actual volume (from Matías 2009) was divided by the total number of days of the eruption, yielding the mean output rate in m$^3$/day. Then the number of days missing at the beginning and end of the flow were counted. The mean output rate was multiplied by the number of missing days to find the volume that should have theoretically been unaccounted for by the satellite measurements. This volume was subtracted from the total actual volume, and the result was used as the target volume for each dataset. The target volume is given by:

$$V_{\text{tar}} = V_{\text{act}} - \left(\frac{V_{\text{act}}}{n} \cdot m\right)$$

(16)

where $V_{\text{tar}}$, $V_{\text{act}}$, $n$, and $m$ are the target volume, actual volume (from Matías 2009), total duration of the flow in days, and the number of days unaccounted for at the beginning and end of the flow, respectively.

The intermediate temperature model ($350^\circ$C) was manipulated to exactly fit the target volume. Best-fitting was accomplished using the convenient “Goal Seek” function in Microsoft Excel ©. This function automatically adjusts the selected cell (total cumulative volume) to the target value (Equation 16) by manipulating a second cell. ($\Delta T$), yielding the set of effusion rates necessary to attain the target volume. Since the $\Delta T$ cell was linked to the

![Image](image.png)

*Figure 6: Best-fitting technique used to calibrate TADRs and volumes. The terms used to calculate effusion rate are $Q_{\text{tot}}$, $\rho$, $C_p$, $C_L$, $\Phi$, $\Delta T$. TADRs are used to estimate the total volume of a flow, which is adjusted to the target volume. Adjusting a single term of Equation 6 (effusion rate equation), in this case $\Delta T$, attains the target volume. Excel © automatically changes the value of $\Delta T$ until the set of effusion rates which attain the target volume is found.*
effusion rate cells for all three temperature models, each model was adjusted simultaneously. Figure 6 illustrates the process used to best fit the cumulative volume data by manipulating $\Delta T$.

When a reasonable value for $\Delta T$ allowed the calculated volumes to attain the target volume, then the effusion rate calculation was deemed a good approximation of the actual physical situation. This is effectively a best fitting method that allows the $M$ value in the Equation (12) conversion to be set on the basis of the final volume that all the component TADR yields. In short, if all the TADR arrive at the predicted volume, then we assume we can trust the TADRs that are used to derive the best-fitting volume.

Theoretically, both the MODIS and GOES datasets of a given flow should have attained the target volume using a consistent $M$ value (Equation 12). However, they only yielded their respective target volumes using considerably different $M$ values (Table 4). Since MODIS data are of higher spatial resolution and generally fit the target volume using more reasonable $\Delta T$ values (especially for the three longest flows, and not necessarily for the smaller flows which had poor coverage), it follows that the MODIS data can be used to estimate TADR and GOES cannot. That is, the lower limit of this methodology may have been reached for the low spatial resolution GOES data and such low intensity (small hot spot) targets.

<table>
<thead>
<tr>
<th>Flow #</th>
<th>Flow Date</th>
<th>MODIS $\Delta T$ (°C)</th>
<th>MODIS $M$</th>
<th>GOES $\Delta T$ (°C)</th>
<th>GOES $M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td>Dec 2004 – Jul 2005</td>
<td>333</td>
<td>8.338 x 10^{-6}</td>
<td>1117</td>
<td>3.209 x 10^{-4}</td>
</tr>
<tr>
<td>#3</td>
<td>May 2005</td>
<td>1037</td>
<td>3.410 x 10^{-6}</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>#6</td>
<td>Apr 2006</td>
<td>-87</td>
<td>5.952 x 10^{-5}</td>
<td>60</td>
<td>1.892 x 10^{-5}</td>
</tr>
<tr>
<td>#7</td>
<td>Apr 2006 – Jun 2008</td>
<td>209</td>
<td>1.118 x 10^{-5}</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>#8</td>
<td>Jul 2008 – Feb 2009</td>
<td>84</td>
<td>1.702 x 10^{-5}</td>
<td>484</td>
<td>6.359 x 10^{-6}</td>
</tr>
<tr>
<td>#9</td>
<td>Jan 2009</td>
<td>175</td>
<td>1.234 x 10^{-5}</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>#10</td>
<td>May 2010 – Jun 2010</td>
<td>-37</td>
<td>3.448 x 10^{-5}</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4: M and $\Delta T$ values used to calculate calibrated effusion rates.
3. RESULTS

3.1 Data Coverage and Quality

Several issues affected data coverage and quality. Usable hot spots were only available in sufficient quantities for seven of the 10 lava flows considered (Table 2). Flow #1 was discarded because no cloud-free data was available from either MODIS or GOES. Flows #4 and #5 were short-lived and occurred simultaneously. Since the areas of two flows cannot be separated they were discarded. MODIS data was available for the remaining seven flows, but GOES was only available for three. GOES data was not available for any dates during flows #7, #9 and #10, very little was available for flow #3, and gaps in available data affected coverage for flow #6. Additionally, flows #3 and #9 occurred during longer, overlapping flows. The overlapping dates were purposefully skipped in the longer flows’ datasets, and were instead used just for the smaller flows. However, obvious errors would have arisen if two separate flows were simultaneously active in an image where only one flow was assumed to exist. So, although data was collected for flows #3 and #9, they were probably of poor quality. In summary, four flows were considered to be of good quality: #2 (Dec 2004), #7 (Apr 2006), #8 (Jul 2008), and #9 (May 2010) (Table 2). However, only 2 flows (#2 and #8) had relatively complete sets of both MODIS and GOES data. Appendix B contains calendars showing the coverage of MODIS and GOES data for each flow.

3.2 Radiances

“Volcanic” radiances (anomalous minus background radiances) for confirmed hot spots were plotted in time series for each eruption (Figure 7). GOES radiances were smaller than MODIS radiances in general because the extra radiance contributed by lava was diluted in the much larger ambient background area. Even though it was ultimately decided that GOES data could not be transformed into accurate effusion rates in this particular case, they still provided relative information about changes in thermal activity at Pacaya. For instance, the GOES data confirmed the same trend of low, scattered measurements that are clear in the MODIS data. This scattering was expected, as effusion rates can change considerably over periods of minutes even during low effusion rate
eruptions (e.g. Bailey et al. 2006). The three long-duration flows (those of Dec 2004, Apr 2006, and Jul 2008) showed the most similar average radiances, standard deviations, and variance in both MODIS and GOES datasets, respectively (Table 5). This was to be expected because some of the shorter flows had issues with data coverage and/or quality.

### Table 5: Radiance and effusion rate statistics (after calibration). The three longest (and best quality) flows are italicized (Dec 04 – Dec 05, Apr 06 – Jun 08, Jul 08 – Feb 09).

<table>
<thead>
<tr>
<th>Flow Date</th>
<th>Sample</th>
<th>MODIS</th>
<th>GOES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 04 – Aug 05</td>
<td>74</td>
<td>1.86</td>
<td>1.37</td>
</tr>
<tr>
<td>May 05</td>
<td>4</td>
<td>2.94</td>
<td>0.71</td>
</tr>
<tr>
<td>Apr 06</td>
<td>5</td>
<td>3.64</td>
<td>3.69</td>
</tr>
<tr>
<td>Apr 06 – Jun 08</td>
<td>67</td>
<td>2.55</td>
<td>1.68</td>
</tr>
<tr>
<td>Jul 08 – Feb 09</td>
<td>82</td>
<td>2.14</td>
<td>1.48</td>
</tr>
<tr>
<td>Jan 09</td>
<td>4</td>
<td>1.00</td>
<td>0.41</td>
</tr>
<tr>
<td>May – Jun 10</td>
<td>10</td>
<td>15.85</td>
<td>18.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow Date</th>
<th>Sample</th>
<th>MODIS</th>
<th>GOES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 04 – Aug 05</td>
<td>74</td>
<td>0.04</td>
<td>0.03</td>
</tr>
<tr>
<td>May 05</td>
<td>4</td>
<td>0.03</td>
<td>0.01</td>
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<tr>
<td>Apr 06</td>
<td>5</td>
<td>0.61</td>
<td>0.61</td>
</tr>
<tr>
<td>Apr 06 – Jun 08</td>
<td>67</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>Jul 08 – Feb 09</td>
<td>82</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Jan 09</td>
<td>4</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>May – Jun 10</td>
<td>10</td>
<td>1.53</td>
<td>1.77</td>
</tr>
</tbody>
</table>

3.3 Effusion Rates

The effusion rate datasets were calibrated to fit adjusted Matías (2009) volumes using the best-fitting technique described above. Figures 8 and 9 show the resulting effusion rate time series for seven MODIS and three GOES datasets, respectively. In general, MODIS effusion rates were calculated using reasonable values for $\Delta T$ (Table 4) (a $\Delta T$ value of about 150 to 250°C has been shown to be a reasonable range that produces good results (Harris et al. 2005)). Considering only the 4 good-quality flows (white rows in Table 4), it is evident that the $\Delta T$ values for MODIS datasets are more realistic than those for GOES datasets and that any unrealistic $\Delta T$ could be adjusted (for example, by simultaneously varying another term in Equation 6, such as vesicularity) to obtain a better $\Delta T$ while holding the same value for $M$. However, GOES effusion rates could only be constrained using unrealistic values for $\Delta T$ (i.e. they were more unrealistic than the associated MODIS values and could not be compensated by manipulating other variables beyond reasonable values). Additionally, each flow required a different coefficient in order to attain their respective target volumes (Figure 10 and Table 4). This discrepancy
probably arose from physical factors unaccounted for by Equation 6 (e.g. slope, terrain, rheology, vent location, etc.) or modeling factors (e.g. choice of temperature model (350°C), accuracy of the volumes calculated by Matías (2009), type of activity occurring during eruption, completeness of the dataset, etc.). Even considering the many sources of potential error, $\Delta T$ and $M$ values were most similar for the four high quality flows (solid lines in Figure 10). Note the negative $\Delta T$ for flow #10 (Table 4). This eruption released a large volume at a high effusion rate, and therefore probably held some characteristics that caused a different $M$ value than the other three high-quality flows.
Volcanic Radiance (MODIS & GOES)

Figure 7. Volcanic radiances were plotted for seven flows. Note that GOES radiances (orange diamonds) were only available in significant numbers for three flows (a, c, and e). Flows a, d, and e are the three longest flows and show similar radiance levels. Flows b, c, and f were short-lived flows that had limited coverage. Note the significantly higher radiances in flow g, a month-long flow with by far the highest effusion rate. Note the interesting trend in c, where radiances were initially high and decreased over a few days, indicating typical effusive activity that begins strong and tapers off. Radiances for low-effusion rate flows tend to stay below 10 Wm⁻²sr⁻¹um⁻¹ for MODIS and 2 Wm⁻²sr⁻¹um⁻¹ for GOES. The large eruption g shows MODIS radiances above 10 Wm⁻²sr⁻¹um⁻¹.
Effusion Rates (MODIS)

Figure 8. Effusion rates were estimated from MODIS radiances for seven flows, and fitted to Matías (2009) volumes. Black crosses represent the minimum, intermediate, and maximum mean output rates calculated by Matías (2009). Note that graphs are not to the same scale. Flows a, d, and e show similar low, but scattered effusion rates. Note the high effusion rates of g the May 2010 flow. Flows b, c, and f were shorter and may have had issues with data quality (see text for discussion). Note the decreasing trend in c, which was discussed above in Figure 8.
Effusion Rates (GOES)

Figure 9. Effusion rates were estimated from GOES radiances for three flows, and fitted to Matías (2009) volumes. Note that the graphs are not to the same scale. Black crosses represent the minimum, intermediate, and maximum mean output rates calculated by Matías (2009). GOES data provided better temporal coverage than MODIS. Flows a and b provided the most complete coverage. Note the large gap in data for flow c, which was due to the unavailability of data. The gap in a in June was due to cloud cover (this gap can also be seen in the corresponding MODIS dataset in Figure 8).

Figure 10: Trends representing the “M” value of Equation 12, used to calculate effusion rates and volumes for each flow (MODIS). Note that dotted lines represent the three low-quality flows, while solid lines represent the four longer, higher-quality flows. The May 2010 (orange) clearly defects from the other three, high-quality flows, which have fairly close slopes. See Table 4 for corresponding M and ΔT values.
3.4 Cumulative Volumes

Cumulative volumes were calibrated to fit adjusted Matías (2009) volumes and were plotted in time series for seven eruptions (Figures 11 and 12). As noted above, MODIS and GOES datasets required different coefficients ($M$) to attain the same volume (Table 4). Though theoretically, the fitted dataset could have been combined, they were kept separate, noting that MODIS data is of superior quality. In the cumulative volume plots, gaps in data coverage are obvious. It is likely that some of the gaps contained increases or decreases in activity that deviated from the average effusion rate, perhaps introducing some error in the total cumulative volume. This is especially true for the shorter-duration flows, which sometimes had only 1 usable MODIS image per day. In Figure 12b, the potential utility of GOES data is obvious; weather conditions were ideal and usable hot spots were available every 15 minutes. Unfortunately, data was only available until the evening of April 5, though the flow continued until April 7.

3.5 Long-term Supply Rate

The total cumulative volume from all flows over a period of 20 years was plotted (supplementary data from Matías (2009) was used prior to the December 2004 eruption (Figure 13)). By combining all the volumes calculated from MODIS data in a time series, two cycles could be identified: 1) steady periods of volumetric increase broken by 2) shorter, more rapid periods of increase (green and blue, respectively in Figure 13). The long-term steady rate of increase was similar for each of the three long-duration flows that were investigation here (Table 5). This rate was suggested to be representative of the supply rate from the magma chamber to, and out of, the conduit. This allowed potential speculation about conduit convection.
Figure 11. Cumulative volumes calculated from MODIS radiances for seven flows, and fitted to Matías (2009) volumes. Note that graphs are not to the same scale. Black crosses represent the minimum, intermediate, and maximum volumes calculated by Matías (2009). The medium temperature model (350°C) was chosen to fit the Matías (2009) value. Note how the slope of the running cumulative volumes continues through gaps in measurements. It is possible that large gaps miss atypical effusion rates that would have altered the final volume.
Figure 12. Cumulative volumes calculated from GOES radiances for three flows, and fitted to Matías (2009) volumes. Note that graphs are not to the same scale. Black crosses represent the minimum, intermediate, and maximum mean output rates calculated by Matías (2009). Note how the slope of the line continues through gaps in measurements. The abrupt cut-off in b is due to a gap in the GOES archive. This was unfortunate because weather conditions during this time were ideal and measurements were taken at about 15 minutes intervals continuously.
Figure 13: Long term erupted volume and inferred supplied volume over 20 years. Two distinct types of activity were identified, 1) long periods with low effusion rates (green), and 2) shorter periods with higher effusion rates (blue). The supply rate was estimated by averaging the mean output rates from the three long-steady flows (A,B,C). Section D is representative of the second type of activity.

4. DISCUSSION

4.1 Supply Rate and Conduit Convection Model

Several studies have used degassing rates and/or heat loss measurements to estimate the amount of magma supplied to a volcano (e.g. Francis 1993, Allard et al. 1994, Kazahaya et al. 1994, Allard 1997). Assuming that Pacaya receives an approximately constant supply of magma to the conduit, the supply rate could be estimated based on the eruption cycles defined here rather than from degassing or heat loss measurements. This hypothesis is based on the premise that fresh magma is continuously supplied to the conduit at a certain rate and is supported by Eggers’ (1971) original suggestion that the petrographic and chemical consistency of Pacaya’s lava is due to a steady supply to an open magma chamber. Two phases of activity at Pacaya were indentified; 1) longer periods with low effusion rates, and 2) shorter periods with
high effusion rates (Figure 13). It is possible that lava bleeds from the conduit during periods of steady, low-effusion-rate activity at approximately the supply rate. (Ripepe et al. 2005, Harris et al. 2005). That is, when a dike taps the central conduit or the vent overflows, the associated low effusion rates are proposed to be representative of the supply rate to the conduit (Figure 14). Therefore, the time-averaged discharge rates for the three low-effusion-rate eruptions (A, B, and C in Figure 13) were averaged to approximate the supply rate (0.0784 m³/s or 7773 m³/day).

Figure 13 shows that the difference between supplied volume and actual erupted volume becomes slightly larger through time. Francis (1993) stated that whenever the inferred supply of mantle-derived magma exceeds the rate of eruption, formation of sub- and/or intra-volcanic intrusive complexes is indicated (i.e. endogenous or cryptic growth). Hypotheses explaining endogenous growth at other volcanoes have been suggested including cumulate formation, convection and recycling in a large magma chamber, or storage as dike intrusions (Francis 1993, Allard et al. 1994, Kazahaya et al 1993, Allard 1997). Allard (1997) concluded that the supplied magma flux at Etna (which greatly exceeds the actual erupted volume) was due to convection and recycling or magma, and the recycled magma may be stored in the crust as cumulates. At Pacaya, unerupted magma may continue to convect in the conduit and collect in the shallow magmatic system between eruptions. Pacaya is a continuously degassing volcano (Dalton et al. 2010), and in such a system, the supplied volume may travel to the top of the conduit where it degasses, and sinks back down due to an increase in density (i.e. density-driven convection) (Kazahaya et al. 1994). It would therefore be interesting to obtain an estimate of the long-term supply rate based on SO₂ degassing to compare with the supply rate assumed here.
The short, but voluminous bursts of activity such as in 2000 and 2010 may be explained by the eruption of the “collected” volume that had been circulating in the conduit between eruptions. That is, these eruptions may release larger volumes of magma at higher effusion rates, bringing the actual erupted volume closer to the supplied volume (however, these large pulses might also be due to temporary increases in supply rate). Further work may include comparing lava chemistries of the two phases to find any petrological or chemical differences between the samples, and obtaining an estimate of long-term SO2 degassing levels. Additionally, seismic tomography, gas geochemistry, gravity surveying, and ground-based thermal imaging may contribute to the understanding of this process.

4.2 Applicability of Method

Effusion rates were successfully calculated from thermal infrared satellite data using the technique of Harris et al. (1997a) and by calibrating to independent volume measurements. In general, GOES measurements yielded higher effusion rates than MODIS, and the coefficient $M$ (which relates area to effusion rate) differed significantly between MODIS and GOES datasets for the same flow. That is, GOES effusion rates could not be made to fit the Matías (2009) volumes without significantly different (and more unrealistic) values for $\Delta T$ than the corresponding MODIS effusion rates. For example, the December 2004 flow required a $\Delta T$ of 1117°C for the GOES dataset and 333°C for the MODIS dataset (Table 4). Therefore, MODIS data was deemed better suited for this method due to higher spatial resolution, and the fact that $\Delta T$ values for MODIS datasets were more realistic as compared to those for GOES datasets. Ultimately, GOES datasets were not deemed unsuitable for quantitative analyses and were not merged with MODIS datasets. However, GOES data may have been more useful for larger flows, such as in 2000 and 2010.

Though MODIS results were considered to be of good quality, each flow required a different $M$ to reach their respective target volumes. These differences may have been due to a number of physical factors unaccounted for by Equation 6, such as slope, terrain, vent location, and rheology, or due to modeling factors such as the choice of temperature model (350°C), accuracy of the volumes calculated by Matías (2009), type of activity...
occurring during eruption, and comprehensiveness of datasets. Even so, the three longest flows (also having the most complete datasets) had the most similar $M$ and $\Delta T$ values (Table 4 and Table 5), implying that the actual values for Pacaya’s lavas may lie within this range. Study of future flows could help to further constrain this value.

It is likely that the physical conditions encountered during this investigation surpassed the practical limits of the effusion rate calculation technique in the case of GOES data. Thus, if effusion rates at Pacaya are monitored via satellite, a higher-resolution sensor such as MODIS should be utilized. However, it may prove useful to acquire GOES data for larger eruptions, since they would likely yield better results. In the near future, fieldwork will help to better constrain the parameters of the Equation 6. Lava samples will provide better estimates of vesicularity and crystallinity for Pacaya’s lavas in general, and possibly reveal differences between individual flows. If flows are active during fieldwork, ground-based thermal imagery may help to define an average lava surface temperature, and more importantly, could be used to independently estimate effusion rates.

4.3 Implications for Hazard Mitigation

Two types of effusive activity were identified from the subset of flows analyzed in this investigation; 1) longer periods with low effusion rates, and 2) shorter periods with high effusion rates. The latter pose more risk since their flows move quickly and cover larger areas and/or distances, so the ability to quickly distinguish between these two types of activity is useful for hazard mitigation. This investigation has produced a record of the relative radiances emitted by these two types of activity in MODIS and GOES imagery (Figure 7). Continued long-term monitoring of radiances may provide a means of determining the relative rate of eruption and hence the relative level of risk. However, in emergency situations, data would need to be acquired in near-real time and at fairly high temporal resolution in order to serve a practical purpose (e.g., issuing warnings or evacuations). Because of their very high temporal resolution, GOES data might prove useful for documenting the thermal evolution of larger flows. However, MODIS imagery is better suited for quantitative estimates (e.g., heat flux, volume flux), and monitoring the geographic extent of larger flows.
Post-eruption effusion rates were successfully estimated from MODIS imagery, but because a single $M$ value that converts spectral radiance to TADR could not be confined for all flows, accurate real-time estimates for active eruptions might not be possible at this time. However, an $M$ value averaged from the three high-quality flows could possibly be used to test real-time calculations, and be compared with ground-based measurements. Even if this approach produces good results, ground-based effusion rates may still be more valuable than satellite-based measurements (mostly due to poor temporal resolution). Therefore, though quantitative satellite-based TIR data is useful for long-term monitoring and making relative observations, it should not be used as a primary means of risk assessment at Pacaya at this time. Future work aims to better constrain of the parameters of Equation 6 so that calculating effusion rates in near real-time may be possible.

Additionally, the effusion rates estimated here can be used as inputs in lava flow modeling software. If simulations using these effusion rates can generate flow directions and extents comparable to actual mapped dimensions, then a reasonably accurate lava flow risk map based on vent location and effusion rate can be produced. Then preliminary estimates of the extent of a new flow can be approximated and appropriate action can be taken to reduce losses at this active volcano.
5. CONCLUSION

This project aimed to independently calculate effusion rates for a subset of Pacaya’s historical flows using thermal infrared satellite imagery. Flows were chosen from the database of Matías (2009) based on the availability of satellite data. Images were acquired for each flow and hot spots were identified manually. Manual identification was necessary due to the low intensity of hot spots. Time-averaged discharge rates were estimated for each hot spot using the method of Harris et al. (1997a), and cumulative volumes were subsequently calculated, which were then calibrated to fit the values listed by Matías (2009).

It was determined that reasonably accurate TADRs could be estimated using this technique for MODIS data, but not for GOES data. Possible sources of error were discussed, and it was ultimately decided that GOES data should not be combined with MODIS data for quantitative assessment of the typical flows investigated here. For MODIS datasets, the coefficient $M$ necessary to attain the target volumes varied between individual flows. This variation was due primarily to an inability to precisely define the parameters of Equation 6 for each flow. Further research will aim to better constrain these through field observations and analysis of lava samples. However, four flows were considered to be of good quality because they had relatively complete datasets and were able to be fitted to Matías (2009) values using the most reasonable parameters. From these flows, two types of activity were identified 1) longer, low-effusion rate periods, and 2) shorter, high-effusion rate periods. It was suggested that the average effusion rate observed during the former represents “bleeding” of the conduit, so that the eruption rate approximates the supply rate to the shallow system. Within this model, sometimes lava is able to leak from the system at rates equal to the supply rate; other times, larger eruptions represent the release of lava that has accumulated during the non-eruptive, convective phases.

Radiance records for both types of activity indicate that MODIS imagery may be useful for determining relative levels of effusive activity in near-real-time at Pacaya. However, real-time quantitative monitoring (i.e. effusion rate estimation) is probably not a possibility until supplementary work to better constrain the parameters of the effusion rate equation can be carried out.
This project will be expanded over the next year (as the second part of this masters thesis), to explore several directions. This will include provision of information useful for hazard assessment; lava flow hazard maps will be made which take into account lava emplaced from vents around the cone fed at two characteristic effusion rates identified here. Field data and mapping will be also carried out to see if the morphological and chemical characteristics of the flows fit the proposed model.
6. REFERENCES


7. APPENDICES

7.1 Appendix A: Selected examples of hot spots

The following images are representative of the various types of hot spots encountered during this investigation. Each image shows the MIR band and corresponding LWIR band, with the hot pixels outlined in each image.

a. Ideal single-pixel MODIS hot spot. Note that there is essentially no increase in radiance in Band 31, justifying the use of the Band 31 pixel as background radiance.

b. Ideal MODIS hot spot. Note the two saturated pixels. These would still appear in the corresponding Band 21 image.

c. Hot spot with moderate cloud cover. Though the hotspot is very bright, it is unusable due to cloud cover.

d. Hot spot with heavy cloud coverage. Though the hot spot is very bright, it is unusable due to cloud cover. Note that the second pixel is saturated in Band 22.
e. Solar heating is evident over the entire image, and a thin layer of cloud covers the center and lower portion of the image. This hot spot is three pixels large, however two pixels are very dull.

f. Distorted hot spots that appear “broken”. These types of hot spot lie towards the edge of an image, and are unusable for effusion rate calculations.

g. A typical GOES hot spot, which is significantly duller than a MODIS hot spot. Note there is no cloud cover in this image.

h. A very bright GOES hot spot. Note that there is still no noticeable increase in brightness in Band 4.

i. A GOES image with slight cloud coverage. Note the very dull appearance of the hot spot.

j. GOES image exhibiting solar heating, but with a hotspot still evident.
7.2 Appendix B: Data calendars

The following calendars represent data coverage for each of the seven flows. In each cell, the top and bottom numbers are the number of usable MODIS and GOES images for that day, respectively.

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The calendars are designed to help visualize the data coverage for each day, with specific cells indicating the number of usable images for MODIS and GOES, along with designated areas for the beginning/end of the flow and month ends.
7.3 Appendix C: Lava chemistries and calculated densities

Lava chemistries were available for the prehistoric, historic, and modern (1961 – present) subphases in Eggers (1971), Bardznieff & Deniel (1992), and Matias (2009). Densities were calculated from the modern samples using the technique of Bottinga and Weill (1970). The average density was used in Equation 6 for each flow. Note the very similar chemistries throughout the dataset.

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## Bardinzteff and Deniel (1992)

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## Matías (2009)

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**Average Density:** 2678 kg/m$^3$